MŰEGYETEM 1782

SIZE EFFECT ON THE COMPRESSIVE STRENGTH OF RECYCLED AGGREGATE CONCRETE

Scientific Student Conference TDK 2019

Student: Amina Dacić
Supervisors: Dr. Oliver Fenyvesi
Dr. Rita Nemes

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
Department of Construction Materials and Technologies

Table of Contents

List of figures

List of tables

Symbols and abbreviations

C&D- construction and demolition

D- upper sieve size in mm

d- lower sieve size in mm

EN- European norm

FRP- fiber reinforced polymer

H/D- height to the diameter ratio

NA- natural aggregate

NAC- normal aggregate concrete

RAC- recycled aggregate concrete

RCA- recycled concrete aggregate

SE- size effect

w/c- water-cement ratio

Definitions

Coarse aggregate - aggregate of larger aggregate size with D larger or equal to 4 mm. (CEN, AGGREGATES FOR CONCRETE DIN EN 12620 : 2008, 2008)

Fine aggregate - aggregate of smaller aggregate size with D less than or equal to 4 mm. (CEN, AGGREGATES FOR CONCRETE DIN EN 12620 : 2008, 2008)

Natural aggregate - aggregate of mineral sources and which has not been subjected to anything other than mechanical processing. (CEN, AGGREGATES FOR CONCRETE DIN EN 12620 : 2008, 2008)

Recycled aggregate - aggregate which comes from processing of material used previously.

Recycled aggregate concrete - concrete manufactured with waste materials. (Cabrera, Agrela, & Galvín, 2019)

Size effect - property of concrete referring to decrease in compressive strength with the increase in specimen size. (Chen, Liu, & Wang, 2018)

1. Literature Review

1.1. Introduction

Concrete is the most widely used material in the construction industry. Generally, it is more used than any other material, except water. Since 70 % of concrete is occupied by aggregates, the topic of using construction and demolition (C&D) waste as a substitution of traditional, natural aggregate (NA) can have a major effect on developing new technologies and strategies in making concrete. C&D waste by definition is waste that arises from construction, renovation, and demolition activities, but also can include surplus and damaged products and materials arising in the course of construction work or used temporarily during the process of onsite activities (Lu & Yuan, 2011). Nevertheless, it is impossible to imagine the construction of any structure without using aggregates. So, using recycled concrete aggregate (RCA) as an alternative to NA would benefit both society and the environment.

However, in order to use a material in practice quality of that material has to be assured. In construction industry for determination of quality of concrete various tests are done. One of the most important factors to be examined is compressive strength. In order to evaluate compressive strength, concrete is casted, cured and eventually tested. Throughout this procedure there are many things that can affect final results of compressive strength. One of them is the shape and size of the specimen. (Buller, Oad, & Memon, 2018) Size effect (SE) is a property of concrete which refers to decrease in compressive strength with the increasing concrete specimen size. (Chen, Liu, & Wang, 2018) The focus of earlier studies was mainly on pure tension and shear loading conditions rather than compressive ones. But, in case of structural application of concrete and absence of an effective confinement, compressive failure is major brittle failure mode of concrete. Recently, focus on the compressive loading conditions have become of interest and there are many theoretical and experimental investigations done. (Kim & Yi, 2002) Yet, there are no so many studies conducted for investigation of SE in case of recycled aggregate concrete (RAC).

There is no surprise that the topic of SE is gaining more and more popularity since the construction industry is undergoing development in sense of size of the structures. The gap between the scales of the structures in practice (e.g. high-rise buildings, bridges, dams) and the scale of the specimens in the laboratory experiments is obvious. (Bažant Z. , 1999) So, there is no doubt that studying this phenomenon would give more comprehensive understanding of behavior of concrete in practice as well. Furthermore, in this study focus will be on the usage of recycled concrete as the aggregate replacement to the NA. The plain (un-reinforced) concrete specimens using 45 % replacement of NA with RCA from demolished concrete will be used. Two recipes will be used in order to compare also SE for different compressive strengths of concrete. Furthermore, both cube and cylindrical specimens will be used. Also, the comparison between cube and cylindrical specimens' compressive strength will be part of the study. Moreover, 14 days compressive strength will be conducted as a starting point for future investigation of the phenomenon. This study in the end will provide both information about the compressive strength of RAC with 45% replacement of NA with RCA and SE of RAC. Finally, the results will be compared with the results conducted by other researchers.

1.2. Size Effect

The beginnings of SE observations date back to 16th century when Leonardo da Vinci stated that ``among cords of equal thickness the longest is the least strong". In advance, concerning statistical theory of SE, it emerged with Peirce's (1926) formulation of the weakest-link model for a chain and introduction of the extreme value statistics originated by Tippett (1925), Fischer and Tippett (1928), and FreÂchet (1927), and refined by von Mises (1936) and others. (Bažant Z. , 1999) However, when it comes to SE two types of theory exist, strength theory and linear elastic fracture mechanics one. First one is based on the concept of failure surfaces, where failure is in terms of stresses or strains. This theory conducts calculations based on theories of elasticity, plasticity or viscoplasticity. Second one, so called linear elastic failure mechanism takes into account failure as an expression of energy consumed per unit crack length increment. (Bažant Z. , 1984)

One of the first researchers who studied the SE of concrete in 1925 was Gonermann. His finding was that the ratio of the compressive failure stress to the compressive strength decreases as the specimen size increases. (Kim & Yi, 2002) After Gonermann, Blanks in 1935 investigated both influence of aggregate size and column diameter on the compressive strength of concrete. Also, many researchers have focused on the effect of height-diameter ratio and cross-sectional shape on the size effect of concrete. By conclusions of many the SE is more significant in case of prisms and cubes than cylinders. In addition, it was concluded that slenderness ratio when H/D is larger than two has less influence on the SE than increase in the absolute size of the specimen. Another approach of the researchers was to take water-cement ratio (w/c) into concern when investigating SE and it was shown that it does not have significant influence on it. Yet, dynamic load influence on SE gave opposite results, in case of dynamic loading SE is a major issue. Event though, in this study plain concrete will be taken into concern it is worth mentioning that there have been some researchers concerning inclusion of FRP-confined and reinforced concrete. These researches have shown that FRP-confined concrete is influenced by the column diameter. Whereas, for reinforced concrete influence was based on level of confinement. (Chen, Liu, & Wang, 2018)

There are many factors that can affect experimental results of the concrete. Some of those factors are curing conditions, rate of load application, used molds for casting, specimens' shapes and sizes. There are two shapes of specimens utilized for compressive strength test and it depends on the country which specimen's shape is used. (Neville, 2011) For example, cylinders are used in Australia, Canada, France, New Zeeland, the United States, Turkey, etc., while cubical ones are mostly used in European countries including Germany and United Kingdom.

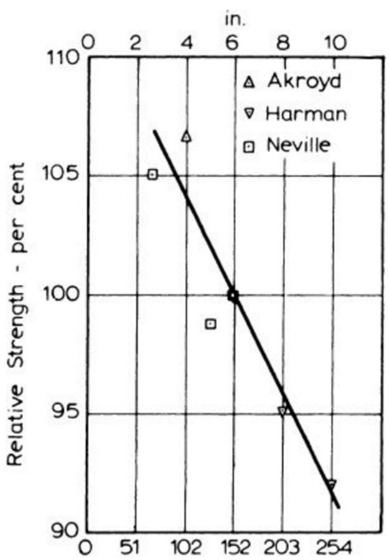
In our research we will refer to European norms, EN 206:2013 introduces 150 mm by 300 mm cylinders or 150x150x150 mm cubes as standard sizes of the specimens used for determination of compressive strength class. (CEN, 2016)

Even though, in the relevant standards, the size of the specimens used for strength testing is prescribed, occasionally usage of more than one size is allowed. However, there are obvious advantages of using smaller specimens, so it is reasonable why are they more preffered. (Arioz, et al. , 2009) Some of the advantages are:

1. They are easier to handle and less possible to be accidently damaged.
2. The molds are cheaper.
3. Testing machine with lower capacity is needed.
4. Less amount of concrete is used.
5. Less storage and curing space are required. (Neville, 2011)

Moreover, Neville in his book graphically shows the relationship between mean strength and specimen size for cubes (Figure 1) and cylinders (Figure 2). Also, it is important to mention that SE is of significant interest for researchers because it has been attributed to variety of causes including:

1. The wall effect, which points out that the amount of mortar needed to fill the space between aggregates is less than the one between mold's wall and aggregate. (Figure 3)
2. The ratio of the specimen to the maximum aggregate size.
3. The tangential stress occurring at the contact surface between the platen and the testing machine and the specimen because of the friction or bending of the platen.
4. The difference in the effectiveness of curing. (Neville, 2011)



Cube size (mm)

