New scientific results of the Ph.D. thesis

Green Self-compacting High-performance Concrete

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1. INTRODUCTION

The introduction of the idea of sustainable development in the Rio Summit in 1992 (Agenda, June 1992) has not been in vain. It yielded a conscious recognition of the massive population growth witnessed in the last century and the forward-looking assessment of the advent of rapid urbanization of developing countries. Work on sustainable technologies has been the focus in the early 21st century. Meanwhile, concrete is the most widely used material in the construction industry because of its numerous benefits. This industry consumes large amounts of natural resources and emits tremendous CO₂ quantities by cement production alone. Concrete, a composite material mainly composed of cement, aggregate and water, uses approximately 20 billion tons of raw materials annually (Fredonia, 2011). Thus, aggregates that occupy around two-thirds of concrete volume have primarily been contributing to the increase in the world aggregate demand to over 48 billion tons annually after 2010 (Hong Kong Government, 2006), which can double in the next two to three decades if the present rate of consumption of aggregates and concrete continues (Oikonomou, 2005). Furthermore, aggregate processing, such as mining and transport operations used for buy and transfer, considerably increases carbon emission and energy consumption (Limbachiya et al., 2012). The form assumed by construction and demolition (C&D) waste generated by the construction sector cannot be eliminated easily by conventional means. This waste is dumped in landfill sites, where it negatively affects the environment, and space available for landfill is becoming increasingly scarce because of industrialization and urbanization. Means of using C&D structural concrete application waste are urgently needed because of the excessive availability of such waste and the reduction in the cost of acquiring aggregates (Kisku et al., 2017). This development can allow the concrete industry to sustain continuous growth while reducing its carbon footprint and the resulting harm to the environment. The concept of using coarse recycled concrete aggregate (RCA) instead of virgin coarse natural aggregate (NA), which emerged in England during World War II, was initially used in pavement construction.

Researchers’ investigations on recycling demolition waste concluded that it can be used to replace NA, and it paved the way for present use by unlocking the reuse of C&D waste and promoting the use of RCA in new and different concrete types. Various materials have become a necessity for a sustainable, green and innovative future. At the end of 2017, Kisku et al. (2017) investigated hundreds of research papers about RCA and concluded that the use of mineral additives could enhance the properties of recycled aggregate concrete (RAC). They recommended further research about the addition of unconventional waste materials as cement replacement materials (CRMs) and the long-term behaviour of RAC with respect to mechanical and durability properties. Meyer (2009) investigated several waste materials used as CRMs and concluded that the use of RCA, along with the addition of a suitable percentage of industrial wastes, could be highly beneficial. The use of RCA as a replacement of NA for producing RAC has been extensively explored, but only a few studies have applied the concept of RCA on self-compacting concrete (SCC) (Rajhans et al., 2018; Omrane et al., 2017). Industrial application, which will be beneficial from the perspective of technical, financial, direct environmental, indirect environmental, social and its properties, is also scarce (Aslani et al., 2018; Wijayasundara et al. 2018; Wijayasundara et al., 2017). For instance, in a past work, CO₂ emission could be 24% lower than the control mix with the incorporation of RCA (Yap et al., 2018), but
additional superplasticiser was needed for achieving SCC (Guo et al., 2018). According to the literature, the contemporary orientation regarding recycling aligns with non-covenantal utilisation of RCA either by use of special types of waste materials, such as unprocessed waste powder materials, or/and by adopting these materials in special types of concrete, such as self-compacting high-performance concrete (SCHPC).

2. RESEARCH SIGNIFICANCE

Economic activity must be performed such that it is in harmony with the earth’s ecosystem, where the sustainability of engineering products is not a choice anymore but a demand. SCHPC is a new generation of concretes that is based on the concepts of SCC and high-performance concrete (HPC). Therefore, it is a highly advanced type of concrete that possesses adequate self-compactibility, high strength and good durability. A green version of this concrete could be developed by the replacement of a specific amount of its ingredients by waste materials, where sustainable and economic value could be added. Given the increasing daily amount of construction waste (in granulated or powder form), the necessity of eliminating these wastes without harming the environment has become urgent. The concept of utilising the waste materials in construction is a quantum leap for not merely removing the waste but also introducing them into construction, thereby further contributing to enhancing the properties of concrete. Moreover, modern materials, such as SCHPC, must be accompanied by the application of the principle of the 5-R perspective, which states that the key principles of a sustainable construction material are ‘reduce, reuse and recycle for environment recovery and respect’ and end of life can be new materials for new constructions.

