UiT The Arctic University of Norway

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# Evaluation of the impact of recycled concrete aggregates on the durability of concrete

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# Foreword

The content of this thesis mainly focuses on why we would use recycled aggregates in concrete. What is the reason that so much research has been conducted on this subject? However, once the importance of its use is recognized, its properties are frequently refuted. Since this thesis aims to promote the use of the recycled aggregates, this work gives a useful source of information on its properties. Furthermore, it also discusses which influences and changes the concrete experiences when these aggregates are being used instead of the natural ones. It goes without saying that adjustments will have to be made to the processing of the aggregates before they can be used in the concrete mix. The non-obvious use is described in detail. But the extensive literature study also suggests many options for improvement, so that the concrete could still be put into circulation more. By discussing the laboratory tests conducted by fellow students at the Arctic University of Norway, links are made with the literature. We check whether the information obtained is correct and what actions can be taken in the future to increase the use of this type of concrete.

This thesis points out that for a long time a large number of tests have been conducted on the use of recycled aggregates. This gives a variety of results, some of which are even contradictory. Furthermore, I learn that effective widespread use is still a long way off and many studies still need to be undertaken to bring a consistent concrete to the market. I especially look forward to when people experiment more with the possible improvement options.

I want to thank the people who helped me write this thesis, without them I could not have achieved such a comprehensive result. It was a pleasure to work with people who are also passionate and who are open and available to offer any help necessary. Thank you to prof. dr. ir. Veerle Boel, ir. Iveta Novakova, ir. Mr. Boy-Arne Buyle and the students in distant Norway who carried out the tests. I would also like to thank MA Sander Vansevenant for proofreading this work. My parents also deserve thanks for being considerate of me late at night when I was still fiddling with my laptop and for providing me with everything I needed.

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# 1 Introduction

Due to the increase in the world’s population and the accompanying economic developments, large investments are being made in the construction industry (Dhir Obe, Brito, Silva, & Lye, 2019; Freedonia, 2012). Logically, the number of construction practices in the process increases. This causes competition in the construction industry to skyrocket and forces the players to focus on the financial aspect rather than sustainability. This large number of practices results in a high demand for aggregates, since the bulk of recent construction is made of concrete and concrete is about 70% aggregate (Bassani, Diaz Garcia, Meloni, Volpatti, & Zampini, 2019; Saini & Singh, 2020). In doing so, the cheapest and easiest option is gradually chosen, namely the extraction of natural aggregate sources with the adverse effects on the environment that come with it (Dhir Obe et al., 2019). Obtaining these natural aggregates is done largely through extensive mining activities, which consumes an excessive amount of energy and involves heavy equipment (Saini & Singh, 2020; Verian, Ashraf, & Cao, 2018). The mining activities have a major impact on the environment and facilities such as noise, dust, atmospheric emissions from machinery engines, groundwater pollution, etc. Natural resources are being rapidly depleted at a high rate and natural habitats are being destroyed (Dhir Obe et al., 2019; Saini & Singh, 2020). This leads to people having to go the extra mile to obtain good quality of aggregates. This in turn has the negative effect of driving up the cost of extraction. Thus, alternatives must be sought.

The most obvious solution to obtain aggregates that are close, is to start reusing old construction material. This material is called Construction & Demolition Waste (CDW). But what happened (still happens) to CDW, when there is no attempt to reuse them? The main possibility would be to incinerate them. However, CDW has the properties of being inert and having a high density, making this possibility not recommendable. CDW was/is being dumped into landfills (Saini & Singh, 2020), which again makes the reuse of CDW a positive alternative. Construction is one of the industries with the largest volume of waste with a contribution of approximately 5% and it is also the heaviest waste. Concrete is responsible for about 70% of this waste (Dhir Obe et al., 2019; USEPA, 2016). Normally these quantities are tracked but the statistics available now are probably still too low due to uncontrolled operations and the inadequate waste management policies, leading to illegally dumped CDW (Dhir Obe et al., 2019). And unfortunately, older structures that are being demolished do not consist solely out of concrete. CDW consist mainly of many different types of materials that are mixed together (e.g., wood, plaster, etc.) (Dhir Obe et al., 2019; Saini & Singh, 2020; USEPA, 2016). As can be seen in the chart below, all waste from demolition and construction is divided by quantity. The continued increase in construction waste will make recycling concrete waste an important global challenge (Guo et al., 2018).

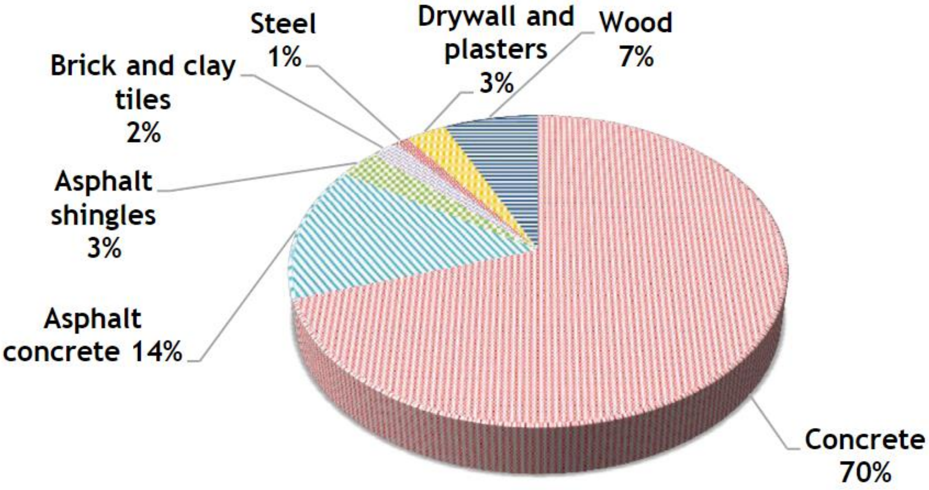

*Figure 1: CDW generated in 2014 for the United States (USEPA, 2016)*

## 1.1 Recycled aggregates: pros and cons

The use of all those recycled aggregates (RAs) carries a lot of advantages. Firstly, it has the effect of lowering the carbon footprint (Dhir Obe et al., 2019). According to (Saini & Singh, 2020; V. W. Y. Tam, Soomro, & Evangelista, 2018), the reduction of carbon emissions is up to 28% and it boosts the conservation of natural resources. According to (Hossain, Poon, Lo, & Cheng, 2016; Verian et al., 2018), the use of RA from CDW in Hong Kong reduces up to 65% of the greenhouse gas footprint and saves the energy consumption up to 58%. Another study by (Coelho & Brito, 2013; Coelho & de Brito, 2013c; Dhir Obe et al., 2019) indicated that up to 85% less energy was consumed through the use of a CDW recycling plant, compared to the conventional approach. This study also reported that 90% lower $CO_2$ emissions were observed. Other studies mentioned a $CO_2$ emissions reduction by about 15% - 20% (Guo et al., 2018; Kazmi et al., 2020; Xiao, Li, Fan, & Huang, 2012). These values can be explained by the reduced transport to and from the mining sites, the reduced consumption of energy and volume of CDW (Dhir Obe et al., 2019). The figure below shows the generated waste by each economic activity during the years 2004 – 2014.

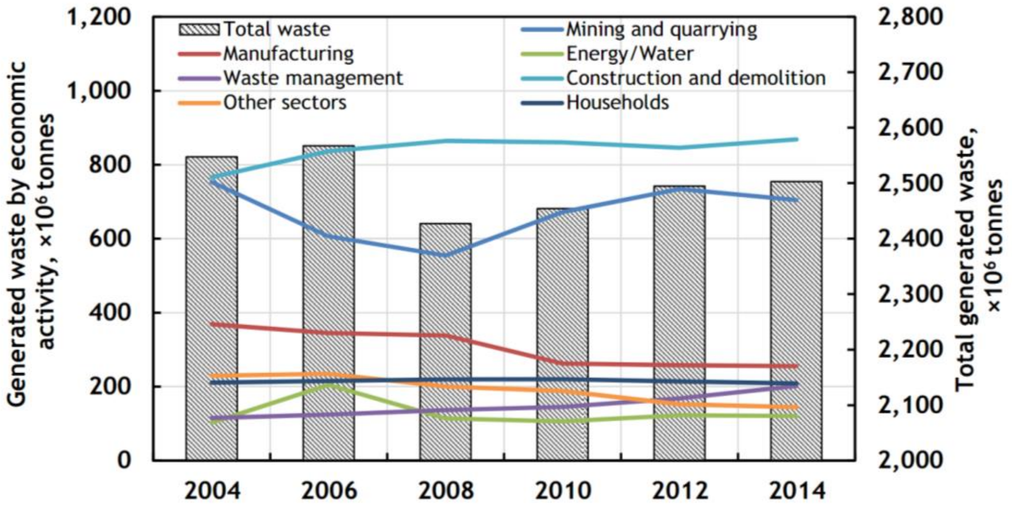

*Figure 2: Generated waste by each economic activity (Eurostat, 2017)*

The use of recycled concrete aggregates (RCAs) instead of natural aggregates (NAs) also ensures that no new mining sites are opened. A well-defined example was given by (Guo et al., 2018; Kazmi et al., 2020; Xiao, Li, Fan, et al., 2012), who stated that the use of RA could save up to 60% of limestone resources. RCA's transport still needs to be done, but since RCA's unit weight is lighter than NA's, less transport energy is required (Verian et al., 2018). According to some experiences in (Dhir Obe et al., 2019), they come to a statement which shows that the extraction of NA poses a higher threat to the environment than the use of RA. The use of RCA logically also ensures that less waste is dumped in landfills (Bovea & Powell, 2016; Dhir Obe et al., 2019; Faleschini, Zanini, Pellegrino, & Pasinato, 2016; James W. Mack, 1993; Verian et al., 2018). The use of RA also has an economical advantage by reducing the construction costs (USGS, 2000; Verian et al., 2018). With all of the above, it can be concluded that the use of RCA can certainly be considered. Especially since it still possesses the qualities that make it possible to make concrete that has a high structural strength. The universal trend aims towards recycling of construction waste as RA in the concrete structures, which can be attributed to the urge to overcome the depletion of natural resources and environmental pollution, to avoid the accumulation of debris in the landfills, to have less air pollution, etc. (Kazmi et al., 2020; Munir, Kazmi, Wu, Patnaikuni, Wang, et al., 2020; Sasanipour & Aslani, 2020a). Although there is still a long way to go, it can be said that the use of RCA is rich in potentials and it can only be encouraged (Guo et al., 2018; Verian et al., 2018).

Despite the benefits, the drawbacks of using RCA must also be considered. It has its own carbon footprint and it can definitely affect nature and the environment in a way that is similar to the use of NA (Dhir Obe et al., 2019; Lopez Gayarre, Gonzalez Perez, Lopez-Colina Perez, Serrano

Lopez, & Lopez Martinez, 2016). To remove the greater amount of mortar that is adhered to the RA there is a need for energy-intensive thermal treatments that can impact the environment greatly (Dhir Obe et al., 2019; Guo et al., 2018). All installations also need space to settle, which in turn takes land. The machines also produce sound, dust, vibrations, gas and odor (DETR, 2000; Dhir Obe et al., 2019; Omary, Ghorbel, & Wardeh, 2016). The aggregates must be removed from the recycled concrete and washed. As a result, there is a very high consumption of water that can also pollute the groundwater and contaminate land (DETR, 2000; Dhir Obe et al., 2019). Furthermore, CDW is difficult to process. Due to the high level of contamination, it affects the end product in a negative way (Dhir Obe et al., 2019). In order to minimize this contamination, quality controls and pre-crushing separation and/or post-crushing separation can be used (Dhir Obe et al., 2019). The low quality of the waste is one of the biggest obstacles that needs to be overcome. The concerns about the durability of RAs in concrete structures are what limits its use (Kazmi et al., 2020). According to (Saini & Singh, 2020), the processing of CDW should be approached according to the mindset of the 3R-concept: Reduce, Recycle and Replace. One solution could be searching and finding sustainable resources that can replace the natural components in the production of concrete (Guo et al., 2018).

Some challenges emerge when working with RAs that are worth mentioning. When buildings are demolished, it usually means that they have been in use for many years and that some of the materials may have reached the end of their useful life. That implies that some parts of the materials are unusable (Dhir Obe et al., 2019). A lot of waste coming from new residential and non-residential constructions is wood, which therefore cannot be used to make new concrete. Demolition and refurbishment activities tend to produce higher amounts of concrete and bricks which makes them more interesting for RAs (Dhir Obe et al., 2019; Mália, de Brito, Pinheiro, & Bravo, 2013). All the different materials found in building waste each have their own characteristics and make it very difficult to maintain a consistent quality of concrete (Bravo, de Brito, Pontes, & Evangelista, 2015a, 2015b; Rodrigues, Carvalho, Evangelista, & de Brito, 2013; Saini & Singh, 2020). In order to keep the demolition as cost-effective as possible, buildings are broken down in one go. What follows is unsorted waste that creates a more complex or even impossible recycling process (Dhir Obe et al., 2019). For an improvement of the identification of the materials and a separation at the source, there should be a selective demolition and adequate on-site operations. On this basis a collection can then be built up and a separation can be made of materials that have the potential to be recycled (Dhir Obe et al., 2019; EC, 2016). This aims to have sound waste management policies that allow for accurate qualification and segregation of CDW. (Dhir Obe et al., 2019; Noguchi, Park, & Kitagaki, 2015). By having standards and specifications, there will be a higher awareness of the use of RA and guidance documents will persuade people more to try out the use of RA (Knoeri, Binder, & Althaus, 2011; Knoeri, Nikolic, Althaus, & Binder, 2014). Aspects that may affect the estimation of the CDW, in order to identify them and decide if they can be reused, are the date and the purpose of the construction that is to be demolished (Dhir Obe et al., 2019). The quality of RAs is highly dependent on the waste separation process. Sorting has to be done at all stages. This results in a large variety of products obtained that are available for various applications. Keep in mind that complex machinery is required for proper dismantling resulting in financial pressure, as well as health, safety and other required standards. Due to the selective dismantling of the structures and in doing so obtaining more different materials, there is an increase in transportation. This therefore has a negative impact on the environment (Coelho & de Brito, 2012). To minimize the road haulage distance, recycling plants should be placed in strategic places. These places should be capable of receiving and processing waste from multiple nearby potential demolition and construction sites. They should preferably be located in the vicinity of potential aggregate users, for the purpose of eliminating a lot of road haulage operations, a minimization of transportation costs and time and encouragement of using recycled materials (Braga, Silvestre, & de Brito, 2017; Coelho & de Brito, 2013b). But if RAs are categorized according to their intrinsic properties rather than their composition, it is possible to maximize the use of RAs, assign the most appropriate application and thus improve the performance of the final product. Unlike NAs where aggregates can be collected at any time, the quantity and availability of RAs depends on buildings being demolished. This results in a low quantity of CDW and an intermittent supply of it. Since only a small amount of RA and conventional raw materials have to be used, this leads to impracticality due to more complex logistics and associated high costs. A lack of provisions/standards for the use of RA prevents a better understanding of these RAs and the concrete in which they are incorporated. And that in turn has the effect of inhibiting their use in practice (Coelho & de Brito, 2011).

The perfect recycling process desires the reuse of aggregates for several times but this is not always possible. As recycling progresses, the RCA will contain less and less of the original NA and more of the attached mortar. This has a significant negative impact on the quality of the recycled aggregates and the newly made concrete. This multiple recycling will increase the coarse RA’s water absorption capacity which will cause a decrease in the effective water-cement ratio (W/C) and inferior workability (Brito, Gonçalves, & Santos, 2006; S. B. Huda &

Alam, 2014). The increased content of the attached mortar will lead to an increase in the requirement of water in the concrete mixes, which in turn will affect the mechanical behavior of the concrete. Furthermore, the recycled aggregates of repeated recycling cycles will show an increase in the rate of strength development. There will also be an increase in the dry RCA's replacement level, which will cause a decrease in the effective W/C ratio and a decline in consistence.

Economically, the costs of access to recycling plants are very high (Coelho & de Brito, 2013a, 2013b). On the other hand, the reclamation of reusable materials and redirecting recyclable wastes to certified beneficiation plants ensures that there can be higher profits compared to ordinary demolition methods (Coelho & de Brito, 2011; Hurley, McGrath, Fletcher, & Bowes, 2001). In addition, there is a high level of uncertainty and lack of shareholder confidence as there is a great lack of recognition for the different materials available. However, they are very important in the process. The shareholders are involved in making decisions such as whether or not to use RA in a construction according to technical feasibility, so their importance cannot be neglected. There is also a price sensitivity towards the supply of RA. The use of NAs was/is a fully developed industry, hence a supply of NAs at relatively low prices is available. Taxes on the mining of NAs do not take into account the effect on the environment (Knoeri et al., 2014).

In order to find a viable solution for CDW and to protect the natural aggregate resources, especially the non-renewable resources, there is a global increase in research on recycling aggregates (Omary et al., 2016).

# 2 Terminology

This section clarifies some of the terms in order for the reader to fully understand the meaning of this thesis.

- Concrete is one of the most widely used construction materials. The constituents of concrete are mainly cement, water, admixture and aggregates. The aggregate takes up approximately 70% - 80% of the concrete mixture and could be coarse and fine (Bassani et al., 2019; Saini & Singh, 2020; Verian et al., 2018).
- Demolition is when a very large volume of materials, whose physical life has not yet expired, is broken down and replaced (Dhir Obe et al., 2019)

- CDW stands for Construction and Demolition Waste and indicates the end of service life of structures.
- The processed CDW that is useful in this work can be divided into three categories:
    - Recycled concrete aggregate (RCA). In order to comply with the name RCA, the product must consist of at least 90%, in mass, concrete fragments and natural aggregates (Dhir Obe et al., 2019). RCA can be obtained by concrete structures that are demolished or crushing existing concrete (Verian et al., 2018). These can be classified in terms of coarse and fine fractions (Saini & Singh, 2020).
    - Recycled Masonry Aggregate (RMA). In order to comply with the name RMA, the product must consist of at least 90%, in mass, a combination of any of lightweight and aerated concrete blocks, blast-furnace slag blocks and bricks, ceramic bricks and sand-lime bricks (Dhir Obe et al., 2019).
    - Mixed Recycled Aggregate (MRA). When the two above are combined, then there could have been spoken about MRA. This means less than 90% of concrete fragments and NA, by mass (Dhir Obe et al., 2019).
- Fine aggregates have a size that is up to 4.75 mm (Constructor)
- Coarse aggregates have a size that can’t go through a sieve of 4.75 mm. The maximum size is dependent of certain conditions. (Constructor)
- Concrete that is made with recycled aggregates is also called recycled aggregate concrete (RAC)
- Durability is the ability of concrete to keep its own shape and serviceability. It’s capable of resisting various types of damage and retains its strength after exposure to the environment (Guo et al., 2018; Kazmi et al., 2020).
- Interfacial Transition Zone (ITZ) is the bond between the paste and aggregates. Usually, the ITZ is weaker than both the aggregate and the hydrated cement paste. In the ordinary concrete with NA, the ITZ is located between the mortar and the aggregate. For concrete made with RCA, between the original aggregate, the old mortar and the new mortar is the ITZ (M. Etxeberria, Vázquez, Marí, & Barra, 2007; V. W. Y. Tam, Gao, & Tam, 2005; Verian et al., 2018) et al.
- SCC is the abbreviation for Self-Compacting Concrete. It primary consists of binder, sand, coarse aggregates and admixture (Saini & Singh, 2020)]. This concrete has the potential to fill every corner of the mold without the need for external vibration, thanks to its self-consolidating properties. SCC has the advantageous properties of high

deformability, good flowability, better finish and resistance to segregations. This makes SCC the best choice for structures that have congested reinforcement. Due to the microstructure that has fewer defects, SCC has enhanced durability.