Figure 1 Compressive strength of cubes of different sizes **(Neville, 2011)**

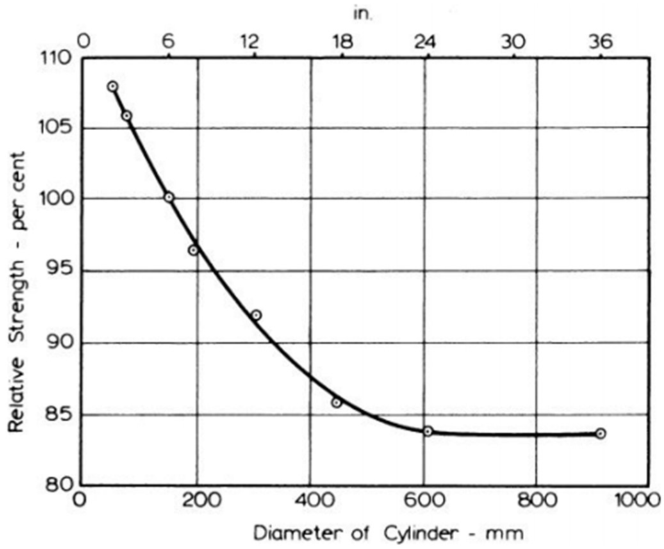


Figure 2 Compressive strength of cylinders of different sizes **(Neville, 2011)**

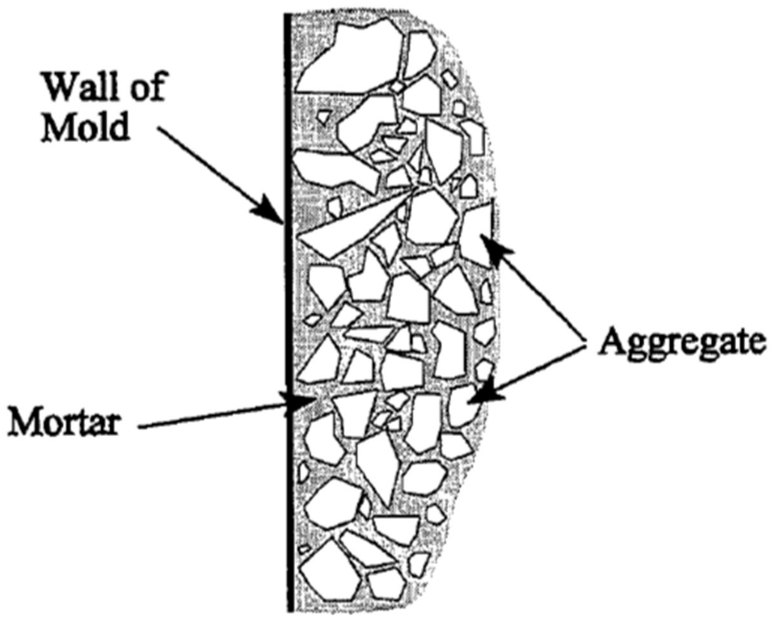


Figure 3 Wall effect **(Neville, 2011)**

Although, design codes referring to concrete include SE, ones concerning reinforced concrete structures do not take it into account. Since in practice, reinforced concrete structures are widely used this phenomenon should be investigated. The failure conditions covered are in sense of strength or yield criteria. It has been shown that there is softening behavior in case of tensile tests performed on concrete and accordingly it affects all the failure modes connected to the concrete failing in tension including punching shear of slabs, torsion, anchor pullout, bar pullout, splice failure and many more. Accordingly, there is a high probability that SE will have influence on concrete failing in case of compression also. In addition, since nowadays widely used high strength concretes increase the brittle behavior of concrete, this experimental investigation is of a great importance. (Muciaccia, Rosati, & Di Luzio, 2017)

1.3. Concrete and the Environment

There is no doubt that concrete is the most popular construction material worldwide and this is due to the advantages it offers including low cost, general availability and wide applicability. But since the environmental aspect has become a major issue worldwide, there are initiatives and willingness to make a change in the concrete industry. One of the most important events dealing with the issue of sustainable development is the Earth Summit which is a decennial event organized by United Nations, where global leaders meet in order to define ways to stimulate sustainable development at global level. First one was held in Stockholm, Sweden in 1972 and from that year every ten years there is such a meeting. These meetings generated formulation of regulations by many countries in order to prevent and preserve the environment. These regulations are mainly about the CO_2 emission and this concerns construction industry in a way that about 8-10% of total world CO_2 emission is coming from the cement manufacturing process in cement factories. In addition, approximately 1.89 billion tons of cement have been produced annually worldwide (Suhendro, 2014). Accordingly, the green concrete industry started emerging and expanding.

By definition, green concrete is concrete which uses waste material as at least one of its components, or its production process does not lead to environmental destruction, or it has high performance and life cycle sustainability (Suhendro, 2014). In advance, the production of Portland cement is a very much energy consuming process. Countries such as Germany, Japan and the USA managed to increase the energy-efficiency in their plants to the current requirement of 4 GJ per ton. Another issue concerning concrete's negative impact on the environment is the demolition and disposal of concrete structures, pavements, etc. Overall construction debris has a high contribution in overall solid waste disposal problem. Just as an example, in US construction industry over 100 million tons of C&D waste is generated annually which then makes 29% of total solid waste and in the UK 70 million tons which makes 50% to the total solid waste (Lu & Yuan, 2011). However, not surprisingly, the largest amount of C&D waste takes concrete. Finally, water also suffers from the construction process, especially in the concrete industry. The concrete industry uses over 1 trillion gallons of water annually, without taking into account the wash and curing water (C.Meyer, 2005). So, it is obvious that something should be changed in concrete industry in order to improve quality of our life but at the same time not to endanger economic development. This balance should be a goal in order to have a proper solution.

From the information provided, one could make a conclusion that the recycled aggregate is one of the possible solutions. Since there are millions of tons of waste produced all over the world each year and a really big portion of it is not recyclable, we end up with the accumulation of the waste on certain areas which endangers the environment. In advance, there are two things that are affected by using waste material in concrete production. First thing is that this approach will for sure eliminate some portion of waste and the second one that these materials can add positive properties to the concrete (Tavakoli, Hashempour, & Heidari, 2018). In general, waste material does not have to be used just as an aggregate, but also as filler or fiber. So, the possibilities are various and the researches in this field are nowadays numerous. However, in our project main focus will be on aggregate replacement.

When it comes to aggregates annual production, it totals about 16.5 billion tons (15 billion metric tons), which can be valued at more than $70 billion. As shown in Figure 4 it is one of the most important mining industries. It is a high-bulk, low unit value commodity. Since its value varies due to the location, its so called "place value" is high. That is why usually aggregate operations are located near the population centers or market areas. By taking this into consideration together with the limited access and distribution of aggregate to some areas in the world, the process of producing aggregates is most likely to be changed for the future. (Langer, Drew, & Sachs, 2004)

Figure 4 Comparison of values of different mining industries (Langer, Drew, & Sachs, 2004)

However, the best solution so far introduced by the construction industry is green concrete. The main purpose of the development of green concrete is the improvement of sustainable development in the concrete industry. Furthermore, it improves three pillars of sustainability: environmental, economic and social. By definition of green concrete, there should be usage of at least one material as its component, so perspective of this project to use recycled concrete as an aggregate will propose one of the possible green concrete practices. Also, green concrete should include reducing, reusing and recycling techniques or at least two two of them which is satisfied by recycling concrete waste and using it as an aggregate. In advance, three main objectives in green concrete production are to reduce greenhouse emission (carbon dioxide emission from cement industry); to reduce the use of natural resources such as limestone, shale, clay, etc, and the use of waste material which results in the air, land and water pollution (Suhendro, 2014). Taking these three objectives into consideration, there is an obvious need for the usage of waste materials as replacement of natural aggregates. It would surely also result in a sustainable development without depleting of natural resources. The reason for choosing concrete and brick wastes is that as stated before concrete takes the biggest portion in C&D. (Wong, et al., 2018) The representation of the percentages of different materials contained in the C&D waste in European countries can be seen in Figure 3.

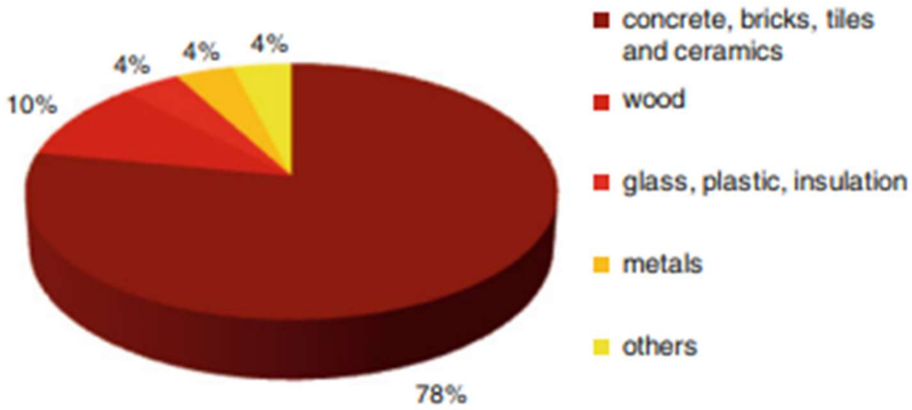


Figure 5 European countries C&D waste statistics (Pepe, 2015)

