PROPERTIES OF GREEN SELF-COMPACTING CONCRETE DESIGNED BY PARTICLE PACKING DENSITY METHOD

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ABSTRACT

Since depletion of natural resources and the amount of construction and demolition waste have overcome the socially and environmentally acceptable level, the construction industry must address this issue and reduce its impact on the environment. A step towards sustainability in the construction industry is the application of recycled aggregates and supplementary cementitious materials as integral components of concretes, which provides conserving natural aggregates and waste reduction. This study adopts a holistic approach to producing green self-compacting concrete with the highest portion of recycled aggregate as a replacement for natural aggregate and fly ash as filler. Based on the particle packing density method, four series of self-compacting concrete were prepared: the first series was made with natural fine and coarse aggregate, the second series was made with fine natural aggregate and recycled coarse aggregate, the third with 50 % (by mass) of fine natural aggregate replaced by recycled fine aggregate and recycled coarse aggregate, and the fourth series completely with recycled fine and coarse aggregate. The content of fly ash remained constant. Regardless of the expected decrease of workability in a fresh state with the increase of the recycled aggregate content, all series exceeded the requirements set for the hardened structural concrete.

Keywords: *self-compacting concrete, sustainability, recycled aggregate, fly ash, physical and mechanical properties*

INTRODUCTION

Sustainable development of construction industry has become a growing concern, and a challenge faced by civil engineers. It is estimated that the worldwide annual production of concrete, as the most prominent construction material, is approximately 20 billion tonnes [1]. The large annual production of concrete consequently leads to an equally large consumption of component materials, aggregates, cement, and water. As a result, the environmental impact of the construction industry is reflected in the depletion of natural resources. On a global scale, the estimated annual consumption of natural resources surpassed 40 % of raw stone, gravel, and sand, 25 % of virgin wood, 16 % of water, and 40 % of total energy [2]. Furthermore, total world production of cement hit 4.1 billion tonnes in 2019 [3], and it was estimated that it will exceed 6 billion tonnes till 2025 [4]. Given that production of cement itself yields approximately 7 % of the total CO_2 emission worldwide, it is recognized as one of the major environmental concerns [4]. On the other hand, significant increase in population and urbanization has led to increase in construction and demolition waste discarded in landfills, representing an environmental hazard. In the EU alone, 850 million tonnes of construction and demolition waste is generated, accounting for around 30 % of total waste [5]. One of the alternatives for reducing CO_2 emissions associated with cement and concrete industry can be sought in the application of recycled aggregates obtained by crushing waste concrete, as well as partial replacement of cement with waste or supplementary cementitious materials, such as fly ash, a by-product of coal combustion processes in thermal power plants [6] considered as pozzolanic material.

Self-compacting concrete (SCC) is a special type of concrete that does not require equipment for compaction process after the placing due to its unique composition and properties [7]. Based on collected data of the numerous research and studies carried out worldwide in previous years, it has been concluded that the application of SCC has significant advantages over conventional vibrated concrete, primarily reflected in social, economic, and ecological benefits [8]. These benefits include faster casting of concrete, reduced equipment and human factor, improved mechanical properties and durability. SCC can support sustainable development, primarily due to the efficient application of various industrial by-products for its production, enabling use of recycled aggregate and fly ash as integral components. Such activity provides reduction of construction waste, and helps preserve natural aggregate, while reducing CO_2 emissions.

A well-designed mixture of concrete is a prerequisite for high quality durable concrete, with good properties both in fresh and hardened state. In this study, four mixtures of SCC were designed using particle packing density method (PPM), applicable both for normal vibrating and self-compacting concrete. The concept of the PPM method is based on achieving dense aggregate packing with minimal voids content, thereby reducing the required amount of water and cement for production of concrete [9]. If the particle composition of a concrete mixture is optimized in such a manner to increase maximum particle packing density, less water is entrapped in voids. Turning this void water into excess water ensures better flowability, and the quantity of water for concrete can even be reduced. Such reduction of water leads to the reduction of cement content, making it possible to produce concrete of good workability and strength. The developed concrete can be qualified as ecological, and thus it can provide contribution to sustainable development.

PARTICLE PACKING DENSITY METHOD FOR SCC

In order to experimentally determine the quantities of each fraction of aggregate for SCC, and the other components consequently, the PPM method was applied. According to the PPM procedure, the content of fractions was adopted based on the experimentally obtained maximum density of mixture of three fractions.

All components ratios in SCC mixture were obtained based on the determined maximum bulk density of aggregate packaging. One of the main features of self-compacting concretes is their fluidity, and as such they require more cement paste than conventional vibrated concrete to achieve targeted slump flow, while retaining homogeneity and lowering the risk of segregation (bleeding or aggregate settling).