3. SCOPE AND LIMITATIONS

RCA and three waste powder materials (raw materials without any processing or modification) were selected for replacing partially the NA and cement, respectively. The three waste powder materials were the following:

1. waste fly ash (WFA), collected from a coal power station in Hungary (Visonta coal-fired thermal power station) and delivered to the laboratory for use in the testing programme without any processing.
2. waste perlite powder (WPP), is an amorphous volcanic silicate/alumina rock originating from raw perlite resulting from the cutting of raw perlite rock.
3. waste cellular concrete (WCC), collected from a factory for cutting cellular concrete masonry in Hungary.

Several laboratory experiments were conducted on the produced concretes, and nearly all properties that were directly interconnected with the concretes’ macro/microstructure were determined for introducing a comprehensive overview with regard to the challenges and possibilities of the new Green SCHPC. The proposed material was optimised for the use of the best possible waste powder materials and achieving the highest performance/cost ratio via specification of constraints and variable parameters. The laboratory tests were conducted at different ages (days 0, 28, 90 and 270) of the produced concrete to cover the short and long terms of the mechanical properties, durability performance and fire resistance, in addition to the fresh properties, of SCHPC.
4. AIM AND OBJECTIVES

The main aim of this Ph.D. thesis was to optimise a green version of SCHPC by analysing the effect of using RCA as a partial replacement of NA and unprocessed waste powder materials as CRMs on its fresh and hardened properties. The reasoning behind producing a green version of SCHPC was to minimise concrete’s impact on the environment while maximising its performance and service life, furthermore to turn a non-renewable resource into a renewable one at least partially. This aim was achieved via the following objectives:

1. To optimise a SCHPC mixture’s proportioning and procedure with 75 MPa target strength and SF2 slump flow class;
2. To determine the maximum replacement possibility of cement by the unprocessed waste powder materials (WFA, WPP and WCC) by testing the effective reactivity index of binder pastes;
3. To specify the possible replacement amount limits of RCA and/or CRMs in the workability window of the SCHPC and define the minimum dosage of superplasticiser;
4. To evaluate the efficiency of using different amounts of unprocessed waste powder materials as CRMs for producing SCHPC, that is, with/without incorporating RCA as a replacement of NA at short and long terms with respect to the mechanical properties, durability performance and fire resistance;
5. To evaluate the possible effect parameters of concrete (replacement amounts and types of CRMs, replacement amounts of RCA and water absorption) on the properties of either RCA or multiple recycled concrete aggregate (MRCA);
6. To verify the possibility of multiple use of RAC as a second generation of recycling with respect to the mechanical properties and microstructural properties.

5. EXPERIMENTAL PROGRAM

The experimental investigation of the various SCHPC mixtures comprised the selection and testing of materials, testing of aggregate blends, design of concrete mixtures, testing of binder pastes, preparation and testing of fresh and hardened concretes and preparation and testing of the fresh and hardened properties of multiple recycled aggregate concrete (MRAC). In addition, several tests for measuring the key properties of RCA and MRCA were developed. The overall experimental investigation procedure is shown in the flowchart given in Fig. 1.