1.4. Recycled concrete aggregate (RCA)

Worldwide there is on one side huge demand for aggregates, which every year is increasing. On another hand huge amount of C&D waste produced on a yearly basis which increases as well. The reasons of a huge amount of C&D waste are the demolition of old structure; natural disasters like earthquake, avalanches, and tornadoes; human causes like war, bombing and structural failures. (Ntaryamira, Quansah, & Zhang, 2017) Even Romans back at the time were aware of the possibility to reuse the C&D waste. They often reused stones from previous roads to rebuild the newer once. Then after World War II, there was an initiation to recycle C&D waste, because there was a depletion of natural resources. Now, in different countries, there are initiatives to increase the recycling percentage of C&D waste. In European Union, the research program supported by the European Commission on Management of Construction and Demolition Waste is working on this subject. The European Demolition Association estimates that out of the 200 million tons of waste produced in Europe annually, about 30% is recycled. By the study published by EU members in recent years, almost one-third of C&D waste consists of concrete. However, it is also shown that this trend is not the same in all the European countries, the best progress is seen in the Netherlands and Belgium with the rate of about 90%. On the other hand, Italy and Spain have a recycling rate of 10%. When it comes to North America, the Construction Materials Recycling Association (CMRA) estimates that about 100 million tons of concrete from all sources is recycled annually. The concrete made from these recycled aggregates is generally used for a base material for road products over which asphalt or concrete finish is placed. (Tabsh & Abdelfatah, 2009)

The main contribution to the concrete waste quantity comes from the demolition works and this kind of aggregates usually contain some impurities due to the presence of cement stone, gypsum, and minor quantities of other substances. But since the aggregate makes 70% of concrete, it makes sense to consider the usage of concrete waste as recycled aggregate. It can have many advantages from the reduction of pollution, needed disposal areas for waste and saving of natural aggregate resources. However right now economical aspect is seen as the disadvantage for RCA, but in the future, it can be changed since the lower transportation cost and energy consumption for the recycled material is a plus in that sense. (Tabsh & Abdelfatah, 2009)

It is important to emphases few researches results in order to have perspective about the behavior or RCA in making concrete. The test results by many researches showed that RCA has higher water absorption capacity which affects many mechanical properties of the concrete.

On the other hand, it was shown that RCA obtained from high strength concrete exhibits better mechanical properties of concrete than the one made with RCA conducted from low strength concrete. This shows that also the source of the RCA affects its behavior. (Ntaryamira, Quansah, & Zhang, 2017) In 1977, Frondistou-Yanna in his study concluded that concrete made with RCA has mechanical properties that match the normal aggregate concrete (NAC) the best when it is enriched by gravel at the expense of mortar. His research also implies that the concrete made with recycled aggregates has a compressive strength of at least 76% and modulus of elasticity from 60% to 100% compared to NAC. Moreover, in the study conducted by Hansen and Narud, it was concluded that the compressive strength of recycled concrete is affected by the w/c of the original concrete if other factors are kept the same. Also, Hansen and Hedegkd in 1984 studied how the addition of a plasticizing, air entraining, retarding, and accelerating admixture to the original concrete did not affect the newly made recycled concrete. In their study, Ajdukiewicz and Kliszczewicz considered RCA from concrete with compressive strength 40–70 MPa. Their study showed that the compressive strength dropped by about 10% when using recycled aggregates. In fact, Olorunsogo and Padayachee investigated the durability of concrete made with different percentages of recycled concrete coarse aggregates (0%, 50%, and 100%). It was shown that the durability of recycled concrete decreases with increasing the quantities of recycled aggregate, and the quality gets better with the age of curing. They concluded that this is probably due to cracks and fissures created within the RCA during processing. (Tabsh & Abdelfatah, 2009)

2. Experimental investigation

2.1. Introduction

The main goal of this study is to investigate SE on the compressive strength in case of RAC. During the research, different concrete specimens of different concrete mixes were tested at 14 days age with same curing conditions. For the mixtures Portland cement CEM I 52.5 N was used, portable water and superplasticizer Glenium 51 were applied. Recycled concrete aggregate (Figure 6) was used as coarse aggregate and as fine aggregate river sand (Figure 7). Prior the casting, sieve analysis in case of both fine and coarse aggregates was done using sieve shaker (Figure 8). Also, water absorption test in case of RCA was conducted. Additionally, loose bulk density test and pyconometer method for particle density of RCA were tested. Right before casting for each mix, moisture content of the aggregates was measured. In the Figure 8 aggregate size distribution of the mixes is shown. From the figure it is obvious that aggregate size distribution of the mixes is between the standard A and C standard grading curves. Maximum aggregate size of used RCA was 8 mm and mixtures were made accordingly.

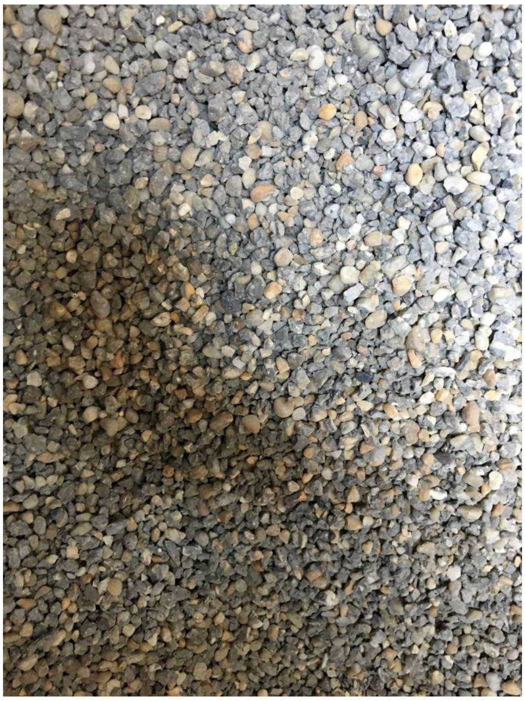


Figure 6 Used recycled concrete aggregate

Figure 7 Used river sand

Figure 8 Sieve shaker machine

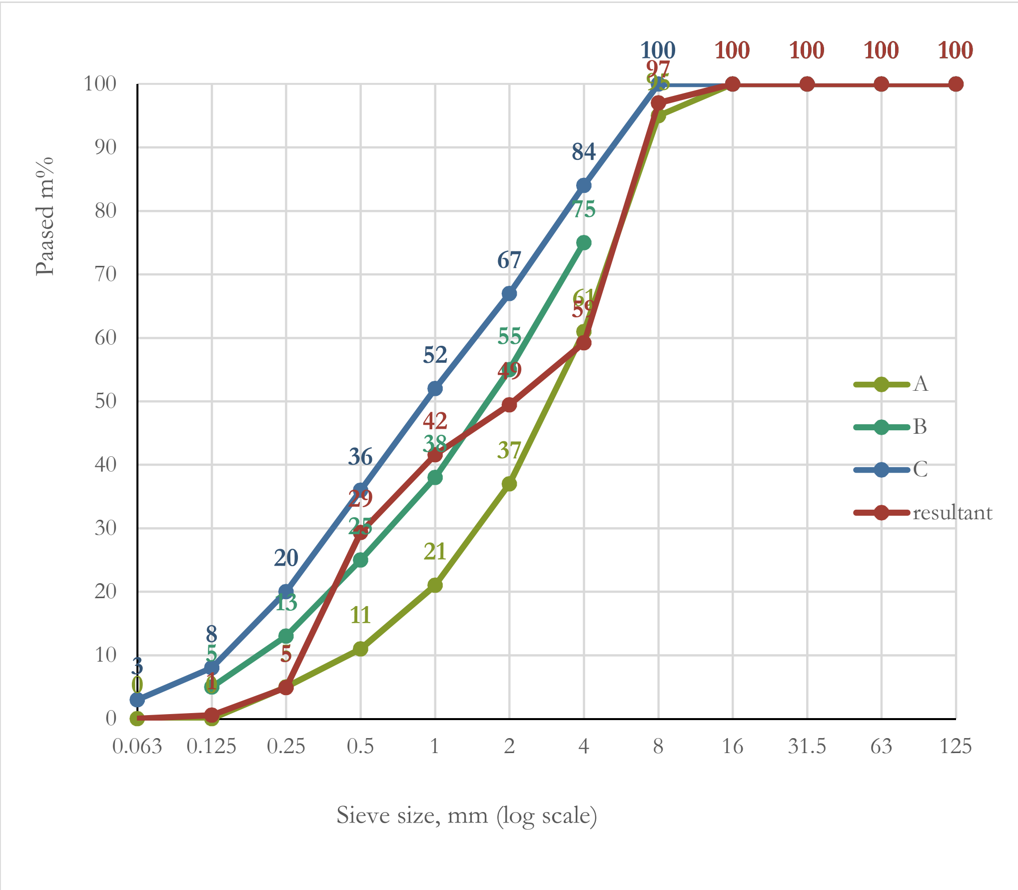


Figure 9 Aggregate size distribution

Two mixtures were chosen for the study. Both mixtures were based on recipes prepared by Gyurko and Nemes for SE investigation of normal and high strength concrete. (Gyurko & Nemes , 2016) The first one is used for preparing concrete class C35/45 and the other one for C50/60. In the Table 2, mixture named AD-B1 and AD-B2 represent C35/45 and C50/60 RAC mixtures, respectively. In the same table reference mixtures of NAC are provided REF1 and REF2 for NAC with concrete class C35/45 and C50/60 respectively. However, reference mixtures unlike the mixtures made for this study contained 8/16 coarse aggregate. Both reference mixtures were made with 25% of 4/8 and 40% of 8/16 fractions. To sum up, 35 % of total aggregate contained in the reference mixture was occupied by 0/4 fraction, 25% by 4/8 and 40% by 8/16. Whereas for AD-B1 and AD-B2 mixtures total aggregate amount was occupied by 55% of 0/4 fraction and 45% by 4/8. As in the reference mixtures, two RAC mixtures differ in w/c, so that for AD-B1 mix it was 0.50 and for AD-B2 0.30. In both mixtures proportion of fine aggregate was 55%, whereas coarse aggregate's was 45%.