Recycled aggregates are by their nature more porous, and they are strong water absorbents because of residual cement mortar. Based on initial experimental procedures and calculations carried out in this study, it was safe to assume that paste volume should be increased by approximately 30 % of the void volume between the aggregate grains. Therefore, with the fixed values of each fraction contributions x_i (already obtained experimentally) and gravities $\gamma_{s,i}$, the void volume v_v in the mixture of aggregate was first determined as:

$$v_v = 1 - \gamma_{mix} \cdot \sum_{i=1}^{3} \frac{x_i}{\gamma_{s,i}} \; . \quad (1)$$

The paste was then estimated, as explained, to have 30 % larger volume than the calculated void volume. Based on that, and the premise that 2 % of entrained air is contained in mixture, the volume of aggregate v_a without voids was obtained for unit volume of concrete:

$$v_a = 1 - 1.3 \cdot v_v - 0.02 \quad (2)$$

Having in mind the following equation for gravity γ_s of the aggregate mixture:

$$\frac{1}{\gamma_s} = \sum_{i=1}^{3} \frac{x_i}{\gamma_{s,i}} \quad (3)$$

the quantities m_i of fractions were calculated for unit volume of concrete as:

$$m_i = x_i \cdot \frac{v_a}{\gamma_s} \quad (4)$$

Furthermore, for the fixed water to cement ratio and for the fixed ratio of cement and fly ash, the quantities of these components were also calculated. The chemical admixture content was fixed based on trial mixtures.

EXPERIMENTAL

General remarks

In this study four mixtures of SCC were produced on the basis of particle packing density method (PPM). The aim of the study was to achieve maximum density of aggregate packaging, and thus reduce cement paste needed, while retaining fresh state properties that are necessary to be characterised as self-compacting (i.e. being able to flow and compact under its own weight, to fill formwork completely and to wrap around reinforcement bars, flowing uniformly between the obstacles, while maintaining homogeneity). Because of these requirements, the component materials had to be critically evaluated, regarding their properties and ratios in final concrete mixtures.

Materials

Fine and coarse natural river aggregates (NA) from the river Danube were used at different amounts. The aggregates were separated in three usual fractions: I (0/4), II (4/8), III (8/16). Gravity of the aggregates were 2.68, while densities of these three fractions were respectively: 1662 kg/m^3, 1526 kg/m^3 and 1502 kg/m^3 in loose, and 1793 kg/m^3, 1634 kg/m^3 and 1612 kg/m^3 in compacted state. Water absorption of natural aggregate fractions was also an important property, which had to be determined (Figure 1).

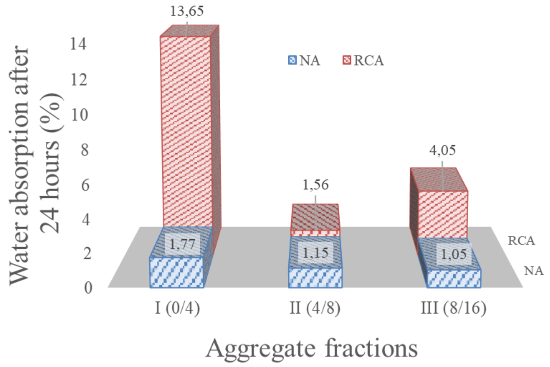

Figure 1. Water absorption of NA (natural aggregate) and RCA (recycled concrete aggregate)

Recycled concrete aggregates (RCA) (Figure 2) were obtained by crushing laboratory cube specimens using *Retsch Jaw Crusher BB 300*, and then screened and separated into three fractions: I (0/4), II (4/8), III (8/16) by motor operated sieve shaker. Gravity of the RCA was

2.60, while densities of three RCA fractions were respectively: 1422 kg/m^3, 1457 kg/m^3 and 1319 kg/m^3 in loose, and 1449 kg/m^3, 1482 kg/m^3 and 1345 kg/m^3 in compacted state.

Figure 2. Different sizes of fine and coarse RCA (recycled concrete aggregate)

One of the main differences between recycled and natural aggregate is higher water absorption of recycled aggregate, attributed to quality and thickness of adhered mortar layer around the grains of aggregate. Increased water absorption of recycled aggregates harshly affects the consistency of concrete and several properties of hardened concrete of interest for durability (water absorption, frost resistance, carbonization, etc.). To obtain the necessary amount of water for the cement hydration process, and the additional water to fill the aggregate pores in the mixing process, the water absorption of each fraction of the recycled aggregate was determined (Figure 1).