Mixes with 500 kg/m$^3$ powder content and 0.35 w/b ratio were kept constant throughout the experiment. The water absorbed by the RCA was compensated by the addition of water to the mixture. Twenty-one concrete mixes of SCHPC incorporating RCA and different CRMs were designed. The mixes were divided into seven series, depending on the substitution ratios of cement and NA. The cement substitution ratios by CRMs were 0%, 15% and 30% by mass (based on paste stage results for the activation index), whereas the NA substitution ratios by RCA were 0%, 25% and 50% by mass (based on the literature). All mixtures were based on the reference mix design which is initially optimised for the project throughout the seven series, those sample matrixes are explained in Table 1.
Fig. 1 Overall research program
A low w/b ratio was used to achieve the rheological properties of SCC in which the mixture must be more workable than normal concrete. Thus, a considerable amount of superplasticiser was required to achieve the deformability and resistance to segregation at fresh state. The same quantity of superplasticiser was used for each series to investigate the actual effect of each replacement amount of RCA and unprocessed waste powder materials on the fresh properties of SCC.

The specimens were cast in steel molds of different sizes to obtain the standard specimens for each test. All specimens were stored under lime-saturated water for seven days and then moved to laboratory ambient conditions (20 °C ± 2 °C) until the time of the test. The tests were conducted in different ages (28, 90, and 270 days). The objective of this experiment is to study the performance of the fresh, mechanical, durability properties of the green SCHPC in addition to its fire resistance, while taking into consideration the percentage of replacement of NA and cement.

### Table 1 Series matrix

<table>
<thead>
<tr>
<th>Series #</th>
<th>Replacement of cement</th>
<th>0% RCA replacement of coarse aggregate</th>
<th>25% RCA replacement of coarse aggregate</th>
<th>50% RCA replacement of coarse aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series I</td>
<td>0%</td>
<td>RA0</td>
<td>RA25</td>
<td>RA50</td>
</tr>
<tr>
<td>Series II</td>
<td>15% WFA</td>
<td>F15RA0</td>
<td>F15RA25</td>
<td>F15RA50</td>
</tr>
<tr>
<td>Series III</td>
<td>30% WFA</td>
<td>F30RA0</td>
<td>F30RA25</td>
<td>F30RA50</td>
</tr>
<tr>
<td>Series IV</td>
<td>15% WCC</td>
<td>C15RA0</td>
<td>C15RA25</td>
<td>C15RA50</td>
</tr>
<tr>
<td>Series V</td>
<td>30% WCC</td>
<td>C30RA0</td>
<td>C30RA25</td>
<td>C30RA50</td>
</tr>
<tr>
<td>Series VI</td>
<td>15% WPP</td>
<td>P15RA0</td>
<td>P15RA25</td>
<td>P15RA50</td>
</tr>
<tr>
<td>Series VII</td>
<td>30% WPP</td>
<td>P30RA0</td>
<td>P30RA25</td>
<td>P30RA50</td>
</tr>
</tbody>
</table>

6. MULTIPLE RECYCLED CONCRETE AGGREGATE

Then the properties of different types of crushed aggregates have been investigated by taking into consideration the properties of their parent concrete, which was either NA concrete or RAC. After testing the mechanical properties of the 21 concrete mixes of SCHPC, the rubble of the specimens were crushed and saved for up to six months under laboratory conditions for eliminating the effect of proceeding hydration as much as possible and for confirming the behaviour with the normal situation of using crushed aggregates in real applications. Then, they were sieved for obtaining the coarse fraction of the aggregates (4/16 mm). Twenty-one crushed aggregate types were produced, where the main difference between the aggregate types was the type of parent concrete in the first generation. In the final step, the aggregate samples were prepared for testing water absorption capacity and Los Angeles abrasion.

7. MULTIPLE RECYCLED AGGREGATE CONCRETE

This part considered the possibility of using MRCA in concrete production. Two RCA replacements (25% and 50%) of NA for producing RAC (the first generation of recycling), which produced in the previous stage in series I and known by RA25 and RA50. The same procedure is then repeated but with the use of MRCA (resulting from crushing the first generation of concrete) to produce the second generation of concrete. To evaluate the performance of the second generation concrete made by MRCA, the MRCA produced by crushing RA25 and RA50 has been used again for producing the second generation of concrete. Where:
1. **MRA25** is MRCA produced from the first generation of RAC, which was originally prepared with 25% substitution of NA by RCA.