ID	Cement dosage (kg/m^3)	Water dosage (kg/m^3)	Fine aggregate dosage (kg/m^3)	Coarse aggregate dosage (kg/m^3)	Superplasticizer dosage (kg/m^3)
AD-B1	360	180	1010	766	2.52
AD-B2	500	150	987	749	6.93
REF1	360	150	642	1192	2.16
REF2	500	185	595	1131	3.00

Table 1 Table of RAC mixtures

2.2. Materials used

For casting of all the mixtures, same cement type was used, Portland Cement CEM I 52.5 N. The chemical composition and physical properties of CEM I 52.5 N is summarized in Table 2. River sand as a fine aggregate was used and for coarse aggregates RCA. Detailed documentation of sieve analysis regarding used fine and coarse aggregates is given in annex 1 of appendix. Relevant standard for applied sieving method was EN 933-1. Moreover, bulk density, particle density and water absorption of the RCA were calculated using test methods according to relevant standards:

- loose bulk density EN 1097-3
- water absorption capacity and particle density EN 1097-6.

Detailed tables containing results regarding loose bulk and particle density and water absorption capacity are given in annex 2 of appendix. To sum up, loose bulk density of RCA was 1270 kg/m^3, particle density 2455 kg/m^3 and water absorption capacity 2.4 m%. So, by the definition provided in EN 196:2013 normal-weight aggregate is the one which in the oven-dry condition has a particle density higher than 2000 kg/m^3 and lower than 3000 kg/m^3. Since, RCA used in this study had particle density of 2455 kg/m^3 it is considered as normal-weight aggregate.

For all mixtures portable water was used. The applied Glenium 51 is superplasticizer concrete admixture which is a polycarboxylic ether based, high range water reducing agent. It was developed for concrete that targets to high early and final strengths and durability. Typical properties of Glenium 51 are shown in Table 3.

Composition % (mass)	Cement
SiO_2	19.47
Al_2O_3	4.75
Fe_2O_3	3.43
CaO	63.16
MgO	1.43
SO_3	2.68
Na_2O	0.28
K_2O	0.62
Loss on Ignition	3.26
Specific surface area (cm^2/g)	3635

Table 2 Chemical composition and physical properties of CEM 52.5 N

Structure of the Material	Polycarboxylic ether based
Color	Amber
Density	1.082 - 1.142 kg/liter
Chlorine Content% (EN 480-10)	< 0.1
Alkaline Content% (EN 480-12)	< 3

Obtained in +20°C 50% relative humidity conditions.

*According to the manufacturer

Table 3 Typical properties of Glenium 51

2.3. Mixing and preparation of specimens

Reference mixtures were the ones used by Gyurko and Nemes for their two different researches. First mixture was the C35/45 mixture used for his research of *Size effect on cylinder and cube strength of concrete*, published in 2016. Second one was for his ongoing research regarding C50/60 mixture's SE of the high-strength concrete. Prior to the mixing, every time moisture content was measured of both fine and coarse aggregates and according to the results, amount of the ingredients was corrected. After corrections were made, all the ingredients were weighted according to the recalculated amounts. First mixture made was AD-B2 and two times 45 liters of concrete was mixed in order to cast all needed specimens. The results of moisture content of both sand and RCA for this mixture are shown in the first table of annex 3 in the appendix. Second day mixture AD-B1 was mixed in same manner. However, moisture content of aggregates was again measured, and the results are attached to the annex 3 of the appendix. Detailed composition of the mix AD-B1 and AD-B2 shown in annex 4 of the appendix was prepared and used for the mixing. It should be noted that the amounts shown in the attached tables were for 45 liters of concrete.

After determining amount of the material needed for the mixture and weighting them, the ingredients were mixed. In the beginning, mixing drum (Figure 10) was prepared for mixing. It was checked if it was properly cleaned and greased. Then weighted amount of aggregates, cement and water were mixed. Admixture's amount was added gradually in order to achieve best consistency of the concrete possible. While mixing was in the process, vibrating table and required molds for the casting were prepared. Since, the SE on compressive strength of RAC will be investigated in this study, many cubical and cylindrical molds were used. In table below dimensions of the used molds are listed:

Cylinder (diameter x height in mm)	Cube (edge length in mm)
60x120	50
100x200	100
150x300	150
	200

Table 4 Applied cylinder and cube specimen sizes

Moreover, for better representation pictures of used cube and cylindrical molds can be seen in Figures 11 and 12, respectively. When the mixing was over, concrete was poured in the molds which were placed on vibrating table (Figure 13). Vibrating table was used in order to compact concrete in the molds.

Figure 10 Mixing drum

a) Cube mold with 50 mm edge length

b) Cube mold with 100 mm edge length

c) Cube mold with 150 mm edge length

d) Cube mold with 200 mm edge length

Figure 11 Used cube molds

a) Cylinder mold with dimensions of 60x120 mm

b) Cylinder mold with dimensions of 100x200 mm

c) Cylinder mold with dimensions of 150x300 mm

Figure 12 Used cylindrical molds

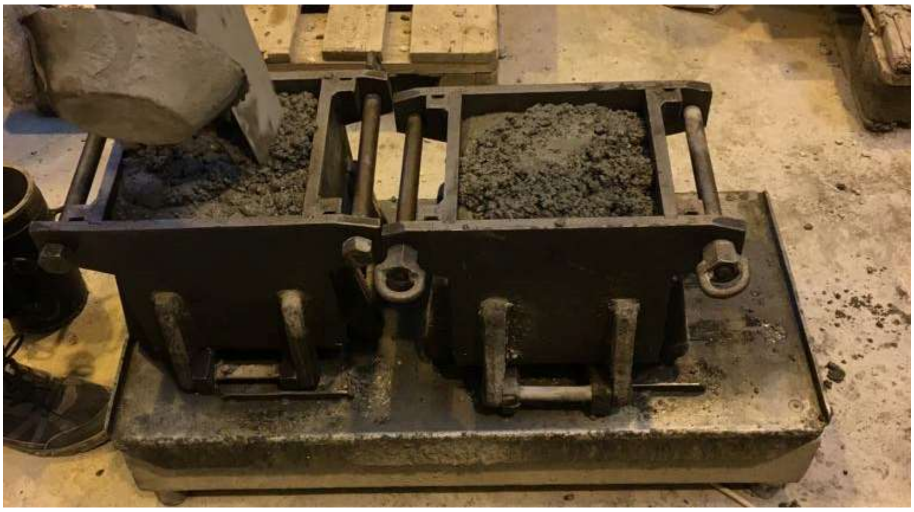


Figure 13 Casting concrete on a vibrating table

The specimens were stored in laboratory environment for 24 hours and then demolded. After demolding they were cured under water until seven days age. Then they were extracted from water and stored for seven more days in laboratory environment in order to perform compressive strength test. All the specimens were used in order to obtain results for 14 days compressive strength.

2.4. Compressive strength test and results

First, all specimens were collected in order to perform the test. Compression testing machine matching EN 12390-3 standards was used. Specimens were loaded in the machine until a failure. Eventually, the maximum load sustainable by the specimen is recorded and accordingly compressive strength of the concrete is calculated. As per EN 12390-3, both cube and cylinder specimens can be used for determination of compressive strength of the concrete. Prior to the testing, specimens were cleaned from excess moisture from the surface. The testing machine was also cleaned prior to each testing from all leftovers from previous testing and any extraneous materials. Also, all of the cylinder specimens were capped properly before the test by layer not thicker than 5 mm using gypsum mixture method (Figure 14).

Figure 14 Capped cylinder specimens with different sizes

For the cubes, width and length of the area which will be placed under the platen of the machine is measured. Also, height and mass of the specimen was also recorded. This was repeated for all the tested cube specimens. When it comes to the cylinder specimens, two times diameter was measured at the mid-height in order to find average of two and use it for area calculation. Same as for cube specimens, for cylinders height and mass was recorded. Then the specimens were placed into the machine, so that they are properly centered. Also, appropriate rate of loading was set for specimens with different sizes as specified in the table given in annex 5 of the appendix. When everything was set properly, the loading began. Finally, failure modes of the specimens differed and some of the examples are shown in Figure 15 and 16.

a) Cube specimen with edge length of 150 mm

b) Cube specimen with edge length of 100 mm

c) Cylinder specimen with dimensions 150x300 mm

Figure 15 Failure modes of specimens casted with AD-B1 mixture

a) Cube specimen with edge length of 150 mm

b) Cube specimen with edge length of 100 mm

c) Cylinder specimen with dimensions 150x300 mm

Figure 16 Failure modes of specimens casted with AD-B2 mixture

In advance, results of testing of the both mixtures will be given in tables below. Firstly, in Table 5 AD-B1 mixture results for compressive strength of cube specimens is presented together with the strength ratio comparing to standard cube size (edge length 150 mm). In the next table, AD-B1 compressive strength results of cylinder specimens are shown (Table 6). In next two tables results of compressive strength of AD-B2 mixture corresponding to cube (Table 7) and cylinder (Table 8) specimens is represented. Moreover, more detailed tables of compressive strength tests and corresponding calculations is given in annex 6 of the appendix, Calculation of the compressive strength of the different specimens was based on the formula provided in EN 12390-3.