# 3 What are the general properties of RA and how do they differ from NA?

If RAs are to be used in concrete, it is very important to know what properties they have that could potentially affect the final product and its performance (Dhir Obe et al., 2019). The mechanical performance of recycled aggregates could turn out to be similar to that of the natural aggregates, but this depends, inter alia, on the source of the RAs. The use of RAs could even improve the performance of the intended applications. But it has been found that properties like density, specific gravity, water absorption capacity, etc. of RAs are generally lower compared to those of coarse NAs (Saini & Singh, 2020). The main reason for the difference in properties of RA to NA is the presence of the old mortar that is still adhered on the RAs. This mortar is responsible for the generally lower specific gravity of RA in comparison to that of NA. It is also the main cause of the higher water absorption capacity and lower resistance to abrasion (Verian et al., 2018). Due to the adhered mortar, RAs tend to be more porous and be coarser and rougher than NAs (Dhir Obe et al., 2019; Dhir, Limbachiya, Leelawat, BS, & 882, 1999; Omary et al., 2016). When working with the bonded mortar, care must be taken to minimize the amount of fine RA, as the finer fraction accumulates a higher quantity of pulverized old mortar and causes the quality to deteriorate (Angulo et al., 2004; M. Etxeberria, Vázquez, et al., 2007; Müller & Winkler, 1998).. The RAs quality is also generally lower than that of NA because of this lower particle density. However, this can be beneficial if there is a need for concrete with lower density, for example to reduce the load of a structure (e.g., floors of skyscrapers). This resistance to fragmentation is expressed by a coefficient, namely the Los Angeles (LA) coefficient, which therefore has a greater value for RA than for NA (Dhir Obe et al., 2019; Omary et al., 2016). The lower quality of RA and the limited use of it is related to the physical properties of RA that tend to show very high variation and can be very inconsistent. On the other hand, the chemical composition of RAs can accommodate to the performance of the final product (Dhir Obe et al., 2019; Sasanipour & Aslani, 2020a; Tabsh & Abdelfatah, 2009). The composition must be determined in advance in order to be able to produce aggregates of good quality,  to minimize the constraints imposed by RA and to avoid complications for the final product (Dhir Obe et al., 2019). RAs can always contain impurities from destruction that can negatively affect the performance of the final product. The quantities of these impurities that can still be worked with are determined by the quality control and depend on the recycling methods (Noguchi et al., 2015). Furthermore, standards and specifications have already been laid down with which the recycled aggregate must comply. These state, among other things, that there is an upper limit of about 5% for the total amount of impurities. Although this may be more for lower quality RAs. Furthermore, there is also a limit for organic materials, namely 2,5% for lower quality RA and between 0,5% and 1% for average RA. The amount of glass is also limited due to the risk of alkali-silica reactions (Bravo et al., 2015a, 2015b; Van Praagh, Modin, & Trygg, 2015).

## 3.1 Mortar content

Some old mortars are intrinsically attached to the surface of the aggregates, making them actually part of the RCA. This causes a lighter system to be created in the RCA (Verian et al., 2018). According to (Q. Liu, Xiao, & Sun, 2011; Roesler, Lange, Salas, Brand, & Arboleda, 2013) the amount of Reclaimed Mortar Content (RMC) of coarser fractions (> 9,5 mm) is lower than the finer fractions of RCA (4,75 to 9,5 mm). The mortar's nature is more porous and less dense than the aggregate mix, which makes the RCA particles have a higher water absorption capacity (Kisku et al., 2017). The higher absorption correlates to the specific gravity having a lower value. However, this is not valid for fine NA, whose average absorption values are relatively constant over the observed range of specific gravity (ACPA, 2009; Verian, 2012). Another study from (Duan & Poon, 2014; Omary et al., 2016; Younis & Pilakoutas, 2013) stated that the low specific gravity could be more ascribed to the quality of the virgin aggregates than the proportion of the old mortar. The old mortar ultimately causes an increase in the water absorption capacity of the RCA, as well as a reduction in the specific gravity (Kisku et al.,

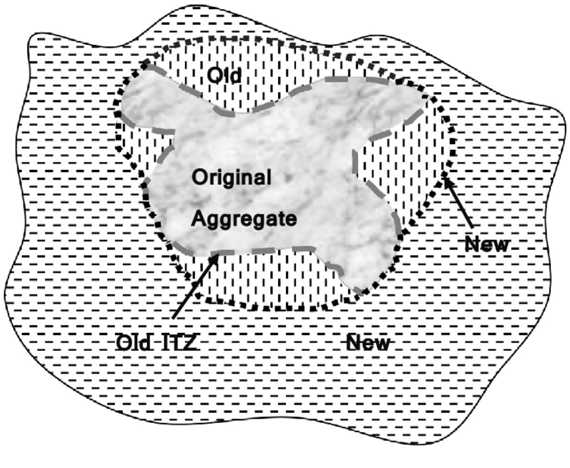

*Figure 3: Schematic figure of old and new ITZ (isku et al. (2017 ))*

2017; Verian et al., 2018). With a surface containing mortar layers, the use of RCA creates two types of ITZ, namely an old and a new one, as seen in figure 3.

The new ITZ and its porosity distribution is significantly affected by the strength of the RCA source concrete and the initial moisture status of the RCA (Le, Le Saout, Garcia-Diaz, Betrancourt, & Rémond, 2017; M. B. Leite & Monteiro, 2016). (Snyder, Vandenbossche, Smith, & Wade, 1994) also noticed a higher mass loss due to the presence of cracked particles during the demolishing process, and softer old mortar.

## 3.2 Influences of R(C)A on concrete

One of the concerns of using RCA is the higher mortar and the impurity contents of fine RCA (Verian et al., 2018). The negative characteristics of RCA that have been discussed up to here, e.g., higher water absorption capacity, higher porosity, and lower density, and the negative effects on the performance on the concrete, e.g., compressive strength, tensile strength, and modulus of elasticity (Sasanipour & Aslani, 2020a), (Kwan, Ramli, Kam, & Sulieman, 2012; Ozbakkaloglu, Gholampour, & Xie, 2018; Sasanipour & Aslani, 2020b) states that the maximum replacement rate of RCA should be limited. Regardless, efforts are always being made to raise that number as high as possible. For concrete in general, the weakest point is the ITZ (J. Zhang, Taylor, & Shi, 2015). Time progressively improves the mechanical performance of concrete. The rate with which this is done depends on the design of the mix (Dhir Obe et al., 2019). The mechanical performance and durability of the concrete is directly related to the physical properties of the coarse aggregates (Kazmi et al., 2019a, 2020; Y. Kim, Hanif, Kazmi, Munir, & Park, 2018; Xuan, Zhan, & Poon, 2017). Due to the higher water absorption capacity of RCA, the rough surface and irregular shapes of the aggregates, the workability of concrete decreases with the containment of RCA (Kurda, de Brito, & Silvestre, 2017a; Verian et al., 2018). Due to the increase of the porosity, the permeable voids and the weaker ITZ, there will be an increase in the W/C ratio which leads to a reduction in the compressive strength of the concrete (Popovics & Ujhelyi, 2008; Sasanipour & Aslani, 2020a). The increased porosity is also responsible for an increase in penetration of $CO_2$ in the concrete, i.e., increased carbonation depth (Amorim, Brito, & Evangelista, 2012; Kazmi et al., 2020). The old porous mortar adhered to the RCAs will reduce the tensile and flexural strength.

RCA also decreases the workability of SCC due to the texture of the surface of the aggregates which inhibits a good flow (González-Taboada, González-Fonteboa, Martínez-Abella, & Seara-Paz, 2017; Saini & Singh, 2020; R. B. Singh & B. Singh, 2018) et al. If there is only a replacement of 30%, then there will be no noticeable change in durability of the SCC, but it may expand the variability of the results (Kapoor, Singh, & Singh, 2016; Santos, da Silva, & de Brito, 2019; N. Singh & S. P. Singh, 2018) et al. What could be important for tests in the laboratory, is the fact that RCA-concrete shows a lower slump than current concrete when they have the same W/C ratio (Smith, 2018; Sturtevant, 2007; Verian et al., 2018) et al. The concrete requires around 5% to 15% additional water in the mix when RCA is used instead of NA, increasing the water to binder ratio of the concrete. This practice could actually be avoided if the aggregates are properly handled and the design of the concrete formulation is done properly (Verian, 2012). The retain of water in RA might work self-healing and cause a slower cure as it releases water at a later time and it might contribute to the additional hydration. Some of the advantages of using RCA in concrete are that both coarse and fine aggregates can be used in concrete and that the concrete could be designed in such a way that it matches the quality of NA-concrete.

# 4 Aggregates and concrete with aggregates

In this comprehensive section, various properties of concrete made from RCA are discussed. To understand these influences, this section starts with the properties of the aggregates themselves. Then it is discussed how these properties affect the concrete. This section is concluded with possibilities with which the concrete can be improved. The challenges to be dealt with can thus be reduced.

## 4.1 The properties that decide/influence the durability of the aggregates

The quality and the properties of RCA depend mainly on the original aggregate’s features and the condition in which the demolished concrete is in (Verian et al., 2018). But the production process is also capable of significantly affecting the properties of RCA (Guo et al., 2018).

### 4.1.1 Density

The density of aggregates is very important as larger values will give better performance (de Brito & Alves, 2010; Dhir Obe et al., 2019). Unfortunately, the density of the recycled aggregates is lower than that of the natural ones (figure 4). This is mainly due to the old mortar that still sticks to the aggregates (Omary et al., 2016; R. V. Silva, de Brito, & Dhir, 2014).

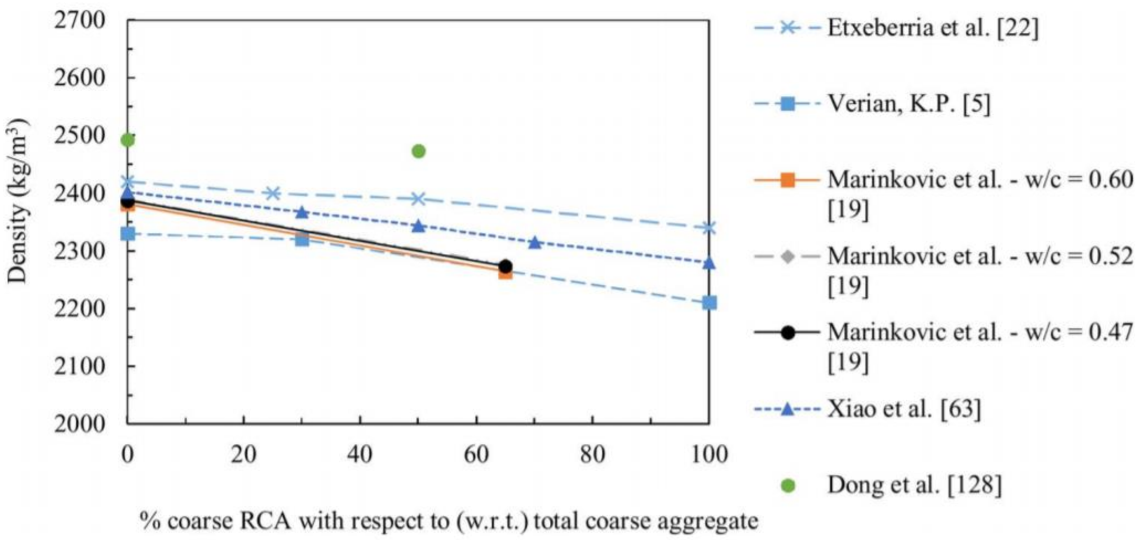

*Figure 4: The dinsity of concrete with different amounts of RCA (J. F. Dong, Wang, & Guan, 2013; M. Etxeberria, Vázquez, et al., 2007; Marinković, Radonjanin, Malešev, & Ignjatović, 2010; Verian, 2012; Xiao, Li, & Zhang, 2005)*

The RCA's density is overall independent of the original concrete's strength. According to [(Padmini, Ramamurthy, & Mathews, 2009; C. S. Poon, Shui, & Lam, 2004)], a contrary statement was concluded, namely if RCA comes from a concrete with lower strength, the aggregates will have a higher density. This was probably due to the lower strength concrete's mortar that was weaker and easier to remove. However, the density of RCA is still higher than that of RMA and MRA, in which RMA has the lowest. Best suited for structural concrete is coarse RCA, although coarse MRA of good quality can also be used. (Dhir Obe et al., 2019) also stated that all fine RA and coarse RMA is best for non-structural concrete. Other properties that influence density are listed below:

- <u>Adhered cement mortar.</u>

  As has been mentioned repeatedly, mortar is very porous compared to natural aggregates, as a result of which RA shows a progressively lower density (Desmyter, Vrijders, & Boehme, 2010; Nixon, 1978; V. W. Y. Tam & Tam, 2009) et al. If the size of the RA-fractions decreases, the content of mortar will increase (Adams et al., 2016). When multiple destruction processes are performed resulting in CDW, the friable material will decrease in size and start to accumulate in finer fractions. Knowing that the density of finer fractions is much lower, this has a negative result (Dhir et al., 1999; L. Evangelista & de Brito, 2007; Ravindrarajah & Tam, 1987) et al.
- <u>Removing the adhered mortar</u>

There are a lot of different processes that exist to remove the mortar. The number of treatments or crushing stages has a direct impact on the RCA's quality. When that number increases, the coarse RCA will have a higher density due to the attached cement mortar that is cumulatively broken up (Nagataki, Gokce, Saeki, & Hisada, 2004; Pedro, de Brito, & Evangelista, 2015). Because of the greater build-up of mortar as a result of the crushing, the greater yield of fine RCA due to the increasing processes will have a decreasing density (Kasai, 2004).

- Strength of the parent material.

  The quality of the cement paste is the cause of the strength of the concrete. If the cement paste is denser and has less porous mortar, than the concrete will have a higher strength (Kikuchi, Dosho, Miura, & Narikawa, 1998). If RCA comes from concrete with lower strength, than the RCA will have a slightly higher density (Padmini et al., 2009; C. S. Poon, Shui, & Lam, 2004). There is a strong correlation between the original brick's compressive strength and the resulting aggregate's density in case of RMA. If original bricks have enhanced mechanical characteristics, the aggregates will have a higher density (Bazaz, Khayati, & Akrami, 2006; Khalaf, 2006; Khalaf & DeVenny, 2004a) et al.

- Fragments from crushed masonry.

  The type of building material plays a huge role in the density of the aggregates. There is a preference for material with a higher proportion of RCA, so that performance can be similar to concrete with NA. When there are high porosity levels of ceramic products, the density of the RMA will usually be lower than that of RCA and there will be an even bigger difference with NA (Khalaf & DeVenny, 2004a, 2004b; Salomon & Paulo, 2007). Higher quantities of NA lead to a higher density, whereby the presence of RCA will slightly reduce the density (Angulo et al., 2004; C. S. Poon & Chan, 2006a, 2006b) et al. The resulting MRA's density will increase with an increase of RCA content and decrease with an increase of RMA content (Angulo et al., 2004; Dhir, Paine, & Halliday, 2008; Jiménez, Agrela, Ayuso, & López, 2011).

The change of the water absorption capacity of RA is influenced by the density. An increase of the water absorption is the result of a decrease in the aggregate's density and since strength is connected to density, it will affect this too (Omary et al., 2016). When the amount of substitution increases the porosity of the concrete, the density of the concrete will decrease.

### 4.1.2 Water absorption capacity

Water absorption capacity is owed to the greater porosity of RCA (Ait Mohamed Amer, Ezziane, Bougara, & Adjoudj, 2016; A. S. Brand, Roesler, & Salas, 2015; Dhir Obe et al., 2019). RCA are, compared with NA, characterized with higher values of water absorption capacity because of the quality and the amount of adhered cement mortar. Aspects that influence the water absorption capacity can be found below:

- Adhered cement mortar.

  Owing to the presence of the attached porous mortar, the absorption capacity of RCA is higher than the capacity of NA (Abdulla, 2015; Nixon, 1978; Ravindrarajah & Tam, 1987). Fine RCA-fractions show higher water absorption (Marinkovic, Dragas, Ignjatovic, & Tosic, 2017), whereas coarse RCAs exhibit the opposite (Ignjatovic, Marinkovic, & Tosic, 2017). This can be explained by the accrual of the crushed mortar in fine material (Chandra, 2004; Amnon Katz, 2003; Müller & Winkler, 1998) et al. The absorption of the fine particles has a slower rate in comparison with the coarse fractions (Bravo et al., 2015b; Pedro et al., 2015; Rodrigues et al., 2013) et al. Old attached mortar residues from lower strength masonry and plaster mortars are likely to be found in RMAs, which contributes to the water absorption capacity of the aggregates. A higher water absorption capacity is caused by the adhered mortar and the cracks present in the RCA. Water can flow into the concrete due to these cracks (de Juan & Gutiérrez, 2009; Dhir Obe et al., 2019; Gomes & de Brito, 2009; Guo et al., 2018).
- Processing.

  RA with high water absorption capacity is likely to be produced by inadequate sorting or disposal methods for contaminants due to the porous contaminant’s presence (C.-S. Poon & Chan, 2007; C.-S. Poon, Kou, Wan, & Etxeberria, 2009). If the number of process stages increases, the water absorption capacity of coarse RA tends to be lower due to the amount of decreasing attached mortar (de Juan & Gutiérrez, 2009; M. Etxeberria, Vázquez, et al., 2007; T. C. Hansen, 1992) et al. The water absorption capacity of RA can be reduced by washing, using admixtures, microwave heating, etc. (Ismail & Ramli, 2014; Katkhuda & Shatarat, 2016; Wegen & Haverkort, 1998).
- Strength of the parent materials.

  The compressive strength of the concrete where the RCA is coming from is not a factor that determines the water absorption capacity of the aggregates when the material is exposed to a high number of processing stages (Gokce, Nagataki, Saeki, & Hisada, 2011). When RCA is obtained from a higher strength concrete with the same mortar bonded to it, the aggregates will have lower water absorption capacity than if they were obtained from a lower strength concrete. For bricks that are stronger and less porous, this will probably result in a less porous aggregate and, logically, lower water absorption capacity (Khalaf & DeVenny, 2005).

- Fragments from crushed masonry.
  RA's water absorption capacity is directly linked with the constituent's porosity. Coarse RAs will absorb less water than their fine fraction counterparts (Khalaf & DeVenny, 2004a).
- RMA has the highest water absorption capacity, followed by MRA and the lowest values can be found at RCA. RMA is usually derived from relatively uniform materials and its properties will therefore usually be similar to the original material when broken into different sizes.

$WA_{24h}$ is the water absorption coefficient defined after a given soaking duration of 24 hours. By increasing the mortar content, this coefficient will increase (Omary et al., 2016; Younis & Pilakoutas, 2013; C. J. Zega, Villagran-Zaccardi, & Di Maio, 2010). This is due to the increased open porosity of the aggregates. Between the relative density and the water absorption coefficient determined after 24 hours is a linear relationship. However, experimental results showed that the 24 hours soaking duration is insufficient to determine the water absorption coefficient. A disadvantage of a higher $WA_{24h}$ coefficient is that the aggregates can then be less resistant to frost (Omary et al., 2016).

### 4.1.3 Resistance to fragmentation

The resistance to fragmentation can be determined by the Los Angeles test (N.F.E.N, 2011; Omary et al., 2016). The LA coefficient will increase as the density decreases due to the rising of the porosity (Perdikou & Nicholaides, 2014; Younis & Pilakoutas, 2013) et al. In other words, gravels with a porosity on the low side, will be characterized with a higher resistance to fragmentation. Below are factors that influence the resistance of fragmentation:

- Amount of old adhered cement paste to the aggregates.
  The properties of the ITZ will affect the strength of the concrete. The mortar attached to the original is RCA's weakest section. The resistance to fragmentation of RCA is lower as the amount of adhered mortar is higher (Abdulla, 2015; Butler, West, & Tighe, 2011; Dhir Obe et al., 2019) et al.

- Processing.

  If there is an increase in the amount of processing stages, the quantity of attached old mortar will reduce, as well as the other low-strength and lightweight pollutants. This increases the resistance to fragmentation of the RCA (Maeda, Shigeishi, Namihira, Ohtsu, & Akiyama, 2008; Nagataki et al., 2004; Narahara et al., 2007). It must be taken into account that some destruction techniques are intrusive and can cause micro-cracks in the RCA. Those micro-cracks will reduce the resistance to fragmentation of the RCAs (CCANZ, 2011). A solution to this might be to treat the RCA by accelerated carbonation and thus improve its resistance to fragmentation (J Zhang et al., 2015).

- Strength of the parent material.