2. **MRA50** is MRCA produced from the first generation RAC, which was originally prepared with 50% replacement of NA by RCA.

The sequences of using NA–RCA–MRCA for producing the second generation of concrete are shown in Figure 2. Seven concrete types were fabricated in total, one non-recycled, two recycled and four re-recycled. The objective of this experiment is to study the performance of the fresh, mechanical, physical and microstructural properties of MRCA while taking into consideration the percentage of replacement of NA by RCA in the parent concrete.

**Fig. 2** Sequences of using NA, RCA, and MRCA (main concept)

8. **DESIGN VARIABLES AND CONSTRAINTS**

The variables and constraints corresponding to the SCHPC mixtures of all produced concretes are shown in Table 2. The main variable parameters were the cement content, coarse aggregate type, type of CRM and the added proportion of CRM. The constant parameters were the slump flow classification, w/b ratio, cement type and the particle size distribution fractions, with an maximum aggregate size of 16 mm. Finally, 19 cement paste mixtures, 26 SCHPC mixtures and 22 types of RCA and MRCA were produced.

**Table 2** Variable and constraint parameters for all produced SCHPC mixtures

<table>
<thead>
<tr>
<th>Variables</th>
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</thead>
<tbody>
<tr>
<td>1. Cement content (kg/m³): 500, 425 and 350</td>
</tr>
<tr>
<td>2. CRM content amount (kg/m³): 0, 75 and 150</td>
</tr>
<tr>
<td>3. CRM content type: WFA, WPP and WCC</td>
</tr>
<tr>
<td>4. Coarse aggregate type and amount (%):</td>
</tr>
<tr>
<td>4.1. NA: 50 and 75</td>
</tr>
<tr>
<td>4.2. RCA: 0, 25 and 50</td>
</tr>
<tr>
<td>4.3. MRA25: 0, 25 and 50</td>
</tr>
<tr>
<td>4.4. MRA50: 0, 25 and 50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Powder content amount (kg/m³): 500</td>
</tr>
<tr>
<td>2. MAS (mm): 16</td>
</tr>
<tr>
<td>3. w/b ratio (by mass): 0.35</td>
</tr>
<tr>
<td>4. Cement type: OPC - CEM I 42.5 N</td>
</tr>
<tr>
<td>5. Aggregate fractions: 0/4 mm (45%) and 4/16 mm (55%)</td>
</tr>
</tbody>
</table>
More than 3000 samples of various SCHPC incorporating partially RCA as replacement of NA and unprocessed waste powder materials as CRMs were produced and tested. More than 200 studies in research papers, theses, books and standards were reviewed, and excerpts from them were used in the preparation of this thesis, which may serve as a valuable document for researchers working in this direction. The constituent materials and the paste components of the concretes were primarily investigated for their key fresh and hardened properties. Subsequently, the key fresh properties and the major hardened properties of the concretes were determined. Three CRMs were investigated, namely, WFA, WPP and WCC. The effects of RCA content, CRM type, CRM content and high-range water reducer admixture (superplasticiser) content were examined. In addition, the possibility of reusing RAC as MRCA for producing a second generation of recycling concrete was investigated after the study of the key properties of RCA and MRCA. Finally, green versions of SCHPC were introduced. The method followed by this research proposes a design procedure for the mixture proportion of SCHPC. The main research findings are given below.

9. NEW SCIENTIFIC RESULTS

Self-compacting high-performance concrete proved its sensitivity to the ingredient proportions and mixing procedure, which is much more than other types of concrete. Where the aggregate fraction distribution, water to cement ratio and cement content, in addition to the mixing procedure had a significant effect on its compressive strength and workability performance. All mixtures have been tested for the V-funnel and slump flow tests and I proved that the workability window of normal self-compacting concrete which suggested by the European guidelines of self-compacting concrete is also satisfied the self-compacting high-performance concrete without any modifications. [2][3][5][6].

The following points presented the main new scientific results, which proved through this work based on the conducted experimental program and analytical study:


Where; RA0, RA25 and RA50 mean self-compacting high-performance concrete incorporated 0%, 25% and 50% of coarse recycled concrete aggregate as a replacement for coarse natural aggregate respectively.