AD-B1 cube specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
200x200x200	7.916	50.81	0.805
150x150x150	3.368	63.13	1.000
100x100x100	0.996	68.83	1.090
50x50x50	0.124	60.06	0.951

Table 5 AD-B1 mixture results for compressive strength of cube specimens

AD-B1 cylinder specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
150x300	5.293	44.22	1.000
100x200	1.608	41.66	0.942
60x120	0.349	48.88	1.105

Table 6 AD-B1 mixture results for compressive strength of cylinder specimens

AD-B2 cube specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
200x200x200	7.828	99.12	0.971
150x150x150	3.305	102.05	1.000
100x100x100	1.011	106.06	1.039
50x50x50	0.126	84.27	0.826

Table 7 AD-B2 mixture results for compressive strength of cube specimens

AD-B2 cylinder specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
150x300	5.383	65.56	1.000
100x200	1.603	65.84	1.004
60x120	0.345	52.94	0.808

Table 8 AD-B2 mixture results for compressive strength of cylinder specimens

3. Results evaluation

In this section focus will be on the evaluation of the results provided by compressive strength test of different specimens. However, comparison of the results obtained by this study and reference mixtures' results will also be covered. Since, EN 206:2013 also deals with the SE as most of the current standards, relevant regulations will be investigated regarding their applicability to RAC.

First of all, the reference mixtures' results will be presented. In Table 9 and 10, the compressive strength test results of REF1 and REF2 mixtures for cube specimens are given, respectively. As one can see, Gyurko and Nemes in their research for REF1 mixture did not use 50x50x50 mm cube specimens. Even though, in most of the researches this size of the cube specimens is not used, there are some researchers who have taken 50x50x50 mm cube specimens into consideration. Mostly this size of cube specimens is used to investigate compressive strength of cement mortar. However, some of the researchers in their works included 50x50x50 mm cube specimens for more detailed investigation of SE on the compressive strength of concrete. One of the researches that included this size of cube specimen is research by Yi, Yang and Choi, *Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete*. Also, del Viso, Carmona & Ruiz in their research of *Size and Shape Effects on the Compressive Strength of High Strength Concrete* included 50x50x50 mm cube specimen. One more research done by Karamloo, Roudak and Hosseinpour used cube specimen with 50 mm edge length for *Size effect study on compressive strength of SCLC*. When it comes to including this size of cube specimen in RAC compressive strength testing, most of the researchers have not taken it into consideration. That is why in this research it has been included, to see if there is SE applied to this size of cube specimen also.

REF1 cube specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
200x200x200	8.035	54.28	0.939
150x150x150	3.423	57.82	1.000
100x100x100	1.023	60.76	1.051

Table 9 REF1 mixture results for compressive strength of cube specimens

REF2 cube specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
200x200x200	8.104	68.21	0.927
150x150x150	3.383	73.62	1.000
100x100x100	1.010	78.64	1.068
50x50x50	0.129	83.75	1.138

Table 10 REF2 mixture results for compressive strength of cube specimens

However, when it comes to REF1 and REF2 mixtures cylinder specimens, consistency regarding the used sizes was present. So, for both mixtures, same as in our research three size of cylindrical specimens were used: 150x300 mm, 100x200 mm and 60x120 mm. Results of the compressive strength test of the mentioned mixtures and specimens are shown in Table 11 and 12. Detailed description of the compressive strength test results is given in annex 7 of the appendix.

REF1 cylinder specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
150x300	5.243	51.53	1.000
100x200	1.553	54.26	1.053
60x120	0.326	57.54	1.117

Table 11 REF1 mixture results for compressive strength of cylinder specimens

REF2 cylinder specimens			
Dimensions [mm]	Average Volume [l]	Average compressive strength [N/mm^2]	Strength ratio (compared to standard specimen) [-]
150x300	5.469	66.74	1.000
100x200	1.638	68.17	1.021
60x120	0.351	69.68	1.044

Table 12 REF2 mixture results for compressive strength of cylinder specimens

If we compare results of reference and RAC mixtures, it is obvious that using reference mixtures recipe RAC mixtures gave higher compressive strength results in case of cubes and lower in case of cylinders. The increase of compressive strength in case of standard cube specimen (150x150x150) were following:

- AD-B1 cubical compressive strength increased by 9.18 % comparing to REF1
- AD-B2 cubical compressive strength increased by 38.62 % comparing to REF2

So, as strength class increases, the percentage also increases. It should be taken into concern that in case of reference mixture maximum aggregate size used was 16 mm, while for RAC mixture it was 8 mm. Furthermore, 40% of the total aggregate in case of REF1 and REF2 was coarse aggregate with 8/16 fraction and 25% with 4/8 fraction. While for AD-B1 and AD-B2 for coarse aggregate only 4/8 fraction was used, occupying 45% of total aggregate in the mix.

For standard cylinder specimen (150x300 mm), the decrease in compressive strength was recorded:

- AD-B1 cylindrical compressive strength decreased by 14.19 % comparing to REF1
- AD-B2 cylindrical compressive strength decreased by 1.77 % comparing to REF2

In this case we see the trend of decreasing percentage when the strength class increases. However, findings of researchers which investigated RAC cylindrical and compressive can explain this phenomenon. The underlying cube to cylinder strength factor (*K*) depends on the compressive strength and varies from 0.78 to 0.83 in EN 206:2013. However, when it comes to RAC value of *K* is changing and the one identified in the standard cannot be applicable. (Pacheco, et al. , 2019) Also, Buller, Memon and Oad in their article called *Relationship between Cubical and Cylindrical Compressive Strength of Recycled Aggregate Concrete* suggested, based on 200 tested samples, that *K* factor in case of RAC can be taken as 0.7.

As per EN 206:2013 standard for each strength class two values are provided. First one corresponds to characteristic strength of concrete measured on a 150x300 mm cylinder and second one on a 150x150x150 mm cube. SE of concrete is expressed by the ratio between these two values, previously mentioned *K* factor. For instance, in case of C35/45 strength class this ratio is equal to 0.78, while for C50/60 it is 0.83. It has to be noted that this standard uses 28 days age compressive strength, while in our case for both reference and RAC mixtures 14 days age compressive strength results are considered. If we take into concern reference mixtures results and calculate the *K* factor, for REF1 mixture we will get value of 0.89, while for REF2 0.83. However, for RAC mixture *K* factor values are 0.70 and 0.64 for AD-B1 and AD-B2 mixtures, respectively. So, our results compile with the results recorded by other mentioned researchers. In conclusion, *K* factor provided in EN 206:2013 for NAC cannot be applied to the RAC.

Moreover, in Figures 17 and 18 results of all the experiments are presented in a way so that the SE of both cube and cylinder specimens can be compared. Tables for these figures are presented in annex 6 and 7 of appendix. However, in both cube and cylinder specimens, the smallest specimens being 50x50x50 mm and 60x120 mm are excluded. For these two specimens SE is not applicable for RAC mixtures. The reasons for that can be that RCA is less homogenous compared to NA. Another possibility for this can be because RCA is crushed, so it makes mixtures hard to compact. In case of cube and cylinder specimens reference mixtures show influence of SE in a way that with the increasing size of the specimens, there is decrease in compressive strength. On the other hand, in case of RAC mixtures, this phenomenon is not entirely applicable. If we analyze cube specimens, the increase in compressive strength is visible with decreasing size until 100x100x100 mm ones. The specimens with edge length of 50 mm for both AD-B1 and AD-B2 mixtures show decreasing value of the compressive strength rather than increasing. The reduction of compressive strength of this type of specimens is even greater when strength class increases. In case of cylinder specimens, there is slight increase in compressive strength from 150x300 mm to 100x200 mm size, but again the decrease is visible from 100x200 mm to 60x120 mm specimens. Also, as strength class increased for cylinder specimens SE was almost negligible from 150x300 mm to 100x200 mm size, since strength ratio of 100x200 mm specimen to standard specimen was 1.004. So, the presence of SE on the compressive strength of RAC is rather questionable.