  As the original concrete's strength increases, so will the RCA's resistance to fragmentation do too (M. Etxeberria, Marí, & Vázquez, 2007; Nagataki et al., 2004) et al. There is a good correlation between the original ceramic brick unit's compressive strength and the aggregate impact values of RMA (Khalaf, 2006; Khalaf & DeVenny, 2004a, 2005).

- Fragments from crushed masonry.

  The composition of RA is highly affecting the resistance to fragmentation. The resistance of MRA is expected to be somewhere between that of RCA and RMA and if the amount of RMA rises, the fragmentation value will decrease (Bazaz et al., 2006; Dhir & Paine, 2007) et al.

### 4.1.4 Quality of RA

Several factors drive the quality of RA, such as the original concrete's quality, presence of impurities and the treatment of RA (Noguchi et al., 2015; Verian et al., 2018). By evaluating the main properties and characteristics of RA, the quality of RA could quantitatively be measured (Dhir Obe et al., 2019). The RA's quality and the bond between the paste and the aggregate are very important in the determination of the fracture behavior of concrete (A. Brand, Amirkhanian, & Roesler, 2014; Verian et al., 2018). The properties of the RAs can be controlled during the processing phase. If there is a decrease in the material's porosity, the mechanical performance of the concrete will improve. This is mostly associated with RCAs coming from concrete with high strength or RMAs coming from ceramic brick units with high strength (Dhir Obe et al., 2019; Khalaf, 2006; Khalaf & DeVenny, 2004a, 2004b, 2005; S.-C. Kou, Zhan, & Poon, 2014). When crushing bricks with an improved mechanical performance, it will yield aggregates with lower water absorption capacity, increased oven-dry density and higher resistance to fragmentation.

In addition to the aforementioned characteristics, special attention should also be given to particle size distribution and organic content. The evaluation of these combined properties may provide an indirect indication of the aggregate's porosity and thus strength of the parent material, which has a substantial influence on the mechanical performance of concrete. With a decreasing quality of RA, there will be a decrease in RAC's relative compressive strength (De Brito & Silva, 2016). Recycled aggregate concrete (RAC) is more likely to be produced with a higher compressive strength than the corresponding concrete with NA when the quality of the RA is better. This rise depends on RA's moisture content, mix design and the superplasticizer's content. RA's strength related to that of the new cementitious matrix is in turn related to the quality of RA. For lower values of the W/C ratio, the RAC's compressive strength is more dependent on the aggregate's strength, which, on the other hand, is dependent on the original material's strength (Le et al., 2017). RACs produced with lower W/C ratios, but with RCAs whose parent concrete has relatively lower strength, will cause a malfunction in the relatively weaker attached old mortar. The breakage of a defective conventional concrete specimen is likely to occur at the ITZ between the NA and the mortar. But in the RA, it will likely develop through the RA, most likely at the level of the old IT. Since it may contain several micro-cracks, thus making it weaker than the adjacent new mortar (Peng, Chu, & Pu, 2016).

### 4.1.5 Adhered mortar

The attached old mortar on RCAs will directly influence the performance of the RAC (Sasanipour & Aslani, 2020a). The RAC mixes made with RCAs differs from the conventional concrete that is cast with NAs, in that the cement mortar on RCA sticks to the former. The RA's inferior properties compared to those of NA may be due to the fact that old mortar sticks to the surface of RA (Kazmi et al., 2020; S.-C. Kou, Poon, & Etxeberria, 2011). The RCA's have lower stiffness in comparison to NA, caused by the presence of attached cement paste that is porous and weak by nature (Dhir Obe et al., 2019). The attached and loose mortars add to the angularity, the rough surface structure and the fine RCA particle's high absorption (L. Evangelista, Guedes, de Brito, Ferro, & Pereira, 2015; Verian et al., 2018). The following is an analysis of the effects of adding fine RAs from CDW on the performance of mortar in its fresh and hardened condition:

- <u>Fresh mortar properties.</u>

Consistence is one of the most important properties that is very widely evaluated to consider in its fresh state. It allows for a practical judgement on the degree and duration of workability and the amount of water needed to obtain sufficient plasticity. An example of why studying the consistency of mortars with fine RAs is so important is their high water absorption capacity (Dhir Obe et al., 2019; R. V. Silva et al., 2014). This results in the absorption of the free mixing water of the mortar and will reduce its consistence and so the workability. Furthermore, the presence of fine RA particles will decrease the yield stress and plastic viscosity, which will cause an anti-thixotropic effect of the mortars (V Corinaldesi, Monosi, & Moriconi, 2007; Valeria Corinaldesi & Moriconi, 2009). A decrease in fresh density is observed when the quantity of fine RAs increases. This is mainly due to the lower density of fine RAs compared to that of fine NAs.

Conflicting results were published about the amount of air. (Cuenca-Moyano, Martín-Morales, Valverde-Palacios, Valverde-Espinosa, & Zamorano, 2014) stated that the amount of air increased with the amount of fine RCA. On the other hand, (A. C. J. Evangelista, Tam, & Santos, 2017; Guadalupe Cabrera-Covarrubias, Manuel Gomez-Soberon, Luis Almaral-Sanchez, Corral-Higuera, & Consolacion Gomez-Soberon, 2017) stated that the amount of air in mortar is most likely to remain untouched when fine RA particles are used as a substitute for fine NAs. To explain what water retentivity affects, it is important to know what it exactly is. It is the mortar’s ability to retain its mixing water. It is an indirect measure of the capacity of mortar to keep its workability for a longer time. The mortar must indicate a high value of this water retentivity since it allows good hydration of the cement.

- Hardened mortar properties.

  In contrast to most other building materials, mortars are usually designed to have a lower compressive strength and a lower modulus of elasticity than the surrounding masonry. This is because overstrength mortars could cause the units to loosen and crack (Dhir Obe et al., 2019; Veiga, 1997). The compressive strength is mostly the main criteria for selecting a mortar type because it is easy to measure and related to other properties. The hardened properties and the consistence of RA-mortars are influenced by the initial water content. But the fine RA’s high absorption capacity can decrease the consistence of the mortar (R. V. Silva, de Brito, & Dhir, 2015b). This could be compensated with extra water to achieve the targeted consistence. But if this isn’t done, the compressive strength will either be unaffected or lower than the target mortar (Cuenca-Moyano et

> al., 2014; A. C. J. Evangelista et al., 2017; M B Leite, Lima, & Santos, 2009) et al. For the incorporation of fine RA with lower rates of water compensation (50 – 70%) the mortar is going to have higher compressive strength due to the effective W/C ratio that is reduced, which leads to a denser cement matrix. If higher water compensation rates (80% - 100%) are being set, the compressive strength of the mortars with fine RA will be similar or slightly lower (Le et al., 2017). Using RA as a partial replacement for sand, decreases the water demand of the mortar, which leads to a decrease in the content of effective water to maintain a constant consistence. An indirect assessment of the durability is the water absorption capacity of a cementitious product. If mortar has a low permeability to water and a high permeability to water vapor, then this mortar would have a good durability. Although the permeability features here mentioned are directly proportional.

To remove the attached mortar, different methods could be used, e.g., heat grinding mechanical grinding and soaking of RA in acid and water. The last method is able to improve the durability of RAC by decreasing the water absorption and porosity of RA (Kazmi et al., 2020; Nagataki et al., 2004; Pedro et al., 2015).

### 4.1.6 Conclusion

Due to the insufficient recycling procedures of the CDW recycling plants, a wide range of RAs are produced that sometimes even have an unknown composition. This is especially the case for recycled sand which will accumulate porous impurities (i.e., old attached mortar). Because of this, the physical properties of the RA often show great variation and are inconsistency, which makes them considered low quality and are therefore used less.

With all the coarse aggregate’s properties, the water absorption and the concrete’s carbonation show a strong relation (Kazmi et al., 2020). The RCA’s water absorption and porosity are higher than the ones of NA, but the RCA has a lower density. The RCA’s fragmentation resistance is greatly lower than the same resistance of NA (Omary et al., 2016).

## 4.2 The properties that decide/influence the durability of the concrete

The durability and mechanical properties of the concrete are highly dependent on the aggregate’s properties, e.g., the specific gravity, absorption, amount of contaminant, etc. (Saini & Singh, 2020; Verian, 2012; Verian, 2015; Verian et al., 2018). Due to its inferior durability performance, the use of RAC is more limited than natural aggregate concrete (NAC) (Guo et al., 2018; Kazmi et al., 2020). This weaker durability of RAC is, among other things, due to the attached mortar on the RA (Guo et al., 2018). This indicates that the amount of attached mortar and the quality of the original concrete have a great effect on the properties of the resulted concrete. Concrete that contains RCA has a lower modulus of elasticity, compared to NAC and that decrease is in proportion to the increase of RCA in the mix (M. Etxeberria, Vázquez, et al., 2007; Verian, 2012; Verian et al., 2018). The durability and mechanical performance of the concrete can also be predicted by the porosity of the coarse aggregates (Kazmi et al., 2020). The porosity of the concrete is greatly influenced by the ratio of substitution. When the percentage of it increases, the concrete's porosity will do so too, leading to a reduction in the concrete's density (Chakradhara Rao, Bhattacharyya, & Barai, 2011b; Omary et al., 2016; Wardeh, Ghorbel, & Gomart, 2015) et al. The raise of the RAC's porosity can be ascribed to the heightened paste volume. The porosity of the concrete is, in addition to the ratio of substitution, also influenced by the volume of the paste and the porosity of the granular mix. The raise in these three aspects ensures that the concrete becomes more porous. The greatest strength properties of RAC are achieved when the RCA was in the partially-saturated moisture state, before the mixing with the TSMA method (see section 4.3.7) (A. S. Brand et al., 2015; Verian et al., 2018).

### 4.2.1 Size of RA

The size and shape of the recycled aggregates are influenced by the number of processing stages and the type of used crusher in these processes (Dhir Obe et al., 2019). The natural gravel's wear resistance depends on the size fraction of these gravels (Omary et al., 2016). All aggregates can be divided into fine and coarse particles. When using both fine and coarse factions of RA, the degree of the loss in strength will be greater. The negative impacts on the concrete often limits or prevents the use of fine RA (Verian et al., 2018; Zaharieva, Buyle-Bodin, Skoczylas, & Wirquin, 2003). The fine RCAs contain many contaminants which reduce the strength of the concrete (Smith, 2018). The high porosity is characteristic of the fine aggregates when compared the coarse aggregates This is caused by the higher quantity of adhered mortar in the fine RAs (Omary et al., 2016; R. V. Silva et al., 2014). The fractions of the fine recycled aggregates with the smaller size (125 – 500 µm) contain a high amount of mortar, while the larger ones (1 – 4mm), in the ITZ between the paste and the aggregates, contains a large number of cracks (L. Evangelista et al., 2015; Verian et al., 2018). Mortars that contain 25% to 100% fine RAs, tend to exhibit higher drying shrinkage due to the greater porosity, which makes it possible for water to rapidly evaporate (Fan, Huang, Hwang, & Chao, 2015). The properties of the fine RAs were in many cases responsible for the problems in workability, the strength reduction of the concrete and the raise in the volumetric instability (i.e., shrinkage, creep and coefficient of thermal expansion) (Obla, Kim, & Lobo, 2007). For fine RCA to have no great effect on the mechanical properties, the lab-made fine recycled particles can be used up to 30% replacement (L. Evangelista & de Brito, 2007).

### 4.2.2 Compressive strength

The compressive strength shows a good correlation with other mechanical properties and durability. This makes it a good quality indicator for the concrete in general (Dhir Obe et al., 2019). Compressive strength is often used to evaluate the general performance of the concrete. It is mostly the main criteria to select a mortar type. The measurement is relatively easy and is relatable to other properties.  The compressive strength of concrete reacts strongly to the mix design and depends on the choice of aggregates, since the compressive strength on its turn heavily depends on the physical and mechanical properties of the used RCA's (Omary et al., 2016). The development rate of the strength of concrete with RCA is higher than that of concrete with NA (Verian et al., 2018). Generally, the overall performance of the concrete will decrease with a larger amount of RA (Dhir Obe et al., 2019). And as (Piaw, 2006) stated, there is thus a very strong correlation between the loss of compressive strength and the increasing amount of RA. This strength decrease of the RAC at a larger amount of RA is more pronounced for mixes with a lower W/C factor (Dhir et al., 1999; A. Rao, Jha, & Misra, 2007) et al. For a given W/C ratio, RA with lower quality will cause greater strength losses.

For concrete mixes with higher W/C ratio, the compressive strength depends more on the new cement paste's strength than the RA's strength. According to (Verian et al., 2018), when there is a high level of water-cementitious material ratio (W/Cm), the cement paste's quality will be closer to that of the old mortar than pastes made with low W/C (Dhir Obe et al., 2019). But by lowering the W/C ratio, the compressive strength of concrete containing RA and NA will be improved (Verian et al., 2018). The quality of the cement paste affects the strength of the concrete: if the mortar is less porous and denser, it will be stronger. Due to the higher water content, the new cement paste will be relatively weak, which makes the porosity increase and yields a poorer bond strength in the ITZ (Dhir Obe et al., 2019). The lower compressive strength in the concrete with recycled aggregates is caused by the existence of two types of ITZ in the matrix (Verian et al., 2018). SCC's strength decreases under a static loading as the recycled aggregates are introduced in the mix. The main cause of this decrease in the flexure and static compressive strength are the RCA's inferior properties that result in the creation of a weak ITZ. This can be compensated by using a blend of silica fume (SF) and metakaolin (MK), because this can improve the refinement of the pore size and microstructure of the concrete (Saini & Singh, 2020). The effects of SF and MK will be discussed later. A reduction in compressive strength is more likely since there is greater number of weaker layers (Sasanipour & Aslani, 2020a). During casting, there are two negative effects that form weak layers valid for both recycled and natural aggregates:

1. The dispersion of anhydrous materials becomes looser in the vicinity of aggregates, resulting in a higher W/C factor and more porosities;
2. An increase in water under aggregate particles is caused by microbleeds during concrete compaction (Ollivier, Maso, & Bourdette, 1995).

(Dhir Obe et al., 2019) stated that the reduction of compressive strength mainly depends on the quality, size and type of the RA's. Only for gradually higher replacement levels the compressive strength would decrease. However, this is not valid for all RAs. The compressive strength also changes when the RAs have extremely changing properties that depend on the main composing material's type and strength, the subjected processes and the moisture state. (Verian et al., 2018) also stated that the attached mortar on the surface of the RCAs contributes to a reducing compressive strength since they have a lower density. If the mechanical performance of the aggregates is considerably lower than that of the old mortar, the compressive strength of the concrete will lessen since there will be a rupture mechanism between the weaker sections of the material (Dhir Obe et al., 2019). There can be an increase in the rate of the development in the strength if the residue of non-hydrated old cement adhering to the surface of the RCAs reacts with water (Verian et al., 2018).

A loss of performance may be less noticeable when working with finer RA derived from ceramic stones or other aluminosilicate materials. They will develop pozzolanic reactions that will mitigate the loss of strength or even produce an increase in strength (Dhir Obe et al., 2019). If the RAs have a higher porosity, the moisture state should definitely be taken into consideration as it affects the development of strength and consistency. Depending on that moisture condition, the compressive strength can have a loss of up to 30% or an increase of up to 20% when the entire 100% of aggregates are replaced with RACs (Verian et al., 2018). The compressive strength of the concrete is also influenced by the resistance to fragmentation, as

Los Angeles coefficient which is related to the relative density and the $WA_{24h}$ (Omary et al., 2016).

Not only do the aggregates play a major role in influencing compressive strength, the other elements in the mix are insignificant as well. The greater amount of water added to obtain a desired workability is also a driver for lowering the compressive strength (Verian et al., 2018). When the water content decreases and the amount of cement content increases, a constant compressive strength will be obtained. For low or medium concrete mixes, the compressive strength will strongly depend on the strength of the mortar phase (Dhir Obe et al., 2019).

The variation of the compressive strength suggests that it is not feasible to explain the compressive strength variation based on the replacement level alone. This scatter depends primarily on the RA's quality and moisture state. The intermediate replacement levels' strength variation can be interpreted without regard to the dispersion normally associated with concrete testing (Dhir Obe et al., 2019).

Concrete with an improved compressive strength can be produced if there is a combination of using saturated RCA and two stage mixing approach (TSMA), see section 4.3.7. There is also a possibility to add extra cement in the mixture to improve the strength of the concrete. By replacing NA with RA at 25% to 50% weight base levels there will be an improvement of the compressive and tensile strength if adjustments are applied in the mixture proportion (Verian et al., 2018).

#### 4.2.2.1 Fraction size of RA

Size of the RAs is one of the factors that influence the compressive strength. When producing with larger RAs, therefore having a lower amount of attached mortar, the loss in strength will come from processing the material (Dhir Obe et al., 2019; Gesoglu, Guneyisi, Oz, Taha, & Yasemin, 2015; Vinay Kumar, Ananthan, & Balaji, 2017). If NA is replaced by coarse RCA up to 30% or by fine RCA up to 20%, there will be little effect on the mechanical performance of the resulting concrete (Dhir & Paine, 2004). The strength producing RAC with a higher compressive strength, is more possible with coarse RA, while lower strengths are usually the result of the use of fine aggregates. Contradictorily, there were some studies that claimed that in adding concrete, the use of fine aggregates provided equal or even better strength over natural sand due to its more uneven and porous surface. This led to a higher surface area and it improves the interlocking bond between the paste and the aggregate (Verian et al., 2018). When using fine recycled masonry aggregates in the mortar, there could be a similar or even better compressive strength observed when comparing it to mortar with NAs. This enhancement comes about through the reaction between the fine RMA’s alumina ($Al_2O_3$) / silica ($SiO_2$) content and the cement paste’s calcium hydroxide that occurs over time.

#### 4.2.2.2 Different types of RA

The lowest strength loss is found in concrete mixes made with RCA, followed by mixes with MRA and then RMA (Dhir Obe et al., 2019). This degree of strength loss can be greater if both fine and coarse fractions of RCA are used (Gesoglu et al., 2015; Vinay Kumar et al., 2017). If there is an increase in the number of ceramic particles or other masonry wall demolition fragments, the RAC will likely show a lower compressive strength (Anastasiou, Georgiadis Filikas, & Stefanidou, 2014). However, a considerable decline of the mechanical performance will not always result from the use of RMA. A decrease in the compressive strength is a likely cause of the use of fine fractions of RMA, but the overall strength reduction will not be that noticeable as that from concrete with coarse fractions of RMA. This is due to the RMA’s pozzolanicity (Debieb & Kenai, 2008; Khatib, 2005; T. Vieira, Alves, de Brito, Correia, & Silva, 2016) et al. If sand is replaced with fine RMA, it may even lead to an increased strength development over time (Khatib, 2005; T. Vieira et al., 2016; Wild, Khatib, Sabir, & Addis, 1996).

### 4.2.3 Tensile and flexural strength

In the mechanics of brittle fracture in concrete, the load applied to the specimen causes the largest crack to be oriented perpendicular to this load, which is the initiation of the failure of the specimen. The size and the shape of the specimen will affect the strength since a larger specimen has a higher probability of containing a larger number of critical cracks (Dhir Obe et al., 2019; A.M. Neville & Brooks, 2010). If concrete is made with RCA, the splitting tensile strength will be up to 6% lower in comparison to that of concrete with NA. Other studies mention that there is a reduction of up to 10% of the tensile strength when coarse recycled aggregates replaced only coarse NA in the concrete (Amnon Katz, 2003; Verian et al., 2018).