The urgent need to utilize the coarse recycled concrete aggregates stems from the general problem of the huge amounts of construction and demolition waste because of wars and natural disasters in some places around the world, not to mention the lack of natural resources elsewhere. The coarse recycled concrete aggregate has been used as a replacement for coarse natural aggregate with up to 50% to evaluate its efficiency in terms of its short and long-term properties, especially that the coarse aggregate is one of the defining factors in achieving the expected benefits from the self-compacting high-performance concrete.
1.1 I experimentally proved that the using of coarse recycled concrete aggregate as a replacement for coarse natural aggregate up to 50% enhances the mechanical and durability performance of self-compacting high-performance concrete, in terms of the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, freeze/thaw resistance, and chloride penetration. [3][6]. Fig. 3 and Fig. 4.

![Graphs showing mechanical properties](image)

**Fig. 3** Mechanical properties (average values) at 28, 90, and 270 days of self-compacting high-performance concrete incorporated 0%, 25% and 50% coarse recycled concrete aggregate as a replacement for coarse natural aggregate

1.2 I experimentally proved that the improvement in the properties continue by time and post hardening in case of incorporating coarse recycled concrete aggregate in concrete is higher at ages longer than 28 days, where its properties are more representative. [3][6]. Fig. 3.

![Graphs showing mechanical properties](image)

**Fig. 4** Chloride migration coefficient (average values) at 90 and 270 days and the average values of scald materials after 7, 14, 28 and 56 freeze/thaw cycles at 270 days of self-compacting high-performance concrete incorporated 0%, 25% and 50% coarse recycled concrete aggregate as a replacement for coarse natural aggregate
1.3 I experimentally proved that using up to 50% of coarse recycled concrete aggregate as a replacement for coarse natural aggregate enhances the fire resistance of self-compacting high-performance concrete, in terms of the residual compressive strength and flexural strength at 90 and 270 days. [4][9]. Fig. 5 and Fig. 6.

Fig. 5 Relative residual compressive strength and flexural strength as a function of temperature for self-compacting high-performance concrete compositions with coarse recycled concrete aggregate replacement rates at age of 90 days

Fig. 6 Relative residual compressive strength and flexural strength as a function of temperature of self-compacting high-performance concrete compositions with coarse recycled concrete aggregate replacement rates at age of 90 and 270 days.


Where; F15 and F30 mean self-compacting high-performance concrete incorporated 15% and 30% of waste fly ash as a replacement for cement respectively. C15 and C30 mean self-compacting high-performance concrete incorporated 15% and 30% of waste cellular concrete as a replacement for cement respectively. P15 and P30 mean self-compacting high-performance
concrete incorporated 15% and 30% of waste perlite powder as a replacement for cement respectively, while RA0 means self-compacting high-performance concrete without incorporation of coarse recycled concrete aggregate.

Self-compacting high-performance concrete requires a high amount of powder materials i.e. cement and cement replacing materials to obtain adequate rheological properties and targeted requirement. Powder materials are of the particular interest as they contribute to partially substitute the cement, which is the most cost and energy intensive ingredients of concrete. Three unprocessed waste powder materials were investigated, in terms its applicability and adequacy as cement replacing materials. In this framework, paste and self-compacting high-performance concrete mixtures were produced with different constant and variable parameters to evaluate the efficiency of such material, in terms of its activation index, mechanical properties, durability performance, and fire resistance.

2.1 I experimentally specified the maximum effective replacement for cement by waste fly ash, waste perlite powder and waste cellular concrete from the perspective of activation index. The maximum effective replacement for cement by any of the proposed unprocessed waste powder materials has been specified to be up to 30%.

![Fig. 7](image)

**Fig. 7** Impact of waste fly ash, waste perlite powder and waste cellular concrete on the activation index of paste after incorporating each of them up to 60% of cement content of the paste.