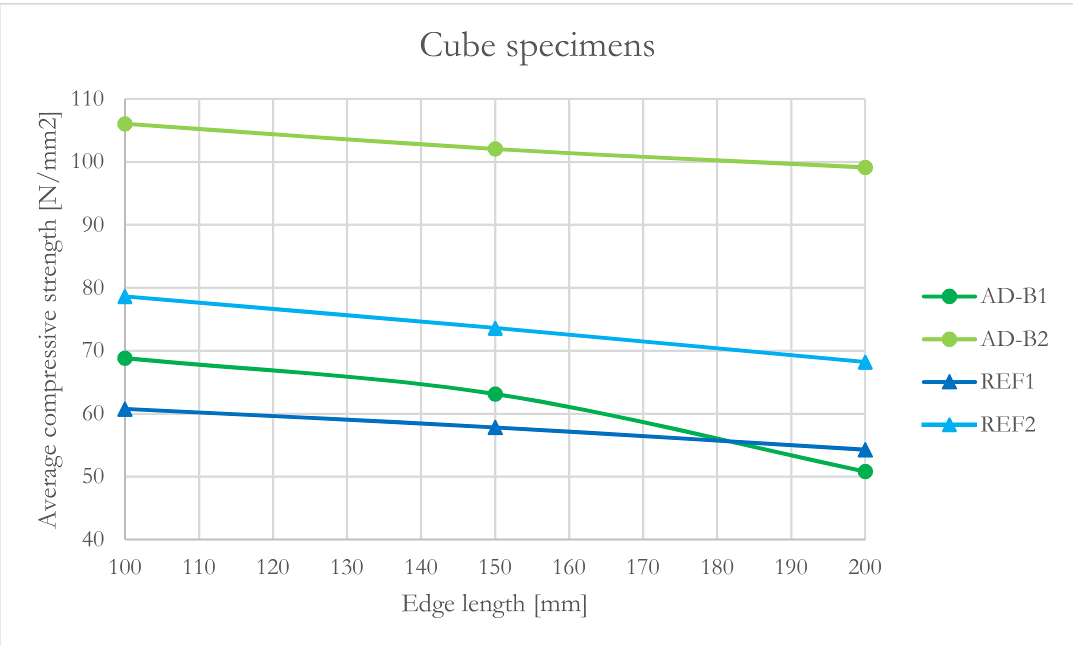


Figure 17 SE representation for both reference and RAC mixtures for cube specimens

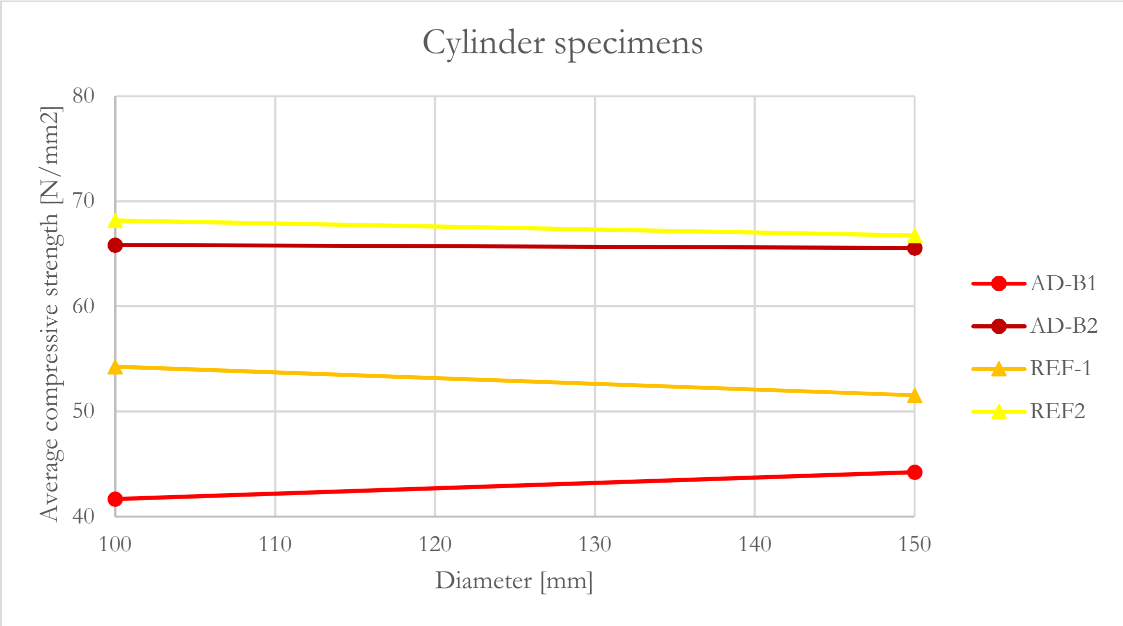


Figure 18 SE representation for both reference and RAC mixtures for cylinder specimens

4. Conclusion

The main goal of this research was to investigate SE on the compressive strength of RAC. Research focused also on green concrete utilization in construction industry. In the research it is shown that even by using RCA high-strength concrete can be produced. Maximum compressive strength achieved was 102.05 MPa for standard cube specimen (150x150x150 mm). However, investigation of SE resulted in findings which show that some of the properties that are applicable to NAC are not valid for RAC. Also, some parts of the relevant standard (EN 206:2013) are not suitable for RAC. Nevertheless, one finding of other researchers was surely identified in this research also. This finding was that SE is more significant in case of cubes than cylinders.

When comparing reference and RAC mixtures in case of cube specimens following conclusions can be made:

- Increase in compressive strength of RAC compared to NAC for standard cube specimen (150x150x150 mm) is recorded.
- This increase of compressive strength of RAC compared to NAC is even higher when higher strength class is considered.
- When size of the specimen decreases in case of NAC, increase in compressive strength is recorded (SE is visible).
- When size of the specimen decreases in case of RAC, increase in compressive strength is recorded until size of 100x100x100 mm (SE visible).
- The compressive strength of 50x50x50 mm specimen size decreases and this decrease is even more significant when strength class increases (SE not visible).
- The specimen size of 50x50x50 mm should not be included in investigation of SE on the compressive strength of RAC.

However, when comparing reference and RAC mixtures in case of cylinder specimens following conclusions can be made:

- Decrease in compressive strength of RAC compared to NAC for standard cylinder specimen (150x300 mm) is recorded.
- This decrease of compressive strength of RAC compared to NAC is lower when higher strength class is considered.
- When size of the specimen decreases in case of NAC, increase in compressive strength is recorded (SE is visible).

- When size of the specimen decreases in case of RAC, increase in compressive strength is recorded until size of 100x200 mm (SE visible).
- The compressive strength of 60x120 mm specimen size decreases and this decrease is even more significant when strength class decreases (SE not visible).
- As strength class increases, even increase in compressive strength of 100x200 mm specimen is reducing (SE not visible).
- The specimen size of 60x120 mm should not be included in investigation of SE on the compressive strength of RAC.

One more major finding of this research is regarding *K* factor. *K* factor in EN 206:2013 corresponds to ratio between characteristic strength of standard cylinder (150x300 mm) and cube (150x150x150 mm) specimen and it varies from 0.78 to 0.83, depending on strength class. It was shown that in case of RAC this value varies from 0.70 to 0.64 for our two different mixtures. So, the value specified for *K* factor in the relevant standard is not applicable to RAC.

To sum up, even though in case of NAC SE is applicable, in case of RAC it is not entirely true. Further investigations should be done for SE phenomenon in case of RAC. Behavior of the different specimen size in case of other mechanical properties of RAC should be focus of future studies. Also, other strength classes should be investigated in order to examine if our findings are applicable to them also. Moreover, influence of different replacement ratios of NAC with RAC in studying SE might be a future research. So, there are many unexplored factors that should be a subject of future researches considering SE of RAC.

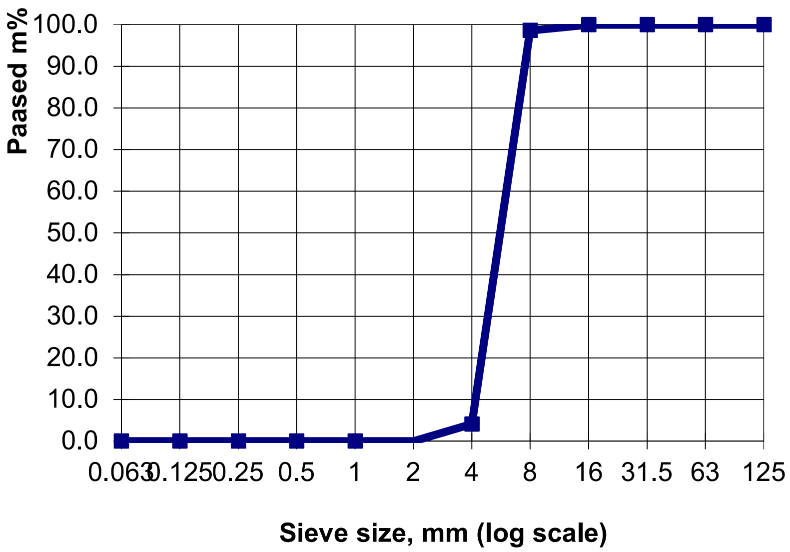
Appendix

1. Sieve analysis of fine and coarse aggregate

Coarse aggregate-RCA

Sieve size (mm)	Percent of volume retained on each sieve Rn (%)	Percent finer 100-∑Rn (%)
125	*0.0*	*100.0*
63	*0.0*	*100.0*
31.5	*0.0*	*100.0*
16	*0.0*	*100.0*
8	*1.4*	*98.6*
4	*94.5*	*4.1*
2	*4.1*	*0.0*
1	*0.0*	*0.0*
0.5	*0.0*	*0.0*
0.25	*0.0*	*0.0*
0.125	*0.0*	*0.0*
0.063	*0.0*	*0.0*
Sum	**100.0**	