Before the coming statements can be made, it is important to know what flexural strength is. It is an indirect assessment of the strength of the material of the carrier adhesion and the crack sensitivity (Dhir Obe et al., 2019). (Amnon Katz, 2003; Verian et al., 2018) stated that the flexural strength of RAC is up to 10% lower than concrete made with NAs, especially when the aggregates that are used are saturated. Due to the stress gradient that can delay the cracking progress, the shape of the aggregate has a greater impact on the flexural strength compared to the compressive or splitting tensile strength of a same specimen. A logical consequence of this is that higher flexural strength will be obtained with angular aggregates than with round aggregates, especially when working with mixes with low W/C ratios. But on the other hand, the latter aggregates need a lower amount of water than the former so the flexural strength of the two can still be equal (Dhir Obe et al., 2019; A.M. Neville & Brooks, 2010). The concrete that contains more angular-shaped aggregates may also explain its higher flexural strength by the improved ITZ between the aggregates and the cement matrix. If aggregates have a glassy surface, then this is not the case, this leads to a poor bond at the ITZ which is the cause of lower tensile strength (Dhir Obe et al., 2019; P, Chisholm, J, & Harrison, 2008). Most of the recycled aggregates to have a rougher surface compared to the natural ones. This causes the cementitious matrix have contact with the greater surface area of the aggregates and the C-S-H's (calcium silicate hydrate) formation into the old mortar's pores due to the ITZ's improved bond strength (Dhir Obe et al., 2019; T. Li, Xiao, & Zhu, 2016). Research unfortunately shows that the fracture will almost never go through the new ITZ, but always through the old ITZ or the recycled aggregates. However these usually have a lower tensile strength compared to the concrete with natural aggregates (Dhir Obe et al., 2019; Xiao, Li, Shen, & Poon, 2015). So far, it can be concluded that the failure mechanism of the concrete with recycled aggregates is a complex phenomenon that depends on a number of factors related to the aggregates such as size, quality, porosity, content and moisture state. The tensile strength is negatively impacted by the concrete's open porosity (O. Cakir, 2014; Gómez-Soberón, 2002; Omary et al., 2016) that is related to the porosity of the granular mixture. The splitting tensile strength will be reduced when an aggregate is used in the mix with an increasing L.A. coefficient.

Some studies analyzed the tensile strength while increasing the number of recycled aggregates.

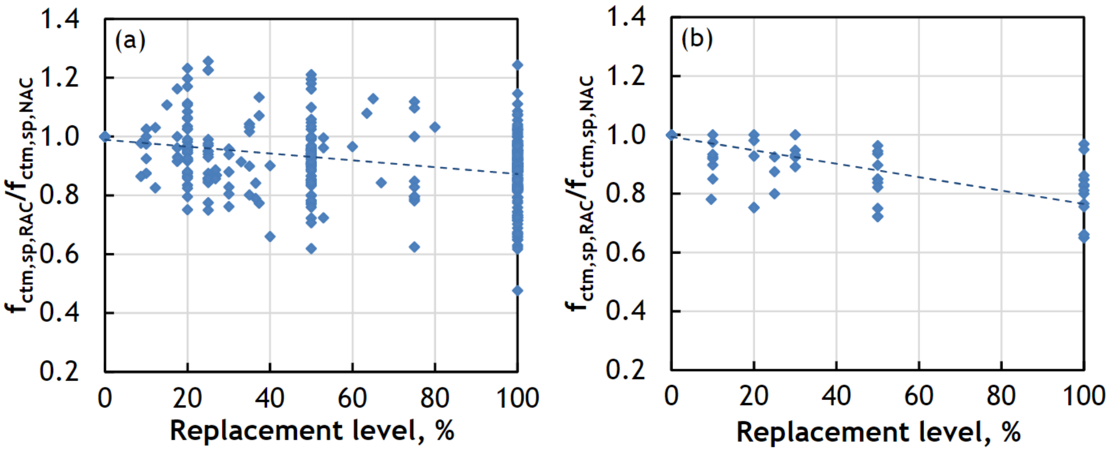

*Figure 5: The RAC's splitting tensile strength with increasing content of (a) coarse RA (b) fine RA (Ajdukiewicz & Kliszczewicz, 2002, 2007; Akbarnezhad, Ong, Zhang, Tam, & Foo, 2011) et al.*

Regardless of the relatively large spread of values, it can be theorized that an equal or even slightly higher splitting tensile strength could be noted when making concrete with coarse recycled aggregates compared to typical concrete (Dhir Obe et al., 2019). This was possibly due to the larger surface area which provided better bond strength at the ITZ. Regardless, usually the insertion of coarse and fine aggregates (figure 5 (a) and (b)) results in a lower splitting tensile strength. The values of the study were divided into type and quality class of the aggregates and from this it was found that the splitting tensile strength underwent greater loss with an increasing amount of MRA as compared to concrete made with RCA (see figure 6 (c) and (d)).

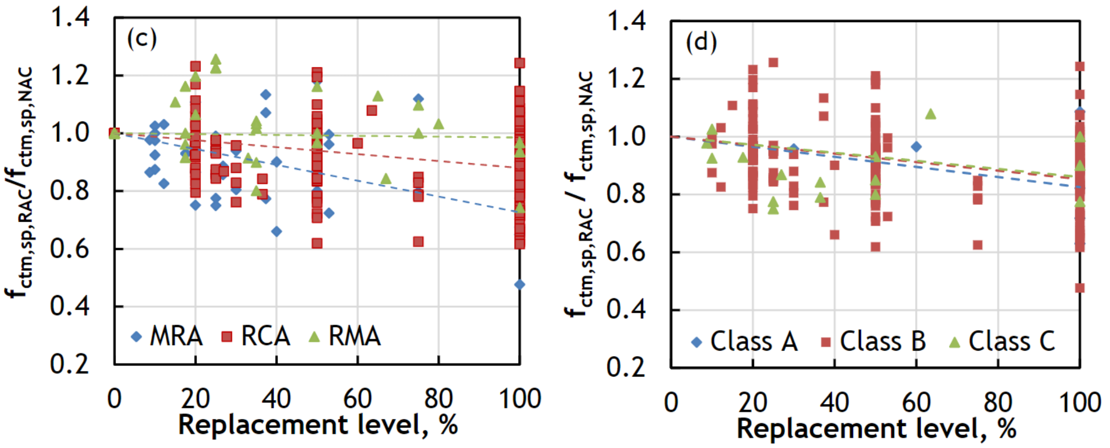

*Figure 6: The RAC's splitting tensile strength with increasing content of (c) different types of RA (d) different quality classes of RA (Ajdukiewicz & Kliszczewicz, 2002, 2007; Akbarnezhad et al., 2011) et al.*

There is a greater possibility that failure through the critical cracks will happen faster at lower loads since the MRAs have greater porosity and are generally weaker than the RMAs (Correia, de Brito, & Pereira, 2006; Dhir & Paine, 2007; Mas, Cladera, Olmo, & Pitarch, 2012). These values also showed that with an increased amount of RA and a decreasing quality of these aggregates, the splitting tensile strength will lower (R. V. Silva et al., 2014). This conclusion is further confirmed by another study by (Yang, Chung, & Ashour, 2008) in which RAs were used with similar oven-dried density and values for water absorption capacity leading to similar loss of tensile strength.

In the way that the compressive strength develops, the splitting tensile strength will also develop in a similar way (Dhir Obe et al., 2019). Although there is a possibility that there may be a smaller probability of the presence of critical locations where failure may occur due to the enhanced bond strength (e.g., the ITZ between the mortar and natural aggregates). (C. S. Poon & Kou, 2010) did a long-term study on the mechanical performance of concrete made with recycled aggregates and increasing content of coarse RCA and fly ash (FA). With an increase in content of RCA, this study revealed a decrease in splitting tensile strength after 28 days. However, after one year of casting, the splitting tensile strength was equal or even higher than that of the usual concrete. This result is possibly due to the superficial pores that were filled with the new cement paste, due to the higher surface area of the coarse aggregates. This thus enhanced the bond strength at the ITZ.

The potential decrease in splitting tensile strength because of the incorporating RCAs, can be compensated by adding more cement. An improvement of the splitting tensile strength was brought about by the TSMA-method (see section 4.3.7) and the use of saturated aggregates (A. S. Brand et al., 2015; Verian et al., 2018). As mentioned in the section of compressive strength, the effect of mineral admixtures in the concrete with RAs is expected to be equal to the effect in concrete with NAs regardless of the number of coarse RAs that were inserted (Berndt, 2009; Dhir Obe et al., 2019; Rohi M. Salem & Jackson, 2003). In a study of (Berndt, 2009; S.-c. Kou, Poon, & Agrela, 2011) where different types of mineral additions were used as replacement of part of the cement, the results suggested that the RCA's higher quantity was not a hindrance to the increase or decrease in splitting tensile strength. Also, the combination of the supplementary cementitious materials (SCM) with the RAs did not influence the strength development. A reduction in strength was however caused by the addition of FA in the concrete, except for concrete mixes that inserted 25% FA. The blend of SF and MK can compensate for the weaker ITZ due to the inferior properties of RCA, which is the main cause of reduction in the compressive and flexural strength. It can enhance the pore size refinement and microstructure by forming hydration products that are relatively dense (C. S. Poon & Kou, 2010). If the RCAs replace the natural ones with 25 % to 50% weight base, the compressive and splitting tensile strengths can then be improved when there are adjustments made in the mixture proportion (M. Etxeberria, Vázquez, et al., 2007; Verian et al., 2018). Further methods and substances that lead to the improvement/deterioration of these strengths can be found in other sections.

Eurocode 2 (Dhir Obe et al., 2019; EN-1992-1-1, 2008) says that the splitting tensile strength from the characteristic compressive strength should be estimated. The relationship between the characteristic compressive strength and the splitting tensile strength of concrete is the same as suggested in Eurocode 2. It is independent of the quality, size of type of the recycled aggregates (R. V. Silva, de Brito, & Dhir, 2015c). Between the measured/predicted value of the flexural strength of the concrete made with recycled aggregates and the concrete made with natural aggregates, no statistical differences were observed by the method proposed in Eurocode 2 (Tosic, Marinkovic, & Ignjatovic, 2016). In practical terms, this means that certain existing provisions can be used without any change. To better understand the impact of various factors related to the RA's use on the splitting tensile strength, the data was broken down by content, type, quality class and size of the recycled aggregates. This resulted in the observation that there are no statistically major differences between the compressive and tensile strength. They are influenced by the same RA-related factors, so it is possible that the addition of RA could lead to a reduction in the performance of both properties. But it also showed that the original natural aggregates have an impact on the relationship between the properties of the concrete made with recycled aggregates. At a given compressive strength, specimens made with RCA which originally involved rolled pebble particles, may exhibit a flexural strength higher than expected (Zhou & Chen, 2017).

### 4.2.4 Flexural fatigue strength

Even when the normally vibrated concrete (NVC) testing is done under controlled conditions, the fatigue life of the concrete will show wide distribution (Saini & Singh, 2020). NVC is a concrete in which a piston is inserted and vibrated during the liquid phase to reduce the amount of air bubbles in the concrete. Due to its fewer defects and enhanced microstructure, SCC presents a greater fatigue performance due to its improper compaction, as in NVC (S Goel, Singh, & Kaushik, 2012; Sanjay Goel, Singh, & Singh, 2012). If the use of recycled aggregates in the SCC rises, it will result in a decrease of the fatigue strength of the SCC. A solution to this could be to use SCMs such as silica fume and metakaolin. The use of SCC is not surprising as it has wide applicability and benefits. It appears that NVC made with natural aggregates is not superior to the fatigue behavior of SCC.

In terms of endurance limit, the SCC made with NA shows superior fatigue performance compared to NVC. The amount of RCA appears to decrease the values of the shape parameter at each stress level, which is evident from the values of the distribution parameters. The SCC mix with 50% replacement level of the NAs with RCA's shows lower values of the shape parameter in comparison with the mix where the replacement level is 0%. The SCC with 50% replacement level's fatigue life's variation in the dispersion of fatigue life is hereby indicated. The SCC with recycled aggregates having lower values for the shape parameter indicate greater variability, while an improvement in the distribution parameter was indicated for mixed SCC mixtures at certain stress levels.

Significant improvement has been found for blended SCC mixes in comparison to control mixes. The main cause of all this is mainly the poorer properties of RCA, which in turn is the cause of the attached old mortar around the aggregates. There are micro defects in the concrete due to the cracks in the mortar and the weaker ITZ between the recycled aggregates and the new mortar. To compensate for the decrease in fatigue performance in the SCC that contains recycled aggregates, SF and MK can be used. The positive effect of using the two is that it provides a denser formation of hydration products which improves the ITZ around the aggregates. The homogeneity of the SCC will be restored through the use of SF and MK. This is done by enhancing the pore size refinement and microstructure to achieve a similar performance to an SCC mix with a 0% replacement level. Positive effects in terms of reducing the variation of fatigue life distribution of SCC were induced by both SF and MK (Saini & Singh, 2020).

### 4.2.5 Water/cement ratio

There will be a strong mortar with lower porosity that does not allow penetration of the chloride ions at low W/C ratios (Sasanipour & Aslani, 2020a). The compressive strength of a sample of RAC is likely to be more dependent on the aggregates' strength, which in turn depends on the parent concrete's strength, when there is a relatively low W/C ratio (Dhir Obe et al., 2019; Le et al., 2017). (Sasanipour & Aslani, 2020a) states that a higher W/C ratio is capable of affecting on electrical resistivity because it has made it easier to make a larger number of porosities in the concrete and the bond between the aggregate and cement past become weaker. The total charge passed (TCP) rises too if the W/C ratio increases due to the fact that the porous structure of the mortar increases with an increase of the W/C ratio (ASTM, 2016). For the W/C ratio to have a value of 0.3, all mixes will behave the same and the TCP-tolerance will not exceed up to 15%. One of the consequences of a higher W/C factor is also that it will cause a higher slump. To obtain the best approach for making RAC, it is best to keep an equivalent W/C ratio and compensate the absorbed water. The disadvantage is that concrete types made in this way will show a reduction in the mechanical behavior (Dhir Obe et al., 2019).

### 4.2.6 Impermeability

The impermeability is mainly determined by the content of recycled aggregates, the W/C factor, the waste concrete's original strength, the curing age and the presence/absence of mineral additives (Guo et al., 2018). A disadvantage is that the impermeability of concrete with RA is weaker than that with NA (Guo et al., 2018; Verian et al., 2018). This was confirmed by (Guo et al., 2018), who reported a decrease in the RAC's impermeability as the replacement ratio of the RA increased, regardless of the RA's quality. Also (Torben C. Hansen, 1986; Verian et al., 2018) stated that concrete with NA had a permeability that is two to five times lower than that of concrete with RCA for mixtures with a W/Cm of 0.5 to 0.7. But on the other hand, RA has a higher porosity, so it can store some water and during the development of the microstructure, provide an internal curing, which improves the impermeability of the concrete (Guo et al., 2018; Jiake Zhang, Caijun Shi, et al., 2015). When the replacement level of the recycled aggregates increases, the penetration depth of the concrete with RA is lower under pressure. (Martínez-Lage, Martínez-Abella, Vázquez-Herrero, & Pérez-Ordóñez, 2012) stated this and explained that this is due to the RAs that are not fully saturated with water and therefore can still absorb more water. For a given W/C ratio and an increased replacement level of RAs, greater oxygen permeability of concrete with RA could be observed (Thomas, Setién, Polanco, Alaejos, & Sánchez de Juan, 2013). But with a constant ratio of RA, the water absorption, penetration depth and oxygen permeability of RAC augmented with the increase of the W/C factor. The production process can impact the RA's physical properties greatly, as well as the concrete's performance (e.g., permeability).

The particle size also impacts the impermeability of the RAC. A smaller surface area is created with a larger size of coarse aggregates, with additional adhering mortar reducing the amount of water required and thus improving the concrete's strength (Guo et al., 2018). On the other hand, they do cause the disadvantage that the number of defects in the RA particles themselves are increasing. The coarse aggregates do not influence the RAC's impermeability as much as fine

RAs doe. This is because of a greater number of capillary channels in the concrete system (Bravo et al., 2015a; Fan, Huang, Hwang, & Chao, 2016; Martínez-Lage et al., 2012). As (Verian et al., 2018) stated, the permeability is dictated as the continuity and the size of the hydrated cement paste's pores. If the W/C ratio is kept relatively small, the permeability of the RAC with fine aggregates is comparable as that of the concrete with NA (Guo et al., 2018; Levy & Helene, 2004; Thomas et al., 2013) et al.

With the increase of the RA's size, the gas permeability of the concrete with RA augmented. This had two reasons. First of all, with the rise of the coarse RA's size, the flow path's tortuosity drops. The second reason is that with the increasing size of the aggregates, there is a decrease in the possibility of bleeding. With a rise of fine/coarse aggregate ratio, the air permeability and the effective W/C factor of the RAC decrease. The RAC's density increases with the increasing curing age, while its water and gas permeability, and the capillary water absorption decreases (Basheer, Basheer, & Long, 2005; Guo et al., 2018).

To enhance the RAC's permeability, mineral admixtures could be used to fill in the pores and so produce a pozzolanic effect. If the mineral admixtures are added in an alkaline environment, the pozzolanic reaction could promote the generation of a secondary C-S-H gel and refine the pore structures (Guo et al., 2018; X. Zhang & Wu, 2002). The incorporation of a bigger number of RA could happen with the mineral admixture's use. Out of all of this could be concluded that an addition of an assured content of mineral admixtures can enhance the interface structure and thus the performances of concrete made with RAs. A study by (Faella, Lima, Martinelli, Pepe, & Realfonzo, 2016; Kurda et al., 2017a; Somna, Jaturapitakkul, & Amde, 2012) showed that concrete with RA exhibited after 28 days, a lower water permeability in comparison with a control concrete sample when cement was replaced by a certain amount of FA. This was also confirmed by (Bhikshma & Divya, 2012; Verian et al., 2018), who used 30% of FA as a replacement for ordinary Portland cement (OPC). What also enhances the RAC's impermeability greatly, is using ultra-fine materials like SF and MK. Due to the fine mineral admixtures who play on the hydration of cement an effect of microcrystalline nucleation, an acceleration takes place of the cement's hydration and a growth of the hydration products. The treatment of the RAs is also a way to affect the RAC's impermeability. There was a decrease of 38% of the water absorption of concrete with microbial carbonate treated RA in comparison to concrete with no treated RAs. Even a slight improvement in the impermeability was noticed in comparison to concrete with NA (Guo et al., 2018; J. Wang et al., 2017). This was due to the $CaCO_3$ that covered the surface of RAs and/or filled its inner pores. A last improvement can be done by silane. It can penetrate into a RA's porous structure and cause a reduction in the water ingression (Zhu, Kou, Poon, Dai, & Li, 2013).

### 4.2.7 Freeze – thaw resistance

To evaluate the durability of concrete, freezing and thawing are frequently used as an index (Guo et al., 2018; Omary et al., 2016). These tests are done to assess the resistance of the material once it is exposed to similar conditions. In this way, the influence on the hardened properties can also be determined by an acceleration of the aging process of the material (Dhir Obe et al., 2019). Studies showed that the durability of recycled aggregates is lower than that of natural aggregates under freeze-thaw cycles in water (Omary et al., 2016). Due to the crushing stage, the old cement paste will contain micro-cracks which will reduce the RCA's resistance to subsequently freezing-thawing. The freeze-thaw cycles have more impact on the recycled aggregates, in comparison to the natural ones because the natural granulates are protected against frost by the old adhered cement paste . (Omary et al., 2016) confirmed, that if there is a strong cohesion between the natural aggregates and the old paste for concrete with recycled aggregates, then the natural aggregates will be protected by the old paste against the degradations caused by frost. Therefore, after the freezing-thawing cycles, there will be a higher wear resistance. Looking at the granular distributing after freeze-thaw cycles, those of natural granulates will remain about the same, while those of the recycled granulates will change. The recycled aggregates are more severely damaged by the freeze-thaw cycles, resulting in a greater production of fine particles in the breakdown of the old cement paste around the RCA that is detached from the NA by the frost. By incorporating fine RA that was pre-soaked, the resistance to freeze-thaw of RAC was not detrimental (Bogas, Brito, & Ramos, 2016; Guo et al., 2018). The W/C factor had more impact on the resistance to freeze-thaw of the concrete than the used type of aggregates. If the degree of water saturation is less than 91.7%, a study by (Zaharieva, Buyle-Bodin, & Wirquin, 2004) stated that the concrete will probably not be subjected to damage from freezing and thawing. With the increase of the number of freezing-thawing cycles, both the relative dynamic modulus and the cubic compressive strength of the concrete with RCA decreased linearly. Under the same freezing-thawing cycles, the cubic compressive strength was lower for RAC in comparison with that of NAC (Wu, Jing, & Wang, 2017). This can be seen in the graph of figure 7. Due to the higher porosity of RAC, it has a lower freezing-thawing resistance compared with current concrete with NA. The RAC will therefore show a higher absorption and decreased mechanical performance (Rohi M. Salem & Jackson, 2003; Verian, 2012; Verian et al., 2018). As the number of freezing-thawing cycles rises, the RAC's, similar to NAC, compressive, splitting tensile and flexural strength will decrease (Guo et al., 2018; Haitao & Shizhu, 2015; Šeps, Fládr, & Broukalová, 2016).