The activation indexes were showed that an increase in the age of specimens incorporating waste perlite powder or waste cellular concrete up to 30% increased the activation index. Otherwise, the behaviour of the activity index returned to decrease after 28 days, thereby rendering the applicability of replacement beyond 30% questionable. Replacing of cement by waste fly ash decreases the compressive strength linearly and the activation index increases by time in case of all replacing amount,
however, a significant reduction in the strength has been occurred by replacing the cement with more than 30% of cement.

2.2 I experimentally proved from the analysis of three types of unprocessed waste powder materials (waste fly ash, waste perlite powder or waste cellular concrete) that using of waste perlite powder as a cement replacing material up to 15% is more effective than others in the mechanical and durability performance of self-compacting high-performance concrete. [3][6]. Fig. 8 and Fig. 9.

Fig. 8 Mechanical properties at 28, 90, and 270 days of self-compacting high-performance concrete incorporated 0%, 15% and 30% of waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement

Fig. 9 Water penetration depth (average values) at 90 and 270 days and average values of scald materials after 7, 14, 28 and 56 freeze/thaw cycles at age of 270 days of self-compacting high-performance concrete incorporated 0%, 15% and 30% of waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement
2.3 I experimentally proved from the analysis of waste fly ash, waste perlite powder and waste cellular concrete that using of waste fly ash as a cement replacing material up to 30% is more effective than others in the long-term chloride penetration resistance of self-compacting high-performance concrete. [6]. Fig. 10.

Fig. 10 Chloride migration coefficient (average values) at 90 and 270 days of self-compacting high-performance concrete incorporated 0%, 15% and 30% of each waste fly ash, waste perlite powder, or waste cellular concrete as a replacement for cement

2.4 I experimentally proved that using up to 15% of any of waste fly ash, waste perlite powder or waste cellular concrete enhances the fire resistance of self-compacting high-performance concrete, in terms of the residual compressive strength and flexural strength at 90 and 270 days. [4][9]. Fig. 11.

(Fig. 11) continued,„
3. Thesis group about incorporating coarse recycled concrete aggregate and unprocessed waste powder materials with self-compacting high-performance concrete as a replacement for coarse natural aggregate and cement respectively.

Where; F15 and F30 mean self-compacting high-performance concrete incorporated 15% and 30% of waste fly ash as a replacement for cement respectively. C15 and C30 mean self-compacting high-performance concrete incorporated 15% and 30% of waste cellular concrete as a replacement for cement respectively. P15 and P30 mean self-compacting high-performance concrete incorporated 15% and 30% of waste perlite powder as a replacement for cement respectively, while RA0, RA25 and RA50 mean self-compacting high-performance concrete incorporated 0%, 25% and 50% of coarse recycled concrete aggregate as a replacement for coarse natural aggregate respectively.

It has been revealed that the properties of normal recycled aggregate concrete could be enhanced by adding mineral admixtures. In this framework, self-compacting high-performance concrete mixtures were produced with incorporating 0%, 25% and 50% coarse recycled concrete aggregate as a replacement for coarse natural aggregate and 0%, 15% and 30% of each waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement. In order to evaluate the efficiency of such material, in terms of its mechanical properties, durability performance, and fire resistance at short and long ages, as well as produce self-compacting high-performance concrete with high sustainable value.

3.1 I experimentally proved that using waste fly ash as a replacement for cement in case of self-compacting high-performance concrete incorporated coarse recycled concrete aggregate is better than in case of using natural aggregate alone. Where using waste fly ash up to 15% and coarse recycled concrete aggregate up to 50% enhance the mechanical and durability performance at short and long ages. [3][6]. Fig. 12 and Fig. 13.

3.2 I experimentally proved from the analysis of using waste fly ash, waste perlite powder and waste cellular concrete that using up to 15% of waste perlite powder with up to 25% coarse recycled concrete aggregate is more effective than others in the mechanical and durability performance of self-compacting high-performance concrete at short and long ages. [6]. Fig. 12 and Fig. 13.
Fig. 12 Mechanical properties (average values) at 28, 90, and 270 days of self-compacting high-performance concrete incorporated 0%, 25% and 50% of coarse recycled concrete aggregate as a replacement for coarse natural aggregate and 0%, 15% and 30% of each waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement.