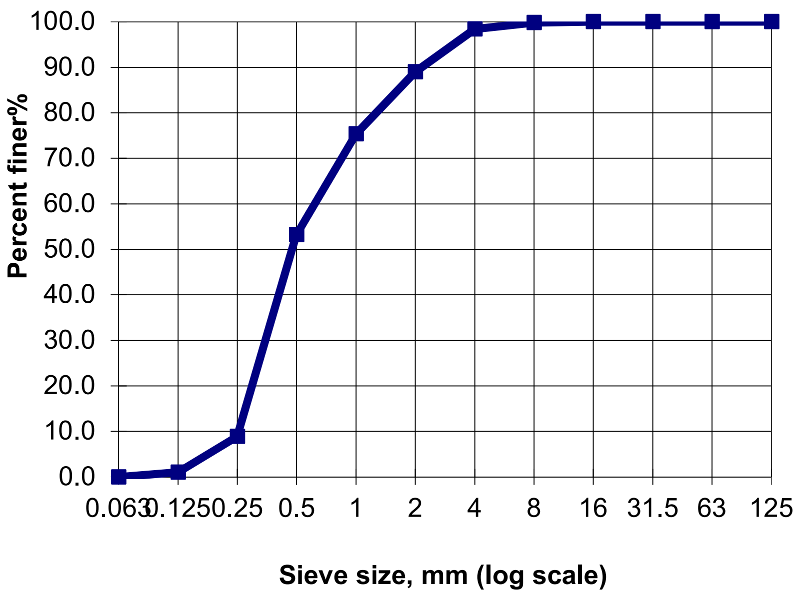
m_{ave}= 6.97



Fine aggregate- river sand

Sieve size (mm)	Percent of volume retained on each sieve Rn (%)	Percent finer 100-∑Rn (%)
125	*0.0*	*100.0*
63	*0.0*	*100.0*
31.5	*0.0*	*100.0*
16	*0.0*	*100.0*
8	*0.2*	*99.8*
4	*1.4*	*98.4*
2	*9.4*	*89.0*
1	*13.6*	*75.4*
0.5	*22.1*	*53.3*
0.25	*44.3*	*8.9*
0.125	*7.9*	*1.1*
0.063	*1.1*	*0.0*
Sum	**100.0**	

$m_{ave}=$ 3.74



2. Loose bulk and particle density, water absorption capacity

Loose bulk density

Sign of product	m_{dry} (g)	$V_{container}$ (cm^3)	Bulk density (kg/m^3)	Average bulk density (kg/m^3)
AM1	1,266.9	1,000.0	**1,266.9**	***1,270.2***
AM2	1,273.5	1,000.0	**1,273.5**	
AM3	1,287.6	1,000.0	**1,287.6**	

Particle density and water absorption capacity

ρ_w= 0.996756 g/ml

M_{w+c}= 825.5 g V_{pik}= 580.68 ml

M_c= 246.7 g

Sign of product	$m_{c+dry\ a}$(g)	$m_{c+wet\ a}$(g)	$m_{c+wet\ a+w}$ (g)	$V_{water\ above}$ (ml)	V_{aggr} (ml)	Particle density (kg/m^3)	Water absorption 24 hours (m%)
						measured	measured
AM1	477.9	483.2	968.3	486.68	94.00	**2459.4**	**2.3**
AM2	426.5	431.0	936.7	507.35	73.34	**2451.7**	**2.5**
AM3	470.7	476.1	963.9	489.39	91.30	**2453.6**	**2.4**
AVERAGE						**2454.9**	**2.4**

3. Moisture content of aggregates for AD-B1 and AD-B2

Moisture content of aggregates for AD-B1:

Aggregate type	Moisture content (%)
River sand	3.7
RCA	1.0

Moisture content of aggregates for AD-B2:

Aggregate type	Moisture content (%)
River sand	4.5
RCA	1.3

4. Detailed composition of the mixes

AD-B1			Dosage [kg/m^3]	Dosage [l/m^3]	ρ [g/ml]	45ℓ (kg/l)
Cement	CEM I 52.5 N	DDC	360	116	3.1	16.200
Water	w/c	0.5	180	180	1	6.9156
Fine aggregate	River sand 0/4	0.55	1010	382	2.645	47.132
Coarse aggregate	RCA 4/8	0.45	766	312	2.455	34.815
Admixture	Glenium 51	0.7	2.52	1	1.1	0.112
Air				10		
∑			**2319**	**1000**		

AD-B2			Dosage [kg/m^3]	Dosage [l/m^3]	ρ [g/ml]	45ℓ (kg/l)
Cement	CEM I 52.5 N	DDC	500	161	3.1	22.500
Water	w/c	0.3	150	150	1	5.112
Fine aggregate	River sand 0/4	0.55	987	373	2.645	46.414
Coarse aggregate	RCA 4/8	0.45	749	305	2.455	34.153
Admixture	Glenium 51	1.4	6.93	1	1.1	0.312
Air				10		
∑			**2393**	**1000**		

5. Rate of loading table of specimens for compressive strength test

Specimen type	**Rate of loading (kN/s)**
Cube 200 mm edge length	20.00
Cube 150 mm edge length	11.25
Cube 100 mm edge length	5.00
Cube 50 mm edge length	1.25
Cylinder 150x300	8.84
Cylinder 100x200	3.93
Cylinder 60x120	1.41

6. Compressive strength results for AD-B1, AD-B2 mixtures

Compressive strength results for cube specimens of AD-B1 mixture

Edge length [mm]	#	Size [mm]			Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
		a	b	h					
200	1	200.52	197.28	200.18	18012.00	2310.00	58.39	**50.81**	0.805
	2	197.06	200.12	200.02	18055.00	1750.00	44.38		
	3	198.09	200.24	200.20	19432.00	1970.00	49.67		
150	4	149.49	149.73	149.83	7690.00	1518.00	67.82	**63.13**	1.000
	5	149.73	147.25	149.99	7560.00	1440.00	65.31		
	6	151.37	150.36	149.66	7650.00	1376.00	60.46		
	7	151.10	150.17	150.04	7720.00	1337.00	58.92		
100	8	100.11	97.24	100.17	2240.00	718.00	73.76	**68.83**	1.090
	9	100.23	101.15	100.52	2310.00	620.00	61.15		
	10	100.30	98.90	100.09	2260.00	710.00	71.57		
50	11	50.00	50.30	50.00	280.00	189.00	75.15	**60.06**	0.951
	12	50.00	50.00	50.00	290.00	123.00	49.20		
	13	50.00	49.20	50.00	280.00	148.00	60.16		
	14	50.00	49.00	50.00	280.00	104.00	42.45		
	15	50.00	51.00	50.00	290.00	161.00	63.14		
	16	50.00	50.00	50.10	290.00	166.00	66.40		
	17	49.64	49.70	50.00	280.00	185.00	74.99		
	18	49.88	49.14	50.00	280.00	120.00	48.96		

Compressive strength results for cylinder specimens of AD-B1 mixture

Diameter x height [mm]	#	Size [mm]		Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
		d	h					
150x300	1	150.14	302.82	12240.00	794.00	44.85	**44.22**	1.000
	2	150.30	295.30	12634.00	741.00	41.76		
	3	150.60	296.40	12852.00	820.00	46.03		
100x200	4	100.05	203.34	3630.00	328.00	41.72	**41.66**	0.942
	5	100.05	205.80	3680.00	327.00	41.59		
60x120	7	60.13	124.32	800.00	120.00	42.26	**48.88**	1.105
	8	60.24	122.38	790.00	156.00	54.73		
	9	60.35	120.70	790.00	142.00	49.64		

Compressive strength results for cube specimens of AD-B2 mixture

Edge length [mm]	#	Size [mm]			Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
		a	b	h					
200	1	191.16	198.32	200.04	19031.00	3603.00	95.04	**99.12**	0.971
	2	200.06	198.16	200.42	18959.00	4340.00	109.47		
	3	199.12	199.58	200.18	19030.00	3690.00	92.85		
150	4	150.00	147.72	150.06	7903.80	2196.00	99.11	**102.05**	1.000
	5	146.00	150.00	150.48	7833.20	2313.00	105.62		
	6	150.12	146.00	150.28	7818.30	2223.00	101.43		
100	9	100.36	100.30	100.08	2429.50	1126.00	111.86	**106.06**	1.039
	10	100.50	100.20	100.32	2378.10	965.00	95.83		
	11	100.70	100.48	100.48	2405.70	1118.00	110.49		
50	12	50.40	50.08	50.12	282.30	222.00	87.95	**84.27**	0.826
	13	49.78	50.10	50.46	299.70	265.00	106.26		
	14	50.20	50.30	49.66	297.90	148.00	58.61		

Compressive strength results for cylinder specimens of AD-B2 mixture

Diameter x height [mm]	#	Size [mm]		Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
		d	h					
150x300	1	150.21	303.10	12780.00	1145.00	64.62	**65.56**	1.000
	2	149.48	303.49	12740.00	1190.00	67.81		
	3	150.11	308.10	13100.00	1137.00	64.25		
100x200	4	100.20	204.76	3810.00	475.00	60.24	**65.84**	1.004
	5	100.26	201.71	3780.00	564.00	71.45		
60x120	6	60.35	121.00	820.00	134.00	46.84	**52.94**	0.808
	7	60.16	122.36	820.00	210.00	73.88		
	8	59.80	121.52	810.00	107.00	38.10		