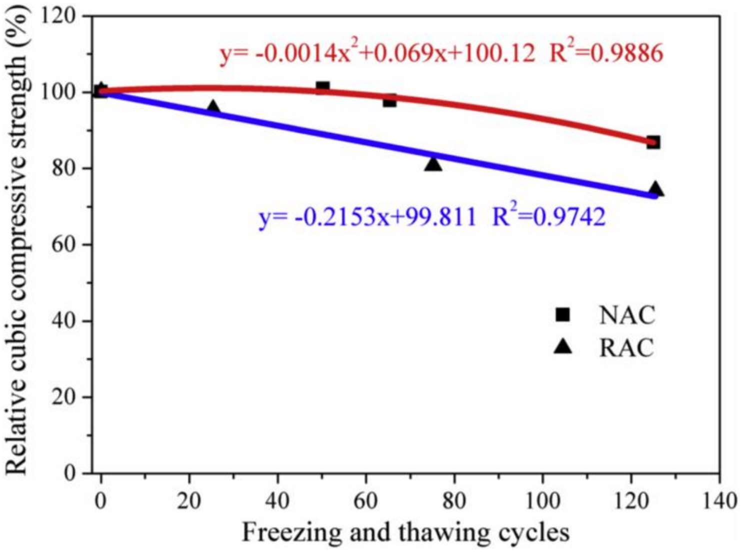

*Figure 7: Comparison of RAC's and NAC's cubic compressive strength in relation to the number of freeze-thaw cycles (Wu et al., 2017)*

When samples are subjected to freeze-thaw cycles, there will be an increase in the weight loss of the concrete and a decrease in the relative dynamic elastic modulus. The loss of relative strength of RAC was similar to that of NAC in a study on resistance of freezing-thawing, regardless if there were air-entraining admixtures used (Dhir Obe et al., 2019). It was found by (Gokce, Nagataki, Saeki, & Hisada, 2004; Verian et al., 2018) that, when subjected to 500 freeze-thaw cycles, there was a better resistance to freezing-thawing for RAC with coarse aggregates that were derived from air-entrained concretes than concrete with coarse RCA from concrete that was not air-entrained. In a study where 25 freeze-thaw cycles were executed, the increase of the RAC's mass with the increase of the number of cycles was rapidly. But the increase slowed down or even ceased to increase after 75 to 100 cycles (Guo et al., 2018). There were two factors that caused this:

- The loss of mass and crumbling of mortar are the result of the internal pressure and internal cracks when the concrete is frozen and all this leads to the further extension of the cracks
- The concrete's mass increases because the water can penetrate into the concrete due to the concrete's enclosed pores that are connected to the freezing action of the water

The two forementioned factors will interact with each other where the total water content that is absorbed will determine the final mass and the spalling of the concrete will determine the mass loss.

(Verian, 2012; Verian et al., 2018; Verian, Whiting, Jitendra, Olek, & Snyder, 2013) used the freezing-thawing cycles in their soundness test on aggregate in a brine solution. This was done to determine the disintegration resistance of the aggregates by repeatedly applying rapid freeze-thaw cycles in the presence of a sodium chloride solution. From this test, it resulted that recycled aggregates experienced a noticeably higher deterioration in comparison to the natural ones due to a higher mass loss caused by the freeze-thaw cycles in the brine solution. In tests to analyse the resistance of frost, it could be observed that the recycled concrete aggregate's resistance to freezing-thawing is less in comparison to that of natural aggregates. But the degradation and porosity of the RCA's, estimated through water absorption, was not greatly (Omary et al., 2016).

### 4.2.8 Frost resistance

The frost resistance of concrete is primarily affected by the water content in the concrete, its porosity, the type of aggregate that is used and the environmental conditions (Guo et al., 2018). To find out the frost resistance of the concrete, it can be subjected to a freeze-thaw cycle that measures the dynamic elastic modulus, the rate at which the concrete loses weight and the rate at which it loses strength. During this freeze-thaw cycle, the absorbed water can penetrate into the cement paste, causing the insertion of RAs to reduce the frost resistance of RAC. If concrete is made with recycled aggregates, their incorporation percentage, source and chemical composition have an important impact on their frost resistance (Omary et al., 2016). With an increase in the fineness and the replacement level of fine RA, the RAC's dynamic elastic modulus will decrease significantly. When the fine RA's minimum size is less than 0,16 mm and the replacement level of it is minimum 40%, there is also a decrease in the RAC's resistance to frost (Guo et al., 2018; J. Y. Sun & Geng, 2012). This is because as the freeze-thaw cycle increases, the cracks inside the concrete continue to increase and water can penetrate into it. Also, the water absorption capacity, which is higher with RAs, and its degree of saturation ensures that RAC has a lower resistance to frost (Zaharieva et al., 2004). This resistance decreases with the W/C factor increase, due to the porosity, average aperture and the RAC's number of capillary pores (Bogas et al., 2016; Cui, Ohaga, Kitatsuji, & Tanaka, 2007; Yildirim, Meyer, & Herfellner, 2015). The RAC's change of weight increases if the replacement level of coarse RA increases and the water absorption capacity is linearly correlated with it (Tuyan, Mardani-Aghabaglou, & Ramyar, 2014). Regardless of the content of fine RA, the losses in mass for high-strength RAC were observed to be a lot lower in comparison to those with normal strength. If concrete is made with RA that comes from non-air -entrained concrete, the resistance to frost was found to be relatively weak, even when there was an incorporation in the concrete of an air-entraining agent (Gokce et al., 2004). This is due to the smaller average aperture and the coefficient of pore spacing of the RA's attached mortars. For these reasons, RAC is usually not used in harsh environment as it has weak resistance to frost.

But (Rohi M. Salem & Jackson, 2003) stated that concrete with RCA, that has W/C factor value of maximum 0.5 and an incorporation of air content of 5% can be used in moderate cold and unsaturated environments. If concrete is prepared with RAs that originates from high-performance concrete, a similar or even better resistance to frost can be observed compared to that of NAC (Ajdukiewicz & Kliszczewicz, 2002). On the other hand, if the RA comes from concrete that was high-strength of air-entrained, the resistance to frost of the RAC will be excellent and will perform equally to that of ordinary air-entrained concrete (K. Liu, Yan, Hu, Sun, & Zou, 2016; Rohi M. Salem & Jackson, 2003). Improving the frost resistance of RAC can be brought about by a decrease in the content of mixing water or decreasing the water saturation. If pre-saturated RA is used, the water that normally is contained in the pores of the RA will be released for a further hydration of the cement (Bogas et al., 2016; Yildirim et al., 2015). This means that, due to this internal curing effect, the resistance to frost of RAC will be enhanced (A. J. Chen, Wang, & Ma, 2015; Seara-Paz, González-Fonteboa, Martínez-Abella, & González-Taboada, 2016; Yildirim et al., 2015). An improvement can also be brought about by using additions to the concrete mix. If FA or MK is incorporated, the mineral admixtures will from C-S-H due to the reaction with $Ca(OH)_2$, which in turn will make the microstructure of the concrete denser and enhance the strength of the concrete (W. H. Luo, Wei, & Luo, 2006; Salem & Burdette, 1998; J. Y. Sun & Geng, 2012). Another option is the addition of a good number of rubber particles, which will provide space in the concrete for the expansion of the volume of frozen water. When the ice melts, the particles will produce an elastic recovery, which in turn will limit the concentration stress, tiny crack's extension and the production of propagation (A. J. Chen et al., 2015).

### 4.2.9 Resistance to high temperature

The exposure of concrete to high temperatures causes a deterioration of the mechanical properties of that concrete. This is due to the changes of the different components which are significant. This mainly indicates the physiochemical changes in the aggregates and mortar, but also the thermal incompatibility (Dhir Obe et al., 2019; J. P. B. Vieira, Correia, & de Brito, 2011). The lower thermal conductivity and the lower thermal expansion coefficient of the RMAs means that concrete containing a higher amount of coarse RMA has a slightly greater resistance to fire damage (Hachemi & Ounis, 2015; Khalaf & DeVenny, 2004a; Martins, Correia, & de Brito, 2016). Within the cementitious microstructure this could lead to lower thermal stresses and, logically, less cracks. Due to the mixing process, the inherently increased moisture content can cause serious explosive splashes if the concrete is heated to above 600°C (T. C. Hansen, 1992; Martins et al., 2016). In concrete with coarse RMA, the damage of the induction of high temperature was likely to be less important. This was due to the lower values of the RMA's coefficient of thermal conductivity and the thermal expansion, which lead to minor thermal stresses within the cementitious microstructure and the decrease of cracks.

In structural applications the use of concrete with RAs may provide enhanced resistance to high temperatures. (H. Dong, Cao, Bian, & Zhang, 2014) stated that the RAC's resistance to high temperatures was better than the resistance of concrete with NA's if they had the same cross section and equivalent class in compressive strength. This was due to the lower rate of temperature penetration and a delay in crack occurrence of the RACs who had a lower density in comparison to NAC. Also (Y. Liu, Ji, Zhang, Wang, & Chen, 2016; Y. Liu, Wang, Chen, & Ji, 2016) stated that an increase of recycled aggregates had a slight influence on the failure mechanism after exposure to high temperature. For temperatures up to 400°C the absolute modulus of elasticity of concrete with RA tended to decrease less rapidly as concrete with NA, although they had a comparable decrease in compressive strength (C J Zega & Maio, 2006). For concrete subjected to high temperature, the incorporation of RCAs did not affect its residual mechanical behavior.

EC2 states that the tensile strength should be ignored for concrete exposed to high temperatures. However, a method adopted in the EC2 can be used whenever needed. The results indicate that concrete with RAs, regardless of the replacement level of RA, can comply with the method mentioned in EC2 for the estimation of the tensile strength for concrete at high temperatures (Dhir Obe et al., 2019).

#### 4.2.10 Resistance to impact loading

The concrete’s resistance to impact loading is proportional to the stiffness and resistance of its components (Dhir Obe et al., 2019; L. Li, Xiao, & Poon, 2016; Nazarimofrad, Shaikh, & Nili, 2017). With the replacement level, the resulted acceleration in RAC samples increased for a given impact energy. The behavior of beams of RAC with different coarse granulate replacement levels (0%, 25%, 50% and 100%) was determined by (Chakradhara Rao, Bhattacharyya, & Barai, 2011a) using the impact of a drop hammer. The vibration of the specimen was influenced by the stiffness of the material. In other words, there was a decrease of the acceleration as the modulus of elasticity increased. For concrete made with a higher replacement level of coarse RCA, the maximum displacement increased due to the weight impact. So far, it can be concluded that there can be a lower resistance to impact loading when the amount of coarse recycled aggregates increases. Another study was done by (Xiao et al., 2015), who examined the RAC’s compressive behavior under quasi-static loading with a high strain rate. The first conclusion was that with a rise in strain rate, the compressive strength and initial modulus of elasticity increased. However, the compressive strength declined when the amount of coarse RCA was increased. Also, under quasi-static loads, the propagation of the cracks in concrete with RCA was different from when it was subjected to impact loading. A third study by (Ismail & Ramli, 2014) investigated the low-velocity impact loading of concrete with treated RCA and untreated RCA. Based on the energy absorbed by the samples, the impact resistance was evaluated. These tests showed that there was effectively a reduction in the resistance to impact loading but they were improved when the aggregates were treated. By visually inspecting the samples, it was concluded that the cracks in the conventional concrete had a more devious pattern compared to the RAC-samples. The RAC-samples showed rather a linear pattern. It is possible that crack propagation was held back by the relatively higher stress capacity of the natural aggregates. (Nazarimofrad et al., 2017) confirms a decrease in impact resistance by using RAC. With an increasing amount of coarse recycled aggregates, the number of weight strokes to the formation of an initial fracture decreased. However, this increased when the amount of attached mortar was increased. What can be concluded from this section is that an increase in the number of aggregates recycled causes a reduction in the resistance to impact. This is not surprising as the resistance and stiffness of the existing parts has a proportional influence on the resistance to impact loading of the investigated concrete. An improvement of this overall performance of concrete subject to impact can be achieved by the insertion of some mineral additives.

### 4.2.11 Carbonation resistance

Carbonation, together with the penetration of chloride ions, is a disadvantage as it is responsible for the corrosion of the reinforcement in the reinforced concrete (Guo et al., 2018). What exactly happens, is that a series of chemical reactions takes place in the concrete under the $CO_2$'s presence, which then enhances the decrease in the pH grade in the concrete. The permeability and the concrete's moisture content affect the carbonation's rate. As the replacement ratio of RAs increases, the depth of carbonation of the RAC increases with it. (R. V. Silva, Neves, de Brito, & Dhir, 2015) examined the influence of the amount of RA on the depth in RAC caused by the relative carbonation. Figure 8 suggests that a replacement level of 100% of coarse RA causes a carbonation depth of RAC that is about 2.5 times higher than with concrete with NA, with a probability of 95% (a). This is about 8.7 times higher with a replacement level of 100% fine RA due to the fine RA's higher capacity of water absorption (b).

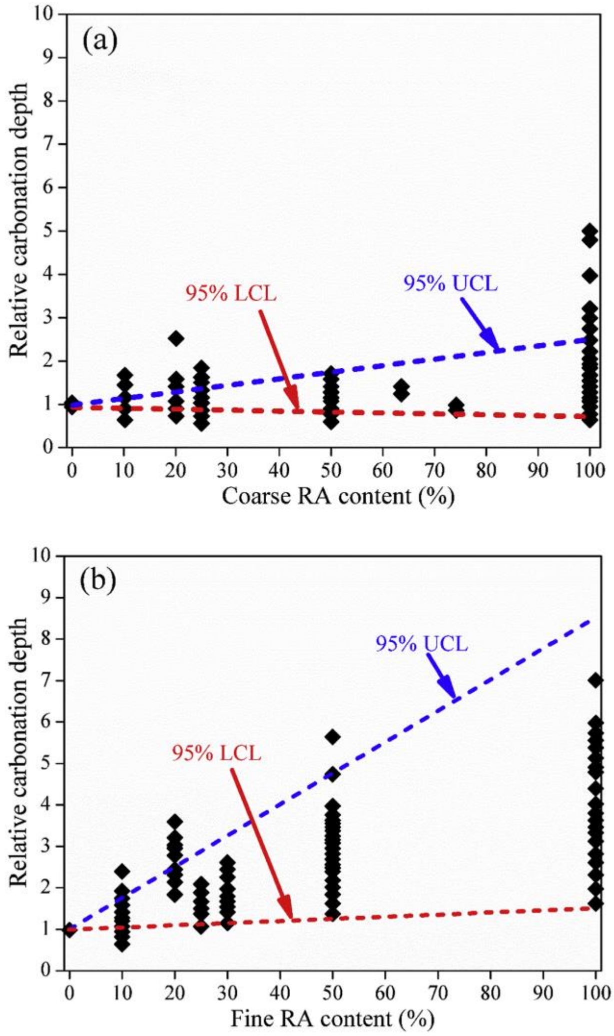

*Figure 8: Replacement level of RA in relation to the relative carbonation depth (R. V. Silva, Neves, et al., 2015)*

One of the important factors for RAC's carbonation is still water, as (Geng & Sun, 2013) mentioned. If the replacement rate of fine RCA exceeds 40%, a sensible W/C ratio should be considered. The cause for this is that an increase in water leads to a rise in the concrete's porosity and thus $CO_2$ can enter the concrete more easily. An increase in carbonation with an increase in the W/C ratio is possible due to the similar effect of the W/C ratio on the carbonation of concrete with RA as it is with concrete with NA (Lei & Xiao, 2008). Unfortunately, the higher porosity of the RAs in the concrete caused a slight acceleration in the carbonation rate compared to NAC (Otsuki, Miyazato, & Yodsudjai, 2003). As FA is often used to improve concrete properties, this had a negative effect on the SCC's resistance to carbonation. (H. Sun, Wang, & Sun, 2006) found that with the increasing FA content, the carbonation depths increased for SCCs with RA. This was confirmed by (S.-C. Kou & Poon, 2013), who stated that an increase of the carbonation depth was noticed if cement was replaced with FA in concrete with RA. What also has an effect on the resistance to carbonation is the application of the TSMA method under a relatively high W/C ratio. This is probably because the mortar that adheres to the RA has a lower water-binder ratio and the lesser amount of water near the aggregate. This can limit the crystal growth causing an amplification of the ITZ (Otsuki et al., 2003).

A study by (Lei & Xiao, 2008) showed a decrease in carbonation depth when the replacement ratio of RA, with 40% content of adhered mortar, was at least 70%. This could be possible due to the greater amount of cement and the reduced rate of carbonation caused by the high amount of attached mortar. The coarse RA's increasing replacement ratio can also make the RAC achieve an equal strength and carbonation depth as concrete made with NA if the RAC has a lower W/C ratio (R. V. Silva, Neves, et al., 2015). The carbonation depth can also be decreased by adding components to the mixture. With an incorporation of slag, the microstructure becomes denser, as well as reducing the number of pores result in a remarkable reduction (Lei & Xiao, 2008). Metakaolin has high fineness particles which can compensate for the loss in the resistance of carbonation and thus against the ingress of $CO_2$ by improving the microstructure (i.e., reduce the number of pores and make it denser) (Singh & Singh, 2016). The presence of superplasticizer (SP) can greatly reduce the depth of carbonation at early ages (Matias, Brito, Rosa, & Pedro, 2014). The improvement of the resistance to carbonation by SP's is due to the hindering of mixed crystal's growth and the denser crystals on the cement particle's surface. Another enhancement to the resistance of carbonation is the addition of a coat oil-type or silane repellent on the RA’s surface (Tsujino, Noguchi, Tamura, Kanematsu, & Maruyama, 2007; Zhu et al., 2013).

### 4.2.12 Chloride penetration resistance

One of the factors that primarily affects the concrete structure’s durability and is considered to be one of the most serious degradation mechanisms, is the corrosion of the reinforcement that is induced by chloride (Guo et al., 2018; Kazmi et al., 2020; Martín-Pérez, Zibara, Hooton, & Thomas, 2000; Otsuki et al., 2003). The problem is that RAC with rebars will be more prone to corrosion and other deteriorations that are chloride-related if there is a higher content for chloride (Verian et al., 2018). The RAC’s resistance to chloride penetration will decrease if the W/C factor increases (Guo et al., 2018). The resistance to chloride penetration will also decrease for concrete that is made with RCA if the permeability of it increases (Verian et al., 2018). And if a compressive load is used, the diffusion coefficient of chloride of the RAC will decrease first, whereafter it increases with the compressive load that increases (Guo et al., 2018).

For the resistance to chloride penetration, a decrease is found for RAC compared to NAC. The increase in the porosity of concrete containing porous RA can be related to this (Guo et al., 2018; Kazmi et al., 2020; T. Vieira et al., 2016). (S.-c. Kou, Poon, & Agrela, 2011; S. C. Kou & Poon, 2012) from (Verian et al., 2018) found that the resistance to chloride penetration was more than 40% less for RAC with 100% RCA in comparison to concrete with NA. According to (Rahal, 2007), NA has a lower content of chloride than RCA. And (Verian, 2012) confirmed that in a leachate solution the RCA’s content of chloride ions was more than double compared to that of NA. The study by (Guo et al., 2018) where different grades of resistance to chloride penetration were observed for a decreasing content of attached mortar. This means that the content of adhered mortar on recycled aggregates have an enormous impact on the RAC’s chloride penetration resistance. Due to the amount of attached mortar that is higher and the content of clay, the effect of coarse RA on the penetration of chloride is less obvious than that of fine RA (Bravo et al., 2015a; L. Evangelista & de Brito, 2010; Guo et al., 2018).