In order to determine the quantities of aggregate, an experimental procedure was performed. For different percentage ratios of II (4/8) and III (8/16) fraction, maximum loose bulk density of II (4/8) and III (8/16) fractions mixture was experimentally determined as 50 % : 50 % (or 1 : 1). In the second stage, with this ratio fixed to 50 : 50, the fine fraction was introduced at different ratios. Finally, this process leads to the determination of the maximum loose bulk density of the mixture of three fractions, which was obtained at I : II : III = 50 % : 25 % : 25% ratio (Figure 3).

In this study, commercially available Portland-composite cement CEM II/A-M (S-L) 42.5R Lafarge, Beočin was used, described by the producer as suitable for high strength and durable concretes. The gravity of cement was 2.98 and densities in loose and compacted state were respectively 1080 kg/m^3 and 1210 kg/m^3. According to the producer, the used cement contained 80 - 94 % Portland cement clinker, 8 - 20 % ground slag and limestone, and 0 - 5 % gypsum and inert mineral fillers.

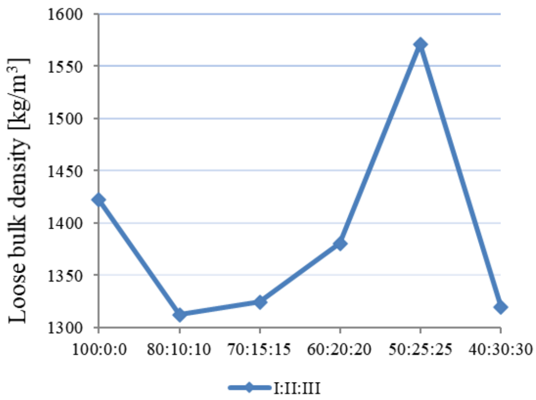

Figure 3. Maximum loose bulk density of RCA mixture

Fly ash (FA) was used as the only filler in SCC and its content was fixed at 45 % of total binder. The gravity of fly ash was 2.21 kg/m^3 and densities in loose and compacted state were respectively 730 kg/m^3 and 950 kg/m^3. Since the content $SiO_2 + Al_2O_3 + Fe_2O_3$ in fly ash was 83.8 %, FA was classified as type F according to ASTM C 618 [10] standard. Chemical composition of fly ash and cement is presented in Table 1.

The chemical admixture *Cementol Hiperplast 463* (TKK) was added to all mixtures in an amount of 1.5 % (determined on the basis of different trial mixes) of cement mass. The used water was tap water from the city water supply.

Concrete composition and tests

The calculation regarding PPM was performed for the reference SCC, and then the components were varied in order to investigate the effects. As shown in Table 2, coarse recycled aggregate (CRA) was used as a substitution of 100 % and 0 % of natural coarse aggregate (CNA) by weight in four mixtures, depending on the mixture.

Table 1. Chemical composition of fly ash and cement

Composition	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	Na_2O	K_2O	MnO	LOI
Values for fly ash (%)	58.24	20.23	5.33	0.45	7.62	2.01	0	2.21	0.52	1.51	0.03	1.64
Values for cement (%)	20.73	5.68	3.32	0.23	59.60	1.89	0	3.72	0.36	0.61	0.01	3.73

Table 2. Mixture composition of SCC in kg/m^3

Mixture	FNA	CNA		FRA	CRA		Cement	Fly ash	HRWR	Total water	W(k)
	I (0/4)	II (4/8)	III (8/16)	I (0/4)	II (4/8)	III (8/16)					
CRA0/ FRA0	695.0	347.5	347.5	-	-	-	404.5	181.2	6.1	200.0	0.44
CRA100/ FRA0	695.0	-	-	-	347.5	347.5	404.5	181.2	6.1	206.0	0.45
CRA100/ FRA50	347.5	-	-	347.5	347.5	347.5	404.5	181.2	6.1	249.0	0.54
CRA100/ FRA100	-	-	-	695.0	347.5	347.5	404.5	181.2	6.1	296.4	0.65

For each of these four mixtures, the incorporation level of fine recycled aggregate (FRA) was fixed at 100 %, 50 %, and 0 % by weight of fine natural aggregate (FNA). All mixtures were produced with fly ash as a filler (the addition was 45 % of the cement mass). Reference concrete was produced only with coarse and fine natural aggregate. The water to cement (W/C) ratio and the high-range water reducer (HRWR) dosage were kept the same for all concretes, i.e., 0.45 and 1.5 % of cement mass, respectively. Additional water was introduced due to the absorption of aggregate, affecting the total water content for each mixture. If the k-value concept would be implemented for the use of fly ash, according to the standard EN 206 [11] (ratio of fly ash to cement restricted to 0.33), the calculated value W(k) of the ratio water/(cement + k x mineral admixture) is given in the last column of the table, for k = 0.4 (CEM I 42.5 and higher).