7. Compressive strength results for REF1 and REF2 mixtures

Compressive strength results for cube specimens of REF1 mixture

Edge length [mm]	#	Size [mm]			Mass [g]	Force [kN]	Comp. Strength [N/mm²]	Av. Comp. Strength [N/mm²]	Strength ratio (compared to standard) [-]
		a	b	h					
200	1	199.80	200.10	200.50	19123.00	2123.00	53.10	**54.28**	0.939
	2	200.70	200.10	199.60	19284.00	2129.00	53.01		
	3	200.50	200.60	200.70	19311.00	2282.00	56.74		
150	4	150.10	151.60	150.20	8133.00	1296.00	56.95	**57.82**	1.000
	5	150.00	151.70	149.90	8172.00	1311.00	57.61		
	6	150.10	152.70	150.10	8147.00	1350.00	58.90		
100	7	100.50	101.30	100.30	2410.00	629.00	61.78	**60.76**	1.051
	8	100.50	100.50	101.90	2420.00	603.00	59.70		
	9	101.00	100.50	100.30	2401.00	617.00	60.79		

Compressive strength results for cylinder specimens of REF1 mixture

Diameter x height [mm]	#	Size [mm]		Mass [g]	Force [kN]	Comp. Strength [N/mm²]	Av. Comp. Strength [N/mm²]	Strength ratio (compared to standard) [-]
		d	h					
150x300	1	149.80	295.60	12669.00	917.00	52.03	**51.53**	1.000
	2	150.30	295.30	12634.00	946.00	53.32		
	3	150.60	296.40	12852.00	877.00	49.23		
100x200	4	100.00	196.80	3774.00	425.00	54.11	**54.26**	1.053
	5	99.80	198.80	3805.00	425.00	54.33		
	6	99.80	199.10	3787.00	425.00	54.33		
60x120	7	58.90	116.20	787.00	153.00	56.15	**57.54**	1.117
	8	59.70	118.40	803.00	169.00	60.37		
	9	59.70	118.20	803.00	157.00	56.09		

Compressive strength results for cube specimens of REF2 mixture

Edge length [mm]	#	Size [mm] a	Size [mm] b	Size [mm] h	Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
200	S32	200.60	201.20	200.50	19021.00	2750.00	68.14	**68.21**	0.927
	S33	200.90	201.50	200.80	18885.00	2770.00	68.43		
150	S21	200.40	200.90	201.00	19063.00	2740.00	68.06	**73.62**	1.000
	S22	150.60	149.40	150.40	7933.00	1781.00	79.16		
	S23	150.60	149.00	151.30	7959.00	1497.00	66.71		
	2S1	150.10	150.60	150.40	7991.00	1695.00	74.98		
	2S2	150.60	151.00	150.30	7922.00	1648.00	72.47		
	2S3	150.10	147.50	150.50	7740.00	1656.00	74.80		
100	S11	100.10	99.10	100.50	2370.00	809.00	81.55	**78.64**	1.068
	S12	100.60	102.00	100.80	2437.00	777.00	75.72		
50	S1	51.50	50.40	50.30	301.00	219.00	84.37	**83.75**	1.138
	S2	50.00	51.40	49.80	302.00	213.00	82.88		
	S3	51.40	49.80	50.50	304.00	215.00	83.99		

Compressive strength results for cylinder specimens of REF2 mixture

Diameter x height [mm]	#	Size [mm] d	Size [mm] h	Mass [g]	Force [kN]	Comp. Strength [N/mm^2]	Av. Comp. Strength [N/mm^2]	Strength ratio (compared to standard) [-]
150x300	M31	152.00	304.40	12909.00	1245.00	68.61	**66.74**	1.000
	M32	150.30	305.50	12646.00	1119.00	63.07		
	M33	151.10	304.70	12746.00	1229.00	68.54		
100x200	M21	101.10	205.90	3838.00	557.00	69.39	**68.17**	1.021
	M22	100.60	204.80	3825.00	596.00	74.98		
	M23	100.80	204.60	3816.00	480.00	60.15		
60x120	M11	60.10	125.20	837.00	229.00	80.72	**69.68**	1.044
	M12	60.10	125.90	829.00	163.00	57.46		
	M13	60.40	119.30	834.00	203.00	70.85		

Bibliography

Arioz, O., Tuncan, A., Ramyar, K., & Karasu , B. (2009). Specimen Size and Shape Effects on Measured Compressive Strength of Concrete. *I. INTERNATIONAL CERAMIC, GLASS, PORCELAIN ENAMEL, GLAZE AND PIGMENT CONGRESS*, (pp. 1044-1052). Eskisehir.

Bažant, Z. (1984). Size Effect in Blunt Fracture: Concrete, Rock, Metal. *Journal of Engineering Mechanics, 110*(4), 518-535. doi:10.1061/(ASCE)0733-9399(1984)110:4(518)

Bažant, Z. (1999). Size effect on structural strength: a review. *Applied Mechanics, 69*, 703-725.

Buller, A., Oad, M., & Memon, B. (2018). Relationship between Cubical and Cylindrical Compressive Strength of Recycled Aggregate Concrete. *International Journal of Innovative Research in Engineering and Multidisciplinary Physical Sciences (IJIRMPS), 6*(5), 133-138. doi:10.13140/RG.2.2.28872.78086

C.Meyer. (2005). *Concrete as a Green Building Material.* New York: Columbia University.

Cabrera, M., Agrela, F., & Galvín, A. (2019). Leaching issues in recycled aggregate concrete. In J. de Brito, & F. Agrela, *New Trends in Eco-efficient and Recycled Concrete* (pp. 329-356). Woodhead Publishing. doi:10.1016/C2017-0-01898-0

CEN. (2001). *Testing hardened concrete-Part 3: Compressive strength of test specimens.* Brussels: Management Centre: rue de Stassart.

CEN. (2008). *AGGREGATES FOR CONCRETE DIN EN 12620 : 2008.* Berlin, Germany: German Institute for Standardisation (Deutsches Institut für Normung).

CEN. (2016). *Concrete - Specification, performance, production and.* Brussels: CEN-CENELEC Management Centre.

Chen, P., Liu, C., & Wang, Y. (2018). Size effect on peak axial strain and stress-strain behavior of concrete subjected to axial compression. *Construction and Building Materials*(188), 645-655. doi:10.1016/j.conbuildmat.2018.08.072

del Viso, J., Carmona, J., & Ruiz, G. (2008). Shape and size effects on the compressive strength of high-strength concrete. *Cement and Concrete Research, 38*(3), 386-395. doi:10.1016/j.cemconres.2007.09.020

Dolan, P. J., Lampo, R. G., & Dearborn, J. C. (1999). *Concepts for Reuse and Recycling of Construction and Demolition Waste.* US Army Corps of Engineers Construction Engineering Research Laboratories (USACERL).

Gyurko, Z., & Nemes , R. (2016). SIZE EFFECT ON CYLINDER AND CUBE STRENGTH OF CONCRETE. *CONCRETE STRUCTURES*, 40-44.

Karamloo, M., Roudak , M., & Hosseinpour, H. (2019). Size effect study on compressive strength of SCLC. *Computers and Concrete, 23*, 409-419. doi:10.12989/cac.2019.23.6.409

Kim, J.-K., & Yi, S.-T. (2002). Application of size effect to compressive strength of. *Sadhana, 27*, 467-484. doi:10.1007/BF02706995

Langer, W. H., Drew, L. J., & Sachs, J. S. (2004). *Aggregate and the Environment.* Alexandria, Va. : American Geological Institute in cooperation with U.S. Geological Survey.

Lu, W., & Yuan, H. (2011). A framework for understanding waste management studies in construction. *Waste Management 31*, 1252-1260. doi:10.1016/j.wasman.2011.01.018

Muciaccia, G., Rosati, G., & Di Luzio, G. (2017). Compressive failure and size effect in plain concrete cylindrical specimens. *Construction and Building Materials*, 185-194. doi:10.1016/j.conbuildmat.2017.01.057

Neville, A. (2011). *Properties of Concrete* (5 ed.). Harlow, United Kingdom: Pearson Education Limited.

Ntaryamira, T., Quansah, A., & Zhang, Y. (2017). ASSESSMENT OF RECYCLED CONCRETE AGGREGATE(RCA) USAGE IN CONCRETE. *IJRET:International Journal of Research in Engineering and Technology*, 72-78. doi:10.15623/ijret.2017.0612013

Pacheco, J., de Brito, J., Chastre , C., & Evangelista , L. (2019). Probabilistic Conversion of the Compressive Strength of Cubes to Cylinders of Natural and Recycled Aggregate Concrete Specimens. *Materials, 12*(2), 280-291. doi:10.3390/ma12020280

Pepe, M. (2015). *A Conceptual Model for Designing Recycled Aggregate Concrete for Structural Applications.* Springer Internation Publishing. doi:10.1007/978-3-319-26473-8

Suhendro, B. (2014). Toward green concrete for better sustainable environment. *2nd International Conference on Sustainable Civil Engineering Structures and Construction Material. 95*, pp. 305-320. Yogyakarta, Indonesia: Procedia Engineering . doi:10.1016/j.proeng.2014.12.190

Tabsh, S. W., & Abdelfatah, A. S. (2009). Influence of recycled concrete aggregate on strength properties of concrete. *Construction and Building Materials , 23*, 1163-1167. doi: 10.1016/j.conbuildmat.2008.06.007

Tavakoli, D., Hashempour, M., & Heidari, A. (2018). Use of Waste Materials in Concrete: A Review. *Pertanika J. Sci. & Technol. 26(2)*, 499-522.

Yi, S.-T., Yang, E.-I., & Choi, J.-C. (2006). Effect of specimen sizes, specimen shapes, and placement. *Nuclear Engineering and Design, 236*, 115-127. doi:10.1016/j.nucengdes.2005.08.004