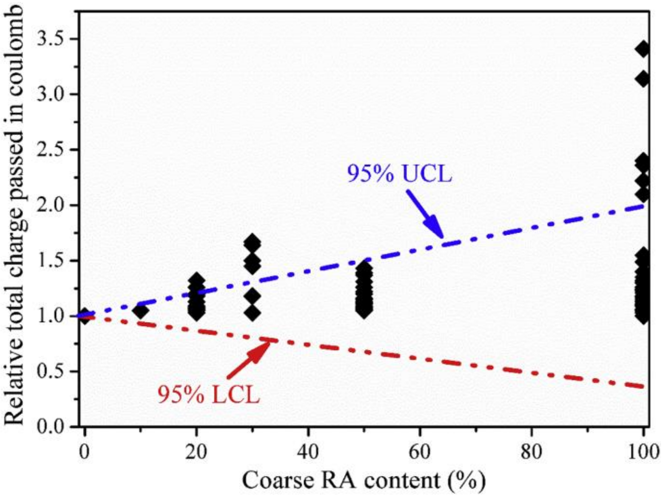

*Figure 9: The total charge passed in relation to the content of coarse RA (Andreu & Miren, 2014; Kapoor et al., 2016; Matias et al., 2014) et al.*

To test the resistance to chloride penetration, the RAC's TPC will be measured, with a testing method called ASTM C 1202, in coulombs (Bravo et al., 2015a; Guo et al., 2018). Figure 9 shows that the TCP increases as the replacement level of the RA increases (Bravo et al., 2015a; Faella et al., 2016; Kapoor et al., 2016), regardless of the RA's quality. The results of the tests by (Bravo et al., 2015a; L. Evangelista & de Brito, 2010) indicated that there is a 95% chance that concrete with 100% coarse RA will have a TPC that is about 2.07 greater than concrete with NA. Due to this higher value of TPC, it can also be deduced that introducing a higher amount of RCA into the concrete will lower the resistivity of this concrete (Verian et al., 2018).

When testing, it should be taken into account that the resistance to chloride enhances with the curing age of the concrete (Bravo et al., 2015a; Guo et al., 2018; Somna et al., 2012). An improved performance in a chloride environment than NAC could be achieved by RAC when it was prepared at a low W/C factor due to the C-S-H gels that assist the binding of the chloride (Vázquez, Barra, Aponte, Jiménez, & Valls, 2014). A lower penetration of chloride in the concrete could be noticed when the RA was derived from a concrete with higher original strength than concrete that contained RA from a lower strength concrete due to the lower water absorption capacity (S.-c. Kou & Poon, 2015). The resistance of chloride penetration can be enhanced with the addition of mineral admixtures. Within the mineral admixtures, the single ones have a less good affect in comparison to the binary or ternary ones. The increased C-S-H amount, caused by the mineral admixtures, can have a bigger absorption of chloride ions. Those admixtures also refine the pore size. The enhancement of the resistance can also be done by a surface treatment of the RAC's outer layer of pretreating the RAs. When this method is used, the surface of the RA or RAC is coated with a slurry of silane or a pozzolanic slurry, which will improve the resistance of the transport of ions and the microstructure (Kong et al., 2010; S.-C. Kou & Poon, 2010; Zhu et al., 2013). The RAC's resistance to penetration can be enhanced by $CO_2$ curing, steam curing, adding superplasticizers and double-mixing the mix or triple mixing (C.-S. Poon, Kou, & Chan, 2006; S.-C. Kou et al., 2014; Matias et al., 2014; Zhan, Poon, & Shi, 2016). Whereas the $CO_2$ treatment a very feasible and effective method is for the RAC in enhancing the resistance of chloride penetration. Besides enhancing the mechanical properties, it will also reduce the water absorption capacity and the porosity of the recycled aggregates.

### 4.2.13 Alkali-silica reaction

The alkali-silica reaction (ASR) is a chemical reaction between the concrete's alkali hydroxides and the unstable silica mineral (Guo et al., 2018). A clear understanding of the ASR's mechanism in RAC has become more difficult since the interface characteristics and microstructure of this concrete is more complex than the regular concrete. The concrete's dimensional stability and durability are affected by the expansion and cracking induced by the reaction. An ASR is expected in new concrete when recycled aggregates are added that have originally reactive aggregates. Comparable expansions as for concrete with original aggregate can be observed if the recycled aggregates come from a concrete already contaminated with ASR, as (Shehata, Christidis, Mikhaiel, Rogers, & Lachemi, 2010) and (Mukhopadhyay, 2013) stated. When the reactive RAs were used to make a new RAC, comparable expansion hazards were used for this reason. When the reactive aggregates were mixed with fine and coarse recycled aggregates in an environment that was highly alkaline, the expansion of the concrete with fine RAs was slightly grander than that with coarse RAs (McCarthy, Csetenyi, Halliday, & Dhir, 2015). The reaction process can be influenced by the changes in the effective W/C ratio that can be brought about by the effect of the water absorption capacity of the aggregates on the ASR, this water absorption must certainly be taken into account. Also, the crushing method affected the expansion of RA, where smaller coarse aggregates result in a bigger expansion. The reduction of the alkalinity of the pore solution can be achieved by the usage of SCMs (Johnson & Shehata, 2016). Another product that can reduce the ASR's caused expansion of concrete with RA effectively, is the introduction of lithium nitrate (Shehata et al., 2010). If the choice is made to add RA that is reactive or possibly reactive, then the ARS must be prevented and this can be done with four methods. Thus, use of low alkali cement is one option, mineral admixtures could also be added, the RA's water absorption capacity could be strictly controlled or the last option is to maintain a low alkali content of concrete.

In comparison to concrete made with NA, the RAC's resistance to all forms of deformation will be potentially lower (Dhir Obe et al., 2019). The structure's overall integrity deflection, and cracking are heavily affected by deformations in the structural design. Due to the hydration, the loading time and the ambient conditions, concrete will experience numerous forms of changes in volume. While the concrete's aggregates deliver an internal restraint, the concrete will encounter a volumetric change while deforming. This means that the deformation's magnitude depends on the aggregate's stiffness in the concrete. The concrete's resistance to load-dependent and load-independent deformations will be lower if the RCA's stiffness in the concrete is lower than that of natural aggregates. If those estimations of the concrete's deformation are inaccurate, unwanted consequences can develop (Dhir Obe et al., 2019). A distinction can be made between the three main deformations:

- The modulus of elasticity is an elastic deformation property that is load dependent
- Creep is a deformation property that depends on load and time
- Shrinkage is the deformation property that is expressed with time and independent of the load.

These deformations are discussed in more detail in the following sections.

### 4.2.14 Elastic deformation

When concrete is subjected to a compressive load, the modulus of elasticity ($E_C$) will describe the concrete's instantaneous deformation, based on the stress-strain relationship and its secant slope (Dhir Obe et al., 2019). Because this property is used in structural members of buildings to estimate its deflection and buckling, it is highly important. When there is a replacement level of 100% of coarse NA with RCA, the $E_C$ can show a reduction of 6% to 40% and an average value of 30% (K. W. Anderson, Uhlmeyer, & Russell, 2009; Dhir Obe et al., 2019; K. Sagoe-Crentsil & Brown, 1998).

For concrete in compression the relationship between stress and strain is not truly linear, but for the low levels of strain and stress, it is considered to be. This relationship is dependent of the concrete's stiffness, constituents and testing methods. Several studies have been done to compare the concrete with coarse NA and that with coarse RCA. The comparison between the two is shown in the following picture and can be divided in three regions:

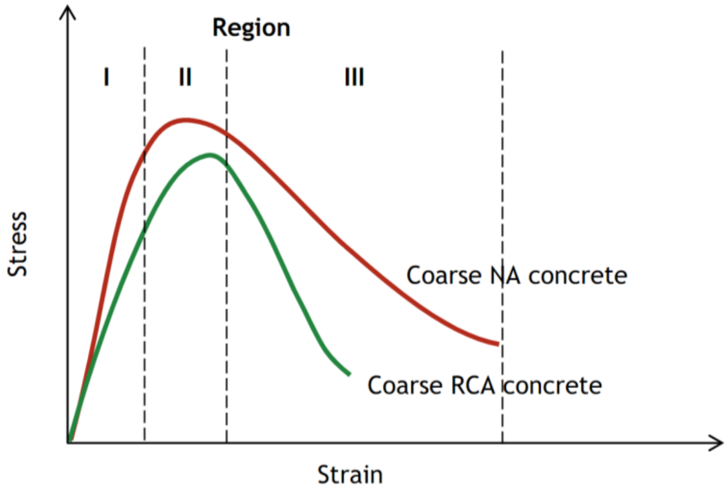

*Figure 10: The stress-strain relationship for concrete with coarse NA (red) and coarse RA (green) (G. M. Chen, He, Yang, Chen, & Guo, 2014; Folino & Xargay, 2014; 陈宝璠 & Chen, 2013)*

- Region 1: the stress-strain relationship is more or less linear for up to 30% of its eventual strength, for the concrete with coarse NA, as for the concrete with coarse RCA. The stress of the NA concrete will be higher at a given strain compared to that of the concrete with RCA.
- Region 2: the relationship between stress and strain is more parabolic. It can be noted that the RAC with coarse RCA has a higher peak strain (= strain corresponding to the peak stress) in comparison to that of concrete with NA.
- Region 3: the curves of both the RAC and NAC will soften after the peak, this means that they will descend after the peak. The rate of this descending is normally faster for the RCA concrete than for the NA concrete. Unfortunately, it can also be deduced from the figure that the ultimate strain of the concrete with coarse RCA is less than that of the concrete with coarse NA. The strain where the crushing failure of the concrete occurs, is called the ultimate strain of the concrete.

Regardless that the test to determine the $E_C$ is simple, to study the coarser RCA's behavior, the variables that are used for doing this, often vary in terms of type of test method, the type of specimen used, the curing conditions and the properties of the aggregates (Dhir Obe et al., 2019; Lye, Dhir, & Ghataora, 2016). Because the attached cement paste on the coarse recycled concrete aggregates is weak and porous, the $E_C$ of the RAC was theoretically higher than that of the corresponding concrete with coarse NA for 4.5% of all the data. If all other properties were kept equal, the $E_C$ could not be increased by the usage of RCA. A study by (Dhir Obe et al., 2019) showed a decreasing rate in the decrease of the $E_C$ of the concrete as the content of coarse RCA increased. If the concrete's compressive strength increases, the drop in the relative value of $E_C$ will decrease at a given content for coarse RCA. As the strength of the concrete increases, the volume of coarse aggregates will decrease. This causes a reduction in the overall effect on the concrete's properties. At a higher strength, a relatively smaller decrease in the concrete's $E_C$ will occur due to the relatively smaller impact on the attached cement paste where coarse RCA is used. High-quality coarse aggregate is required to make concrete with high strength. It is expected that the quality of the coarse RCAs will be better to produce concrete with high strength. As a result, the decrease in the $E_C$ will probably be smaller due to the use of RCA.

To estimate the concrete's $E_C$, the rock types of the used aggregates will be taken in by the Eurocode 2 who has limited them to basalt, quartzite, limestone and sandstone. For concrete that is made with basalt, quartzite, limestone and sandstone, the different $E_C$ values are shown in the figure 11.

The line for concrete with NA where the strength is less than 60 MPa, can be found between sandstone and limestone, but for a strength more than 60 MPa, the line can be found between limestone and quartzite. If at a given strength, the concrete's $E_C$ reduces while the content of coarse RCA increases, the trend lines will move from between limestone-concrete and quartzite-concrete progressively to the area between sandstone-concrete and limestone-concrete.

Another property is the dynamic elastic modulus $E_D$ to measure the concrete's damage evaluation after an exposure to weathering (e.g., freeze-thaw). If coarse NA is replaced with coarse RCA, the concrete's $E_D$ will result in a reduction.

The ratio under axial load of the axial strain to the corresponding transverse strain within the elastic range is called the Poisson ratio. This ratio will marginally increase when the coarse NA is replaced with coarse RCA in concrete in most cases (Ajdukiewicz & Kliszczewicz, 2002, 2007; Dhir Obe et al., 2019; S. Huda & Alam, 2015) et al.

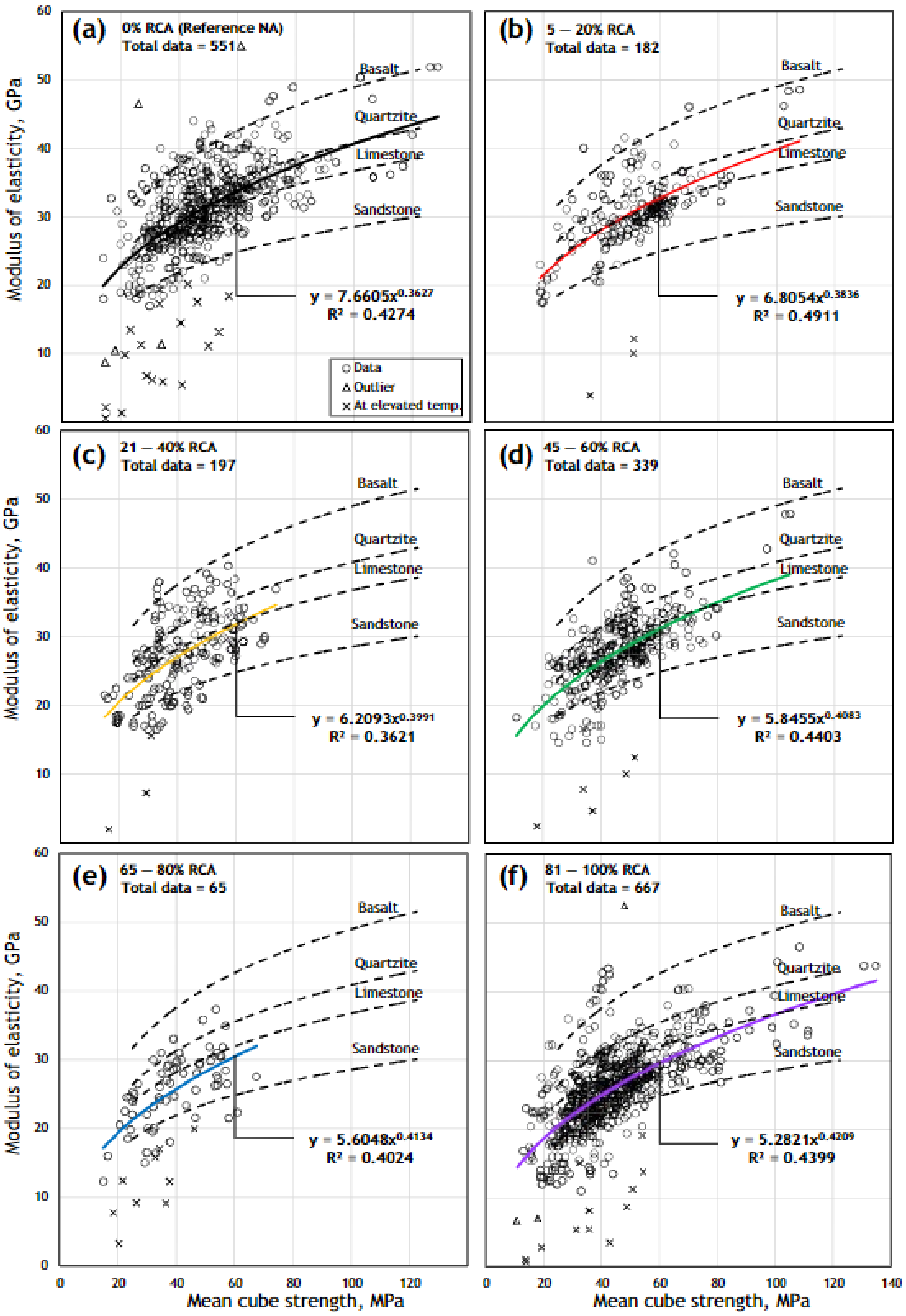

*Figure 11: Ec in relation to the concrete with coarse NA's / coarse RCA's compressive strength (Dhir Obe et al., 2019)*

### 4.2.15 Creep deformation

Due to a sustained load over time, dimensional change will occur and that phenomenon is called creep. The serviceability of structures can be affected by this time- and load-dependent phenomenon, so it is a very important matter to structural engineers. Aggregates that are used in the production can't undergo creep; it will take place in hardened cement paste (Dhir Obe et al., 2019; A M Neville, Dilger, & Brooks, 1983). The deformation by creep in concrete can be affected by some physical properties of the aggregates (e.g., stiffness). (R. V. Silva, de Brito, & Dhir, 2015a) found that an increase in the creep strain of the concrete with values in the orders of 20% to 90% and an increase in the creep coefficient of the concrete in orders of 10% to 65% can be obtained by using an RCA content of 100%, depending on its quality. A study by (Task Force of Standing Committee of Concrete of Spain, 2004) stated that a content of coarse RCA of 20% resulted in no change in the concrete's creep. While the content of 100% resulted in values for concrete's creep that were widely varied. As the content of coarse RCA in the concrete increases, the rate of the concrete's creep increase will decrease. For an increase in the content of coarse RCA, the relative creep will increase and for a given content of coarse RCA, that increase will become smaller as the strength of the concrete increases (Dhir Obe et al., 2019). This could be explained as the concrete's design strength increases, the content per unit volume of the coarse aggregates will decrease due to the content of the cement that increases. If coarse RCA is used, the presence of the attached cement past in the RCA and its impact will proportionately decrease but will in turn slightly increase the concrete's creep deformation. The concrete's creep increase due to the coarse RCA is mainly caused by the concrete's porosity that is caused by the porous property of the attached cement paste on the RCAs. But regardless of the content of coarse RCA that is used, there is a strong relationship between the porosity of the concrete and its creep. Due to the higher volume of paste in RAC in comparison to concrete with natural aggregates, there will be a greater creep for RAC up to 30% to 60% in comparison with current concrete (Committee, 2001; Verian et al., 2018). This is caused by, as stated before, that the paste or mortar amount in concrete is proportional to the concrete's creep. With an increasing rate, the drying creep coefficient of the concrete will increase as there is an increase of the RAC's porosity (Dhir Obe et al., 2019). The concrete's porosity is still a function of the duration of the moist curing. Good cement hydration can take place by sufficient curing time. This has the ultimate positive effect that the concrete's porosity can be reduced due to the denser structure of the cement paste. But as the duration of curing increases, the creep ratio will show a decrease for both RAC and concrete with natural aggregates. At a given time in this curing duration, the RAC's creep ratio will have a lower value than that of concrete with natural aggregates. This suggests that at that time the NA's concrete is less sensitive than that of concrete with RCA.

Out of all this information, following conclusions can be drawn. First, as the content of sand is kept the same in the mix of concrete that contains coarse RCA, the concrete's creep will increase at a rate that decreases as the replacement level of NA increases. Second, the magnitude of this creep increase will decrease due to the increase in the concrete's design strength when coarse RCA is used. The creep of concrete with NA is less sensitive to the duration of moist curing than that of concrete with RCA (Dhir Obe et al., 2019).

### 4.2.16 Shrinkage deformation

Shrinkage is a time-dependent property, just like creep, but in this case, there is no load necessary for the deformation to occur in the concrete (Dhir Obe et al., 2019). Shrinkage comes in four types: plastic, autogenous, drying and carbonation shrinkage. As it is the most common cause of cracks formed in concrete, its structural interest is increasing. The shearing allows gases and liquids to flow into the concrete and reduce the performance of the concrete or even cause corrosion of the steel reinforcement. (Dhir Obe et al., 2019) stated that with a replacement level of 20% of RCA, the concrete's shrinkage was not significantly influenced. But when that level was increased to 100% of coarse RCA, the shrinkage increased by 20% to 50%, other studies have been suggesting lower as higher percentages. An increase of 70% to 100% shrinkage was found for concrete with both fine and coarse RCAs compared to concrete with NAs. Whereas for concrete made with coarse RCA and natural sand the increase was 'only' 20% to 50% (Committee, 2001; Verian et al., 2018).