A laboratory concrete mixer with a capacity of 60 l was used. The coarse and fine aggregates were mixed for one minute in the concrete mixer, then the filler and cement were added and mixed for 30 s. Afterwards, water with the superplasticizer admixture was added and mixing was continued until homogeneity (270 s). The preparation was performed at the ambient temperature (20 - 22 °C).

Tests performed on SCC mixtures included tests of fresh and hardened properties. Fresh tests included: density, slump flow, slump flow time (t_{500}), and V-funnel time (t_v). Tests on hardened concrete included: density (12 x 12 x 36 cm prisms), compressive (10 cm cubes) and flexural (12 x 12 x 36 cm prisms) strength, and static modulus of elasticity (Ø15/H30 cm cylinders). All tests were performed according to the standards specified in EN 206 [11], with exception of flexural strength, which was done according to the standard SRPS U.M1.010 [12] due to the shape of the specimens. The obtained results present average of at least three measurements.

RESULTS AND DISCUSSION

The results of the tests performed on fresh SCC mixtures are presented in Table 3. As can be seen from the table, density of the mixtures decreased substantially with incorporation of higher content of recycled aggregate. The incorporation of fine recycled aggregate resulted in higher decrease in density than for the coarse recycled aggregate. All the mixtures showed high flowability with values of slump flow on the upper limit according to the standard EN 206 [11], and only the mixture that contained both fine and coarse recycled aggregate had higher viscosity, i.e., measured time t_{500}. The obtained classes for the slump flow (SF), flow time (VS), and V-funnel time (VF) according to the limits from the standard EN 206 [11] are also given. Nevertheless, V-funnel values were quite high for all mixtures, and the highest value was recorded for the mixture with coarse recycled aggregate and 50 % river/recycled fine aggregate. The value was above the upper limit according to the standard EN 206 [11], which is why it cannot be classified into any V-funnel category. With exception of the last mixture, increase in fine aggregate contributed to the noted negative effect of incorporating coarse recycled aggregate as replacement for river aggregate. Also, as expected, a significant decrease in workability and placeability was observed shortly after mixing for mixtures containing recycled concrete aggregate (Figure 4). This issue cannot be attributed only to the fly ash presence, but also to the process of water absorption by recycled concrete aggregates.

Table 3. Properties of the fresh SCC mixtures

Mixture		CRA0/FRA0	CRA100/FRA0	CRA100/FRA50	CRA100/FRA100
Density	(kg/m^3)	2337	2268	2239	2188
Slump flow	(mm)	910	895	895	910
	class	SF3	SF3	SF3	SF3
t_{500}	(s)	1.89	1.85	1.90	2.45
	class	VS1	VS1	VS1	VS2
V-funnel	(s)	18.84	23.32	32.00	19.65
	class	VF2	VF2	-	VF2

The results of tests performed on hardened SCC mixtures are presented in Table 4. These tests were performed on 28-day-old concrete, although the further increase in compressive strength was expected due to presence of fly ash in all mixtures. Trends for the densities were similar to those recorded on fresh SCC. The values of compressive strength were quite high, having in mind the water to cement ratio, as well as the use of recycled aggregate.

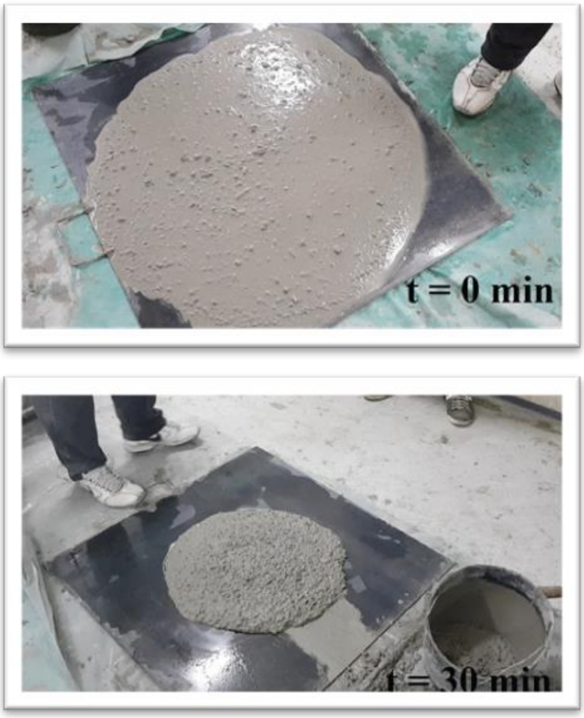

Figure 4. The decrease in workability of SCC characterized by slump-flow measurements immediately and 30 minutes after the mixing