3.3 I experimentally proved that using up to 15% of any of waste fly ash, waste perlite powder or waste cellular concrete with up to 25% coarse recycled concrete aggregate enhances the fire resistance of self-compacting high-performance concrete, in terms of the residual compressive strength and flexural strength at 90 and 270 days. [4][9].

Fig. 14.

(Fig. 13) continued...
**Fig. 13** Durability properties (average values) at 90, and 270 days of self-compacting high-performance concrete incorporated up to 50% coarse recycled concrete aggregate as a replacement for coarse natural aggregate and up to 15% of each waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement.

**Fig. 14** Relative residual compressive strength and flexural strength as a function of temperature of self-compacting high-performance concrete incorporated up to 15% of each waste fly ash, waste perlite powder and waste cellular concrete as a replacement for cement. In addition to up to 25% coarse recycled concrete aggregate as a replacement for coarse natural aggregate at 90 and 270 days.

4. **Thesis group about long-term properties of crushed aggregate**

Where; MRCA (25%) means multiple recycled concrete aggregate produced from the first generation of recycled aggregate concrete, which was originally prepared with 25% replacement for coarse natural aggregate by coarse recycled concrete aggregate. While MRCA (50%) means multiple recycled concrete aggregate produced from the first generation of recycled aggregate...
I investigated the properties of different types of crushed aggregates by taking into consideration the properties of their parent concrete, which was either natural aggregate concrete or recycled aggregate concrete. Twenty-two crushed aggregate types were tested, where the main difference between the aggregate types was the type of parent concrete in the first generation.

4.1 I experimentally and analytically proved from the analysis of twenty-two types of crushed aggregate (recycled concrete aggregate and multiple recycled concrete aggregate) that there is no relationship between the Los Angeles index of crushed aggregate and its parent concrete, but there is a strong one in case of water absorption of both. [8]. Fig. 15.

4.2 I experimentally proved that incorporating unprocessed waste powder materials as a cement replacing materials in concrete enhances the abrasion resistance of its crushed aggregate regardless of the strength of parent concrete and the type of unprocessed waste powder material due to enhancing the mortar attached to the crushed aggregate. [8]. Fig. 16.

4.3 I have experimentally proved that there is strong relationships between the properties of multiple recycled concrete aggregate and the replacement amount of coarse natural aggregate by coarse recycled concrete aggregate in its parent concrete, where this relationship is a linear relationship in case of the water absorption capacity and binomial relationship in case of the Los Angeles index. [8]. Fig. 17 and Fig. 18.

The binomial relationship had the lowest resistance for abrasion (the highest Los Angeles value) in case of replacing the coarse natural aggregate by 50% of coarse recycled concrete aggregate in the parent concrete. This behaviour has been justified by the homogeneity of the aggregate mixture in the parent concrete, which affected the distribution of aggregates inside the mixtures.
Fig. 16 Effect of using unprocessed waste powder material as partial replacement for cement of self-compacting high-performance concrete on the Los Angeles indexes of its crushed aggregate (recycled concrete aggregate and multiple recycled concrete aggregate). Where; WFA is waste fly ash, WCC is waste cellular concrete and WPP is waste perlite powder.

Fig. 17 The relationship between the Los Angeles index of crushed aggregate and the replacement amount of coarse natural aggregate by coarse recycled concrete aggregate in its parent concrete.

Fig. 18 The relationship between the water absorption capacity of crushed aggregate and the replacement amount of coarse natural aggregate by coarse recycled concrete aggregate in its parent concrete.