When concrete has just been made, it is in its fresh state. The concrete is still damp and it can lose water because the water can evaporate from the surface when the concrete is placed but not hardened. This is how plastic shrinkage occurs. If the rate of bleeding, water in the concrete that rises to the surface, is lower than the evaporation's rate, plastic shrinkage cracking can occur (Dhir Obe et al., 2019). If NA in the concrete is replaced with coarse RCA, the plastic shrinkage increases (Bendimerad, Rozière, & Loukili, 2016; Gonzalez-Corominas & Etxeberria, 2016; Souche et al., 2017). And if RCAs are used with a higher absorption property (Gonzalez-Corominas & Etxeberria, 2016) or the concrete is exposed to drying circumstances (Souche et al., 2017), the plastic shrinkage increases even more. Higher plastic shrinkage can also increase if concrete is made with RCA in a condition that is fully saturated and surface-dry in comparison to concrete that was made with RCA in a condition that was partially saturated or oversaturated (Gonzalez-Corominas & Etxeberria, 2016). The cause of this could be the excess of water that in the first situation the partially saturated RCAs did not fully absorbed the water, or in the second situation that the oversaturated RCA released water. But in a study by (Souche et al., 2017), one case showed that the use of oversaturated RCA in concrete had a higher plastic shrinkage than concrete that used partially saturated RCAs. No opinion can be expressed for the comparison of fine and coarse recycled concrete aggregates, since studies have proven contradictory matters (Eckert & Oliveira, 2015; Salgues, Souche, Devillers, & Garcia-Diaz, 2018). The RCA's saturation condition also affects the plastic shrinkage cracking of the concrete. With a rise in the degree of the RCA's saturation, the crack initiation time increases, as the crack width does (Salgues et al., 2018; Souche et al., 2017).

In contrast to the previous type of shrinkage, no moisture exchange takes place with the surrounding environment with autogenous shrinkage. This type takes place during the hydration of cement and is relatively small. High autogenous shrinkage can be found in concrete that has a W/C ratio that is very low (A. M. Neville, 1995). Regardless of the little information available about the autogenous shrinkage, it does say that concrete with coarse RCA (Gonzalez-Corominas & Etxeberria, 2016), fine RCA (H. Kim & Bentz, 2008), and a mix of the two (Maruyama & Sato, 2005) cause a decrease in the concrete's autogenous shrinkage. This is due to the supplementary internal curing water in the RAC, provided by the RCA's higher water absorption capacity. Unfortunately, this cannot be seen in the total shrinkage of the concrete, despite this positive effect. There is less inhibition on drying shrinkage, due to the lower stiffness of RCAs compared to NAs, which plays a greater role in the overall shrinkage of the concrete.

Drying shrinkage is caused by the ceasing of the damp curing of concrete and it consequently being exposed to drying conditions that cause the internal moisture of the cements paste to be lost. It is an important factor because it is inevitable (Dhir Obe et al., 2019). It is influenced by the concrete's W/Cm and content of paste (Verian et al., 2018). Because of its attached and new mortar, RAC contains a higher amount of paste, thus compared to concrete with NA, it has a higher drying shrinkage's magnitude (Beltrán, Barbudo, Agrela, Galvín, & Jiménez, 2014; Khatib, 2005; Verian, 2012) et al. A higher drying shrinkage occurred with the incorporation of fine RCA's because of its higher absorption due to the relatively higher content of old paste in comparison to coarse RCA (Fan et al., 2015). For the fact that follows, the following method was used to test the concrete: the samples were largely moist cured for a maximum of one month, after which the tests were prepared in an environment with a temperature of 20°C to

30°C and a relative humidity (RH) of 40% to 60%. For 2 weeks to 6 months, the RAC with coarse RCA was mainly stored in a dry environment (Dhir Obe et al., 2019). RAC's W/C ratio was kept comparable to that of the reference concrete with NA. These tests showed that the shrinkage of concrete with NA could be more than that of concrete with coarse RCA. However, because the stiffness of the natural aggregates must be higher than the coarse RC aggregates, this could not be accepted. This is due to the presence of the attached cement paste in the RCA's, which is porous and weak. If NA is replaced by coarse RCA in concrete, the shrinkage of the concrete is expected to increase at a decreasing rate if the content of coarse RCA increases. If the replacement level is 100%, on average, the concrete's shrinkage could be up to 30% higher. The eventual concrete's shrinkage can be influenced by the void's development and the moisture's movement, which in turn are affected by the rock type, packing, particle size distribution and the coarse aggregate's grading that is used in the concrete. As already mentioned, the drying process of the concrete is the cause of most of the shrinkage stresses. The exposure condition's relative humidity is what mainly affects the drying process. With relative humidity increasing, for a given coarse RCA content, the magnitude of the shrinkage value will decrease. In estimating the effects of shrinkage under the presence of coarse RCA when exposing the structural concrete to different humidity conditions, the foregoing relationship can be very helpful (Dhir Obe et al., 2019).

The images of figure 12 show the profiles for the concrete with RCA's rate of shrinkage change compared to that of concrete with NA and that for each individual force group. This figure shows that those profiles are quite similar, but for a given amount of RCA, the strength of the concrete will increase, with the result that the relative change will decrease (Dhir Obe et al., 2019).

Due to the lowering of the acidity of the concrete, corrosion can occur in the reinforcing steel, this is due to carbonation. But shrinkage can also be the result of carbonation. The coarse RCA does not necessarily participate in the carbonation process, but its natural porosity can have an effect on the carbonation's rate and the amount of it. But it can also affect the carbonation-induced shrinkage, which is dependent on the RCA's saturation degree and ambient humidity (Dhir Obe et al., 2019).

If coarse NA was replaced with coarse RCA while the use of sand was kept equal, and the content of RCA increases, then the concrete's shrinkage increases at a decreasing rate. As the ambient humidity increases, the shrinkage's relative increase of the concrete will decrease if there is a usage of coarse RCA and the corresponding sand and its content is kept the same. When using coarse RCA, the concrete's design strength will influence the shrinkage's relative increase. Here, the design strength's increase will decrease the magnitude of the shrinkage's increase of the concrete.

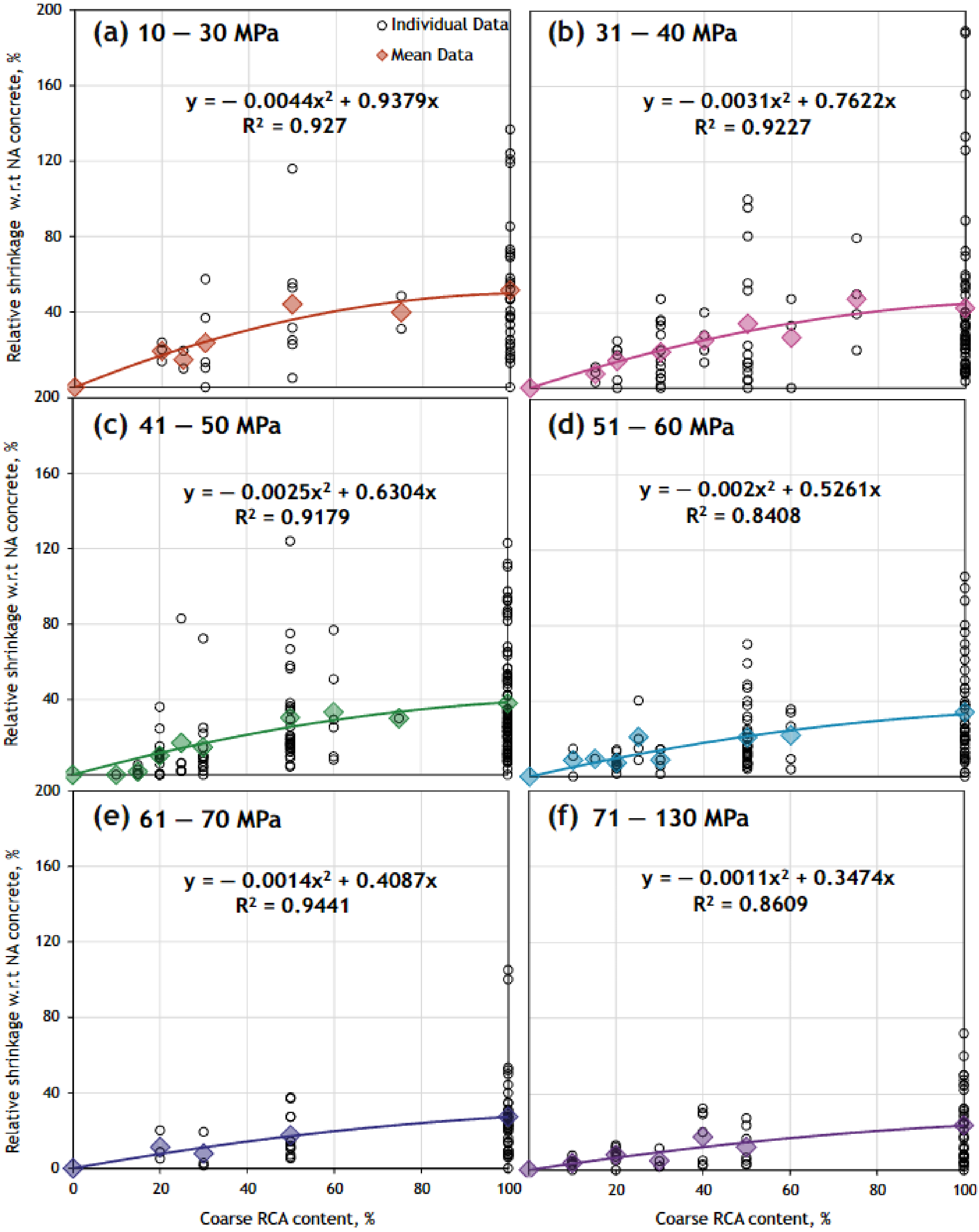

*Figure 12: Shrinkage of coarse RCA WRT the NA for a variation of strength groups (Dhir Obe et al., 2019)*

### 4.2.17 Conclusion

Between the compressive strength of the concrete and the coarse aggregate's water absorption capacity and its porosity, a strong relationship can be observed. Likewise, there is a strong relationship between the splitting tensile strength of the concrete and the coarse aggregate's porosity. Furthermore, between the concrete's flexural strength and the coarse aggregate's crushing value, porosity and attached mortar, a good relation can be noticed (Kazmi et al., 2020). Despite that the aggregates have lower elasticity modulus and strengths (i.e., compressive, splitting tensile and flexural), the concretes that contain RCA have in some way yielded a comparable or even higher fracture energy than those with natural aggregates. Some other studies agreed on this and have shown similar results (Amirkhanian, 2012; S. Kou, 2006; Verian et al., 2018). However, other studies found a decrease in the fracture properties for the addition of RCA in the concrete (Q. Liu et al., 2011; Roesler et al., 2013) et al.

The attached mortar of the RAs will primarily determine the RAC's durability. The higher this content is, the higher the water absorption and porosity will be and this in turn will cause a worse performance of RAC's durability (Guo et al., 2018). (Kazmi et al., 2020) also stated that to predict the concrete's durability performance, the coarse RCA's porosity is an important property. The RAC's durability will also decrease with a higher amount of RA and higher W/C factor. For fine RA will this effect be more obvious in comparison to coarse RA (Guo et al., 2018; Kazmi et al., 2019a, 2020; Munir, Kazmi, Wu, Patnaikuni, Zhou, et al., 2020). The two key reasons for the higher water absorption and porosity of the RA are the old adhered mortar of the RA's surface and the ITZ between the aggregate and this adhered old mortar. All of this can lead to a poor permeability to chloride-ions, a low carbonation resistance, acid resistance and low resistance to sulfate-attack (Kazmi et al., 2020; Sáez del Bosque et al., 2017; J Zhang et al., 2015) et al. It can be stated that all the concrete's mechanical properties have a strong relationship with the durability properties. But this RAC's durability problem can be minimized by adding a mineral admixture. More information on this can be found in the next section (Guo et al., 2018).

## 4.3 Ideas for improvement

This section provides opportunities that can improve and sometimes remove the challenges that the use of recycled aggregates in concrete causes. In this introductory section, some general matters or less relevant but interesting matters are mentioned.

The first matter that should be discussed are the supplementary cementitious materials (SCM). Like the dosage of superplasticizer (SP) and the change of the viscosity modifying agent (VMA), the SCM can change the rheology of SCC (Saini & Singh, 2020). The usage of SCMs can improve the RCA's performance, according to (Verian et al., 2018). Some SCMs can improve the ITZ and the RAC's cement paste (e.g., fly ash), which causes an improvement in the durability behavior (Kazmi et al., 2020; S.-C. Kou & Poon, 2013; S.-C. Kou, Poon, & Etxeberria, 2011; Singh, M, & Arya, 2019). Due to the increase of RCA content, the SCC's durability and mechanical properties decreased. To some extent, this could be controlled by the usage of SCM, filler materials, method of surface treatment or presoaking the RCA (Guneyisi, Gesoglu, Algin, & Yazici, 2014; Khodair & Luqman, 2017; Saini & Singh, 2020; Y. F. Silva, Robayo, Mattey, & Delvasto, 2016) et al.

Other aspects that can help enhance the properties of the concrete are listed below:

- Since fine/coarse have a significant impact on the concrete's characteristics, particles with a more regularly shape can be achieved by using a two-crushing stage (Barbudo, Agrela, Ayuso, Jiménez, & Poon, 2012; Dhir Obe et al., 2019; Ferreira, Brito, & Barra, 2011) et al.
- A strength gain can be obtained by recycled aggregates coming from materials with high-strength and/or the usage of partly dry RAs in combination with greater contents of plasticizers (Dhir Obe et al., 2019).
- Dependent on the debris constituents, the pulverized CDW's usage could have positive results (Asensio, Medina, Frías, & de Rojas, 2016; V. Corinaldesi & Moriconi, 2011; Dhir Obe et al., 2019; Y.-J. Kim, 2017). To replace part of the cement with waste concrete powder, without any treatment could decrease the concrete's mechanical performance. In this way, pozzolanic reactions could be achieved by the hydrated state of the cement particles and the reactive constituents that are missing (Dhir Obe et al., 2019; J. Kim, Nam, Behring, & Muhit, 2014).
- An increase in strength development rate of the concrete over time can be done by the usage of fine RMA (Dhir Obe et al., 2019; Khatib, 2005; T. Vieira et al., 2016; Wild et al., 1996).
- The production process can also have a significant influence. The durability performance of the RAC can be enhanced by a two-stage and triple-step RAC mixing. On the surface of the RA will be a formation of the cement paste layer (Kazmi et al.,

2020; V. W.-Y. Tam, Gao, & Tam, 2006; V. W. Y. Tam & Tam, 2008; V. W. Y. Tam, Tam, & Wang, 2007).

- Another improvement method for the durability performance is the usage of bacterial bio-deposition of calcite on the RA's surface. It decreases the RA's water absorption by filling in the pores of the adhered mortar (Grabiec, Klama, Zawal, & Krupa, 2012; Kazmi et al., 2020).
- The presence of SP can reduce the carbonation depth significantly at early ages. The resulting depths could even be lower than for concrete with NA. The SP can also hinder the mixed crystal's growth, it makes them denser on the cement particle's surface, whereby the resistance to carbonation improves (Guo et al., 2018; Matias et al., 2014).

In the following subdivisions are the matters that can have a major impact on various properties and/or that may help the lab test.

### 4.3.1 Mineral additions

Mineral additions could be used as an addition to the cement or as a partial replacement of it (Dhir Obe et al., 2019). It is expected when using mineral additions, that it will affect the RAC in a similar way as it will affect NAC, independently from the amount of coarse recycled aggregates that are inserted (Berndt, 2009; S C Kou, Poon, & Chan, 2007; Rohi M. Salem & Jackson, 2003). The use of these mineral additions is mainly to enhance the resistance in durability-related properties, the workability or consistence and sometimes to cause a higher strength. For an improvement of the RAC, one can enhance the RA's properties and/or add mineral admixtures (Guo et al., 2018; C. Shi, Wu, Cao, Ling, & Zheng, 2018; Jiake Zhang, Caijun Shi, et al., 2015; J Zhang et al., 2015). Because coarse RAs have a higher specific surface area, the reaction of the additions with those coarse RAs will possibly be more inert in the concrete's hydration reactions (Dhir Obe et al., 2019). But due to the specific chemical composition that some of the RA's are composed of, at the ITZ between the cementitious matrix and the RA it is possible that new products of hydration may be formed. A microcrystalline nucleation effect is played by the fine mineral additives on the cement's hydration, which causes an acceleration of the growth of the hydration products and an acceleration of the hydration of cement (Guo et al., 2018). The RAs are capable of reacting with cement and the mineral additions, and with a decrease in size those chemical reactions are potentiated. The amount of C-S-H can be increased and the pore size can be more refined due to the mineral admixture. This results in a bigger absorption of chloride-ions. But the RAC's resistance to chloride penetration can also still be improved by treating the RAs or adding a surface treatment to the exterior layer of the concrete with RAs (Guo et al., 2018; Kong et al., 2010; S.-C. Kou & Poon, 2010; Zhu et al., 2013). If the mineral additions are used for this purpose, the improvement of the resistance to chloride penetration, a single mineral admixture does not cause as many positive effects as binary or ternary mineral admixtures can (Andal, Shehata, & Zacarias, 2016; Kapoor et al., 2016; Leng, Feng, & Lu, 2000). However, it is not likely that the development of tensile and flexural strength is influenced by the RA and mineral additions combination (Dhir Obe et al., 2019; C. S. Poon & Kou, 2010).

Pozzolanic materials are generally used to enhance the overall durability of concrete in an effective and feasible way. Fly ash (FA) and silica fume (SF) are widely used powders that improve the durability and mechanical properties of the concrete, by forming a thin but strong layer (Guo et al., 2018; A Katz, 2004; Sasanipour & Aslani, 2020a) et al. It covers the RCA's surface to limit the absorption of water during the mixing process. Especially SF will improve the durability properties because it will reduce the RCA concrete's permeability (Dimitriou, Savva, & Petrou, 2018; Verian et al., 2018). Because each of these pozzolanic powders has different impacts, each of them is assigned a separate section.

### 4.3.2 Fly ash

Partially replacing OPC by FA can mitigate the prejudicial effects of RCA (Kurda et al., 2017a; Verian, 2012; Verian et al., 2018; Verian et al., 2013) et al. FA creates a pozzolanic reaction that can produce a C-S-H that in turn can densify the concrete's paste matrix. Of concretes made with RCA, the C-S-H can compensate for its porous nature (Lothenbach, Scrivener, & Hooton, 2011). The required C-H for the pozzolanic reaction in RAC comes from the hydration reaction between the water and new cement and also from the adhered mortar on the RCA particle's surface (S.-C. Kou & Poon, 2013). The SCC's workability can be maintained by the help of FA with a lower SP dose and VMA by FA's ball bearing effect in the matrix (Saini & Singh, 2020). Along with OPC, a constant content of 30% FA was used in SCC mixes to maintain the intrinsic fresh state properties that could have been degraded due to the RCA inclusion in the concrete (Saini & Singh, 2020). Admixtures like water reducers or plasticizers, FA and the combination could enhance the concrete's workability if it contains RCA (S.-c. Kou, Poon, & Agrela, 2011; Kurda, de Brito, & Silvestre, 2017b; Verian et al., 2018). Because a lot of research was done on this and the amount of information is not little, this was discussed in a separate section:

Compressive & splitting tensile strength.

With time, concrete will progressively exhibit an improved mechanical performance, and the mix design of the concrete is responsible for its rate (Dhir Obe et al., 2019). The concrete's 28-day compressive strength will reduce due to the addition of FA as a replacement for cement (Dhir Obe et al., 2019; Otsuki et al., 2003; Sasanipour & Aslani, 2020a; Shaikh, 2016) et al. The reduction is proportional to the cement's content replacement unless the FA that is used is very fine. An even greater decrease of the concrete's mechanical performance can be brought about by using FA combined with RA (Dhir Obe et al., 2019). Materials with a mechanical performance loss that was lower than expected could be obtained because the FA may react chemically with the RCA's attached mortar. There was some interaction between the FA and the coarse RCA since the compressive strength's decrease of the concrete with coarse RCA's content that increased was lower as the content of the FA also increased (S C Kou et al., 2007). Due to the combination of fine RCA and the sand that is replaced by coarse FA, this decrease will become even greater (Kurad, Silvestre, de Brito, & Ahmed, 2017; Ravindrarajah & Tam, 1987). Depending on the size of FA and the pozzolanic activity with the cement, the addition of FA with RCA with a larger surface area can be beneficial for the concrete's strength development. Compared to concrete that contains 100% of coarse RCA, the combination of FA with the increase of fine RCA has a positive impact on the 28-day compressive strength (Dhir Obe et al., 2019). Replacing OPC by 20% of FA was stated by (Verian, 2012; Verian et al., 2018) to enhance the 28-day concrete's compressive strength by more than 10% and 5% when it contained respectively 50% and 100% coarse RCA. A study by (Dhir Obe et al., 2019; C. S. Poon & Kou, 2010) evaluated the 10-year concrete's mechanical performance with increasing amount of coarse RCA and FA. The tests were done 28 days, 1, 3, 5 and 10 years after casting. If the casting was done at 28 days, the highest values of compressive strength were found for concrete that had 0% of fly ash. But as the content of FA increased, these values started to decrease. The initial strength development of the samples is generally slower due to the use of additives that exhibit pozzolanicity such as FA. Equivalent or higher compressive strength than blends without additives can be noticed after some time.