Table 4. Properties of the hardened SCC mixtures

Property	CRA0/FRA0	CRA100/FRA0	CRA100/FRA50	CRA100/FRA100
Density after 28 d, kg/m^3	2326	2256	2226	2178
Compressive strength after 28 d, MPa	78.1	74.5	71.0	57.3
Flexural strength after 28 d, MPa	9.9	10.7	7.8	6.4
Elasticity modulus after 28 d, GPa	37.07	35.83	30.24	26.83

Even the last SCC mixture, where aggregate and filler were environmentally favourable, reached a value that could be classified as C 40/50 concrete, which is quite high, and is used for more complex and demanding structures. This can be explained by optimisation performed by PPM, as well as the use of fly ash. As expected, as a trend, a higher content of recycled aggregate led to lower mechanical performances, both in compressive and flexural behaviour. Modulus of elasticity (Figure 5) followed the trend recorded for compressive strength. If changes of modulus of elasticity and compressive strength with aggregate are considered as linear trends, a decrease in modulus elasticity can be characterized as milder compared to the decrease in compressive strength.

Figure 5. Measurement of the modulus of elasticity of SCC series

CONCLUSION

This paper presents the application of several contemporary concepts in order to produce green concrete, while preserving self-compacting capacity. Environmentally favourable components were used - recycled concrete aggregate (both fine and coarse), and fly ash as filler.

The main concept applied in the design of the studied mixtures was particle packing density method. By experimentally obtaining ratios of fine and coarse aggregates on the basis of packing requirements and applying sufficient amount of proper paste component, it was shown that optimal compositions of self-compacting concrete can provide higher than average mechanical properties.

Nevertheless, the use of recycled concrete aggregate and fly ash embodies challenges such as higher amount of water, fast decrease in workability, and decrease in mechanical properties in hardened state. Although identified and successfully addressed in this study, these issues must be considered as main obstacles for wider application of compositions similar to those in this study.

REFERENCES

[1] P.K. Mehta, Greening of the Concrete Industry for Sustainable Development, Concrete International 24(2002) 7, 23-28.

[2] M.K. Dixit, J.L. Fernández-Solís, S. Lavy, C.H. Culp, Identification of parameters for embodied energy measurement: A literature review, Energy Build 42(2010) 8, 1238-1247. https://doi.org/10.1016/j.enbuild.2010.02.016

[3] https://www.statista.com/statistics/219343/cement-production-worldwide/, Accessed: February 28, 2022.

[4] R.M. Andrew, Global CO_2 emissions from cement production, Earth System Science Data 10(2018) 1, 195-217. https://doi.org/10.5194/essd-10-195-2018

[5] C. Fischer, M. Werge, EU as a Recycling Society: Present Recycling Levels of Municipal Waste and Construction & Demolition Waste in the EU, European Topic Centre on Sustainable Consumption and Production, Copenhagen, 2009.

[6] V.M. Malhotra, Role of Supplementary Cementing Materials in Reducing Greenhouse Gas Emissions, in: Concrete Technology for a Sustainable Development in the 21st Century, ed: O.E. Gjorv, K. Sakai, CRC Press. London, 2000. https://doi.org/10.1201/9781482272215-23

[7] H. Okamura, M. Ouchi, Self-Compacting Concrete, Journal of

Advanced Concrete Technology 1(2003) 1, 5-15. https://doi.org/10.3151/jact.1.5

[8] A. Savić, Istraživanje svojstava svežeg i očvrslog samozbijajućeg betona sa mineralnim dodacima na bazi industrijskih nusprodukata, Univerzitet u Beogradu, Građevinski fakultet, Beograd, 2015.

[9] M. Vasić, Fizičko-mehanička svojstva zelenih samougrađujućih betona projektovanih metodom maksimalne gustine pakovanja zrna, Univerzitet u Beogradu, Građevinski fakultet, Beograd, 2019.

[10] ASTM C 618: Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, 2003.

[11] EN 206:2013 Concrete. Specification, performance, production and conformity, 2013.

[12] SRPS U.M1.010 Ispitivanje čvrstoće betona na zatezanje pri savijanju prizmi (koncentrisano opterećenje u sredini raspona).

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