5. Thesis group about multiple recycled aggregate concrete

Where; RA25RA25 and RA25RA50 mean the second generation of recycling, prepared with 25% and 50% substitution of coarse natural aggregate by MRCA (25%) which defined in the previous thesis group number 7.4. While RA50RA25 and RA50RA50 mean the second generation of recycling, prepared with 25% and 50% substitution of coarse natural aggregate by MRCA (50%) which defined in the previous thesis group number 7.4.
This finding in this section serves as a link between the results of the studies of Huda (2014) and Salesa et al. (2017) the former presented a decrease in strength of up to 20% replacement for coarse natural aggregate, whereas the latter presented an increase in strength of up to 100% replacement. In the present study, the effect of replacing coarse natural aggregate by percentages between 20% and 100% indicated a changing point of 50% replacement for obtaining a positive effect of recycled concrete aggregate replacement especially for self-compacting high-performance concrete.

5.1 I experimentally proved that using up to 25% multiple recycled concrete aggregate as a replacement for coarse natural aggregate enhances the mechanical properties of multiple recycled aggregate concrete in terms of the compressive strength, flexural strength, modulus of elasticity. [5][12]. Fig. 19 and Fig. 20.

![Fig. 19](image1.png)

**Fig. 19** compressive strength (average values) at 28 and 90 days of self-compacting high-performance concrete incorporated 25% and 50% of multiple recycled concrete aggregate as a replacement for coarse natural aggregate.

![Fig. 20](image2.png)

**Fig. 20** Flexural strength and modulus of elasticity (average values) at 90 days of self-compacting high-performance concrete incorporated 25% and 50% of multiple recycled concrete aggregate as a replacement for coarse natural aggregate.

5.2 I experimentally and by computed tomography proved that using up to 50% multiple recycled concrete aggregate as a replacement for coarse natural aggregate decreases the porosity of the multiple recycled aggregate concrete. [5]. Fig. 21.
**Fig. 21** Porosity of self-compacting high-performance concrete incorporated up to 50% of multiple recycled concrete aggregate as a replacement for coarse natural aggregate

**LIST OF PUBLICATIONS**


LIST OF PRESENTATIONS

1. Influence of Recycled Aggregate Concrete on the Properties of Lightweight Concrete, Miskolc University - Miskolc, Hungary - Faculty of Materials Science and Engineering, 2017
2. Effect of Cellular Concrete Powder on Durability of Normal Strength Concrete (poster presentation), Tokaj, Hungary - Proceedings of Central European Congress on Concrete Engineering, 2017
3. Green Self-Compacting High Performance Concrete, BME University - Budapest, Hungary - Department of construction materials and technologies, 2018
4. Green Self-Compacting High Performance Concrete, BME University - Budapest, Hungary - Pál Vásárhelyi Doctoral School of Civil Engineering and Earth Sciences (Complex exam), 2018
5. Characteristics of Cement Pastes Incorporating Different Amounts of Unprocessed Waste Fly Ash (UWFA), Prague, Czech republic - 12th fib International PhD-Symposium in Civil Engineering, 2018
6. Reused Recycled Aggregate Concrete (RRAC), Melbourne, Australia - The International Federation for Structural Concrete 5th International fib Congress, 2018
7. Effect of Waste Perlite Powder on Recycled Aggregate Self-Compacting Concrete at Elevated Temperature, Melbourne, Australia - The International Federation for Structural Concrete 5th International fib Congress, 2018
8. Properties of Multiple Recycled Concrete Aggregate, University of Pécs - Pécs, Hungary - 14th PhD & DLA Symposium, 2018

LIST OF SUPERVISIED MSc THESES

1. Properties and modeling of concrete with recycled concrete aggregate 2017/2018
2. Properties and modeling of concrete with different maximum aggregate size 2017/2018
6. Experimental and numerical study for the flexural strengthening of concrete beams using epoxy-based resin 2018/2019

STANDARDS

ACI 201.2R. 2008. “Guide to Durable Concrete”, ACI Committee Reports, American Concrete Institute.
BS EN 197-1. 2011. “Cement. Composition, specifications and conformity criteria for common cements”.

20
MSZ EN 14146. 2004. “Natural stone test methods. Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency)”.

Nordest test NT BUILD 492. 1999. “Chloride Migration Coefficient from Non-steady-state Migration Experiments, Nordest”.


REFERENCES


By appreciating the value of the surrounding unused waste materials, we can raise up the sustainability definition…

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