  - For mixes that contained 25% of FA, there was a higher compressive strength development after one year. They acquired a compressive strength that was slightly higher than the samples without FA. This was because of the pozzolanic activity between the addition and the cement. There was an almost parallel rise of all the mixes that contained 25% of FA, and ended with a compressive strength that was similar after ten years. By the addition of FA, a reduction was caused in the concrete’s splitting tensile strength, except for mixes that contained 25% of FA. The concrete’s strength development was similar to those without any additions.
  - A similar higher strength development rate was shown for concrete mixes that contained 35% of FA, but over a longer period of time. After three years, the mix achieved a performance that was comparable to that of the concrete with 0% FA and thereafter, it exhibited a similar development.
  - Mixes with an amount of 55% of FA had almost the same compressive strength achieved after ten years. In comparison with any other mix, this one showed strength development trends that were higher. Meaning, that a similar or higher compressive strength will probably be presented for mixes with 55% FA.

28 days after casting, all the mixes with an increasing replacement level had a compressive strength that was progressively lower. But ten years later the difference between concrete with RCA and that with NA were minor, except for the mixes that contained 55 % of FA and 100% of coarse RCA. An improved ITZ can arise between the new cement matrix and the coarse RCA due to not only the residual cementing properties of RCA’s non-hydrated cement particles, but also the pozzolanic reactions between the FA and the attached mortars can cause this (Amin, Hasnat, Khan, & Ashiquzzaman, 2016; Dhir Obe et al., 2019).

The combination of fine RCA and a high volume of FA can possibly lead to a RAC production that has a loss of tensile strength that is lower than expected (Kurad et al., 2017; Kurda et al., 2017a) or even negligible (S. C. Kou & Poon, 2009).

Another aspect that was extensively explored with the addition of FA was creep. Since there was a lot of information about this, a separate section is also dedicated to it:

<u>Creep</u>.

Dependent on the composition of combination, the addition of FA as a cement component could change the concrete’s creep deformation and affect the gain of the strength rate at an early age. Depending on the curing's nature it can thereafter change the concrete's ultimate strength due to tis pozzolanic reactivity (Dhir Obe et al., 2019). As a Portland cement replacement or addition of cement, FA can enhance the resistance to creep deformation of concrete made with RCA. For testing the creep strain, concrete was made with 0% - 35% FA and 0% to 100% coarse RCA. The FA was used as a PC addition or as a replacement for PC and measured after 120 days. The outcome of the test indicated that as the amount of coarse RCA increased, the concrete's creep increased and that for all samples, both for concrete with and without FA. There are two options for the concrete to achieve a creep strain that is similar to or even lower than that of concrete with NA. The first option is to use FA as a replacement for PC up to 25% and up to 75% of coarse RCA. Secondly 100% coarse RCA can be used with FA as a replacement for PC up to 35%. FA at contents of 25% and 35% as addition on the cement and up to 100% of RCA can also produce a concrete with a creep strain that is smaller than concrete with NA and 100% PC (Dhir Obe et al., 2019).

There are some other mention worthy effects of FA, namely that a proper content of FA or MK can significantly enhance the resistance to frost of concrete with RCA. This is due to the formation of C-S-H gel by the mineral admixtures and $Ca(OH)_2$ that enhances the strength and makes the concrete's microstructure denser (Guo et al., 2018; Salem & Burdette, 1998; J. Y. Sun & Geng, 2012). Also, the addition of 30% FA as a substitute for OPC in the concrete with RCA can reduce permeability (Bhikshma & Divya, 2012; Verian et al., 2018). Materials that help to coat the RCA's surface like cement and FA, improve the concrete's resistance to chloride-ion penetration (Sasanipour & Aslani, 2020a). A disadvantage of using FA is that it provides an increase in the carbonation depth of SCC made with RA and FA. In other words, the replacement of cement with FA can cause the carbonation depth to be increased (Guo et al., 2018).

As a conclusion, it lists all the positive aspects that FA can bring about and which were identified by several researches. First of all, FA can improve the concrete's workability (Jalal, Pouladkhan, Harandi, & Jafari, 2015; Paleti Siva Sai Krishna, 2011; Verian et al., 2018). It can reduce the concrete's permeability by limiting the water and/or other liquid's penetration that could damage the concrete (Verian, 2012; Verian, 2015) et al. Next is that FA can enhance the concrete's compressive strength at a later age (Verian, 2012; Verian, 2015) et al. It also enhanced the concrete's performance when exposed to freeze-thaw cycles (Verian, 2012; Verian, 2015) et al. Further can the shrinkage of RAC be reduced by FA. Due to the concrete's reduced pH by the pozzolanic reaction, FA can increase the $CO_2$ sequestration in concrete if it's in a condition that is favorable for carbonation (i.e., a humidity of 40% to 70%). However, the lower pH can also lead to a de-passivation and make the concrete prone to corrosion. But if the secondary C-S-H gel is formed and the concrete is densified, the carbonation rate will decrease (M. Limbachiya, Meddah, & Ouchagour, 2012).

### 4.3.3 Silica fume & metakaolin

When replacing cement with a small portion of silica fume (SF) the concrete will have an enhanced improved mechanical performance. However, this also depends on the mean particle size of the additive (Dhir Obe et al., 2019; B B Mukharjee & Barai, 2015a, 2015b; Pedro, de Brito, & Evangelista, 2017). Between the SF and $Ca(OH)_2$, there will be a reaction that causes the formation of additional hydration products. Since SF has a rather small particle size, some of them can probably fill up the surface pores and microcracks of the RAs, which can improve the ITZs and prevent the propagation of cracks through them (Bibhuti Bhusan Mukharjee & Barai, 2017; Yaragal, Teja, & Shaffi, 2016). The usage of RA will cause a loss in strength, but an increase will be proportional to the content of SF (V Corinaldesi, Orlandi, & Moriconi, 2002). As stated before, pozzolanic materials will form a coating on the surface of RCAs to enhance the attached mortar. Sealing the adhered mortar's pores can cause an improvement for the RAC's workability, and this can be done by a surface pretreatment such as SF slurry or cement slurry. If this SF slurry is used before mixing in the RCA's production, it can enhance the cracks. This, in combination with the formation of a strong bond between the cement paste and the aggregates can rise the compressive strength up to 15% (Sasanipour & Aslani, 2020a). An increase of compressive and tensile strength of concrete made with RCA will be noticed with the addition of 10% SF (Abd Elhakam, Mohamed, & Awad, 2012; Verian et al., 2018). However, another source, (Pedro et al., 2017), stated that the use of SF in RCA leads to a lower tensile strength. But only at later ages, the positive effects of SF could be observed. The improvement of the RAC's tensile strength is continuous and significant due to the SF's presence. Concrete with SF could achieve a compressive strength of 70 to 85 MPA after around 90 days (Pedro et al., 2017). The use of SF and its pozzolanic activity results in a low permeability of concrete, but it also results in the ability to a reduction of segregation and bleeding of the concrete (Aslani, Ma, Yim Wan, & Muselin, 2018; Sasanipour & Aslani, 2020a). Improving the weaker layers can be done with the coating method on the RCAs and will result in a stronger ITZ. To strengthen the RCAs and especially the attached mortars, two treatment methods were considered:

1. RACCM: immersing the RCAs in the SF slurry. The slurry contains of 250 grams of SF for 8 kg of RCA and 1 liter of water.
2. RACCD: for a duration of 2 hours, RCA, in a dry state, was poured in a desiccator. After that, it was impressed in the desiccator by SF slurry and
3. at last, the RCA's that are pretreated were transmuted to a drying oven machine for 3 days at 45°C.

the methods mentioned above had no influence on the behavior of the concrete's compressive strength, this can be seen on the figure below.

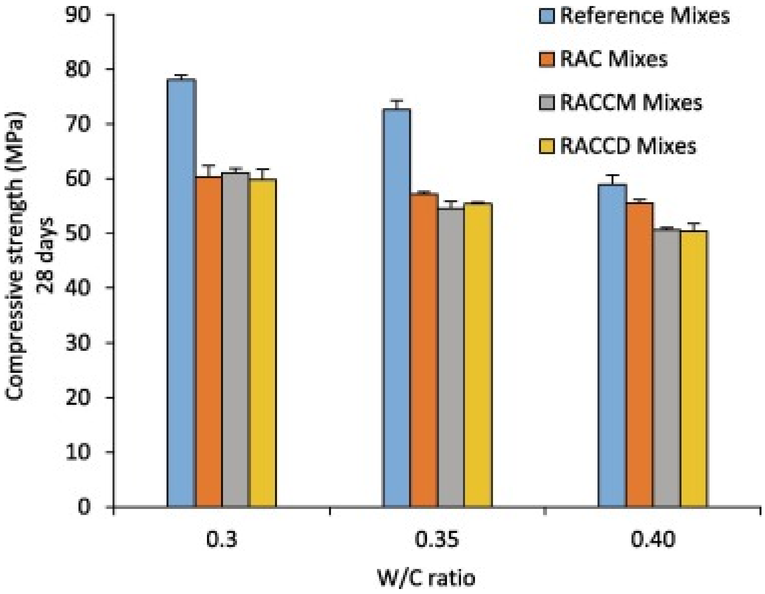

*Figure 13: Results for the compressive strength test (Sasanipour & Aslani, 2020a)*

In the RACCM and the RACCD methods, the category of the compressive strength didn't change. This was confirmed by (OZguR Cakir & Sofyanli, 2015; Pedro et al., 2017; Sasanipour & Aslani, 2020a; Sasanipour, Aslani, & Taherinezhad, 2019) where SF's effect at 7 and 28 days were insignificant and a compressive strength's enhancement could be possible at a later age. To reduce the total charge passed, the surface treatments were very effective. However, the RACCM method was noticed to be relatively more efficient in comparison to RACCD. But both those pretreatments had no great impact on the compressive strength. They both enhanced the electrical resistivity, due to a higher content of C-S-H-gel that was formed. Due to the layers between the mortar and aggregates and the mortar itself being more porous and weaker than the aggregates, there may be penetration of chloride ions. To enhance the chloride-ion penetration resistance, the RACCM method is very effective. A dense structure can be found in the vicinity of the aggregates, as well as in the mortar concrete mixes, which can help the reduction of the penetration of chloride ions. All this is possible thanks to the finer structure of SF, compared to cement, and its pozzolanic activity that will form C-S-H-gel. The density around the aggregates will decrease if the RCAs are coated with SF as the new layer confines the surrounding RCAs.  The RCA's can be strengthened by the formation of a C-S-H-gel in later time in all W/C ratios. This is due to the filling of the RCA's pores with SF that reacts with the calcium hydroxide (OZguR Cakir & Sofyanli, 2015; Nie et al., 2017; Pedro et al., 2017; Sasanipour et al., 2019). The interface between the RCAs and the paste can be enhanced by a thin layer of SF surrounding the coarse RCAs.

SF and MK sometimes have the same properties or influences. Some of these are discussed in this paragraph. Primarily SF and MK are used as SCMs as a partial binder replacement (Saini & Singh, 2020). The properties of SCC with RCA can be enhanced if OPC is partially replaced with SF and MK (Kapoor et al., 2016; Verian et al., 2018). A greatly increase in the theoretical fatigue life and endurance limit for blended SCC mixes that contain RCA can be achieved by adding SF and MK to the mix (Saini & Singh, 2020). By refining the pore size and enhance the microstructure, the addition of SF and MK in SCC can help recover its homogeneity such that comparable performance in fatigue is achieved compared to the SCC with natural aggregates. The improvement of the microstructure can also make the endurance limit increase. A great enhancement of the RAC's impermeability can be achieved by the use of ultra-fine materials such as SF and MK (O. Cakir, 2014; Guo et al., 2018; Singh & Singh, 2016). The compressive strength will increase and the maximum hydration temperature will lower when SF and MK are added in the concrete mixture that contains RCA (Radonjanin, Malešev, Marinković, & Al Malty, 2013; Verian et al., 2018). Despite that SF contains a higher content of silica in comparison to MK, the concrete containing MK sows a higher strength and durability. When comparing SF and MK, it is MK that will show the most favorable results (Kapoor et al., 2016; C. S. Poon, Kou, & Lam, 2006; Saini & Singh, 2020). The loss in the resistance to carbonation can be compensated by the addition of MK, this is due to the higher fineness of the MK particles that are beneficial in the enhancement of the microstructure and the against the $CO_2$ regression.

### 4.3.4 Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBFS) is also known as slag cement and possesses a latent hydraulic property. This property will enhance the concrete properties' long-term durability (Q. Li, Li, & Yuan, 2012; Lübeck, Gastaldini, Barin, & Siqueira, 2012; Verian et al., 2018; Wang, Yan, Yang, & Zhang, 2013). Due to the GGBFS and RA there will be a strength reduction at the initial stages in the concrete after casting, but this will be compensated at later stages by a higher strength gain rate (Berndt, 2009; Dhir Obe et al., 2019; S.-c. Kou, Poon, & Agrela, 2011). A more superior quality concrete has resulted with the use of GGBFS in combination with FA. This means a higher compressive, flexural and split tensile strength in all the levels of the RCA in comparison with the concrete made with OPC and natural aggregates. But the result is actually not expected to be affected by the coarse RA's incorporation (Parthiban & Saravana Raja Mohan, 2017; Verian et al., 2018). In a study by (Majhi, Nayak, & Mukharjee, 2018) where concrete was made with GGBFS, that replaced up to 100% OPC, and up to 60% of coarse RCA, the mechanical properties (i.e., compressive, flexural and split tensile strength) decreased as the amount of RCA, GGBFS or both increased.

### 4.3.5 Chemical admixtures

Due to the RA's higher water absorption capacity and surface that is rougher, the mixes will be stiffer and less workable. This can be remedied by adjusting the mix with (super)plasticizer content so it is possible to produce high-strength and workable concrete with (partly) dry recycled aggregates (Dhir Obe et al., 2019; Prakash & Krishnaswamy, 1998). The action behind this will mainly act on the cement and other finer dense particles, however, this depends on the chemical basis of the admixture. This means that the incorporation of coarse recycled aggregates does not likely affect the efficacy of a plasticizer on the concrete's hardened properties. By increasing the coarse recycled aggregates and making the concrete with plasticizer, the average relative compressive strength can slightly increase. By to the presence of superplasticizers, the strength development of concrete with an increase in the number of coarse aggregates is marginally influenced.

The fine aggregates can influence the water reducing capacity of some admixtures. In a study by (Pereira, Evangelista, & de Brito, 2012a, 2012b), there were two kinds of plasticizer made. One regular one that was lignosulphonate based, and a high-range one which consisted of a combination of modified polycarboxylates. The specific mechanism of the former one made it possible to hinder the efficacy in the reduction of the water content due to the fine RCA's higher surface area in comparison to that of the sand that was replaced. Increasing the effective W/C ratio with a higher number for replacement level had to be done for this reason, which slightly increased the losses of the compressive strength.

Although the plasticizer's effectiveness turned out to be independent of the increase in coarse recycled aggregates, this was still the case with mixes with RAs that were water compensating. This means that there will be an absorption of part of the mixing water if those water-compensated RAs are incorporated at a (partly) dry state. Which will cause a decrease in the effective W/C ratio of the mix, whereby the admixtures activities are also influenced. Nonetheless, flowing mixes with relatively high values for the compressive strength can still be produced by the use of plasticizer. A lab test by (Domingo-Cabo et al., 2009; Domingo, Lázaro, Gayarre, Serrano, & López-Colina, 2010) showed that there is a possibility to achieve an enhanced mechanical performance for a somewhat higher content of plasticizer and same total W/C ratio. From this it can be concluded that the increase in strength through the usage of plasticizers resulted in a less effectiveness when the replacement level of (semi-) dry RAs increased

The expected air content is produced using the use of air-introducing auxiliaries. This is only slightly influenced by the addition of RCA, as (Dhir et al., 1999; Otsuki et al., 2003; Rohi M. Salem & Jackson, 2003) stated, so that effect on the mechanical behavior must remain unaffected. In that study, it seemed that the air content was mostly unaffected for mixes who had the same target strength. This same target strength was achieved by varying the effective W/C ratio while keeping the content of cement the same. The same was observed in a study by (Otsuki et al., 2003), where mixes contained 100% coarse RCA. The air content of the mixes was not affected if mix design and air-entraining admixture content were kept the same. Another study, that examined RAC's freeze-thaw resistance, showed that regardless of the air-entraining admixture's usage, the loss of strength between the concrete with RCA and those with NA was the same (Rohi M. Salem & Jackson, 2003).

### 4.3.6 $CO_2$ treatment of RA

To describe the positive effects of this treatment, there is a briefly explanation about what exactly happens in the lab during this treatment. When $CO_2$ is added to cause carbonation it reacts with calcium hydroxide ($CA(OH)_2$) and calcium silicate hydrate (C-S-H) to produce calcium carbonate ($CaCO_3$) and silica gel ($SiO_2$) (Hosseini Zadeh, Mamirov, Kim, & Hu, 2021). Treatment in the lab is done with a tank of $CO_2$ that is connected to a sealed vessel that holds the aggregates. Treating the recycled aggregates has several positive effects. This method is promising and efficient in improving the general properties of the recycled aggregates and significantly enhances the durability of the resulting concrete (Guo et al., 2018; C. Shi et al., 2016; C. J. Shi, Cao, & Xie, 2016). One of those improved properties is the density of the aggregates. By applying this $CO_2$ method, the density of the aggregates can be increased, there is a decrease in water absorption and a reduction in crushing value. It can also decrease the drying shrinkage, as well as the coefficient of chloride ion diffusion of mortars that have RAs treated with carbon dioxide (C. Shi et al., 2018; Jiake Zhang, Caijun Shi, et al., 2015; J Zhang et al., 2015). The resistance to the chloride permeability of the RAs can be done very effectively and feasibly with treatment of the RAs using the $CO_2$ method. In addition, this method can also enhance the mechanical properties of the aggregates. The $CO_2$ technique will improve the old ITZ between the aggregates and the attached paste. On top of that, it also enhances the new ITZ that was formed between the old and new cement matrix (C. Shi et al., 2018; Jiake Zhang, Caijun Shi, et al., 2015; J Zhang et al., 2015). Like steam curing, adding superplasticizers and double or triple mixing methods, the $CO_2$ can also improve the resistance to penetration of the RAC (C.-S. Poon et al., 2006; S.-C. Kou et al., 2014; Matias et al., 2014; Zhan et al., 2016). The $CO_2$ curing is more efficient on fine RCA where higher paste content is present and need for water absorption reduction is higher.

### 4.3.7 Two stage mixing approach (TSMA)

This modified mixing technique, TSMA, is a technique when RAs are firstly mixed with sand for 60 seconds, then half of the water is added and this mix is mixed for another 60 seconds. Then the cement is introduced into the mixture and mixed for 30 seconds and finally the other portion of water is added after which this final mixture is mixed for 120 seconds. In figure 14 the comparison is made between making concrete according to (A) the normal method and (B) according to the newly discussed method. By using up to 30% of recycled concrete aggregates in the production of concrete and mixing the mixture according to TSMA, there could be an improvement of the properties of the resulting concrete to a level that is similar or even better than those of the conventional concrete (V. W. Y. Tam et al., 2005; V. W. Y. Tam & Tam, 2007, 2008; Verian et al., 2018). This technique will improve the concrete made with RCA's ITZ, and logically enhance the quality of the overall RAC- concrete. A disadvantage to this technique is that because the mixing water is divided into two servings and added in the mixture at two different times, there is a longer mixing time.

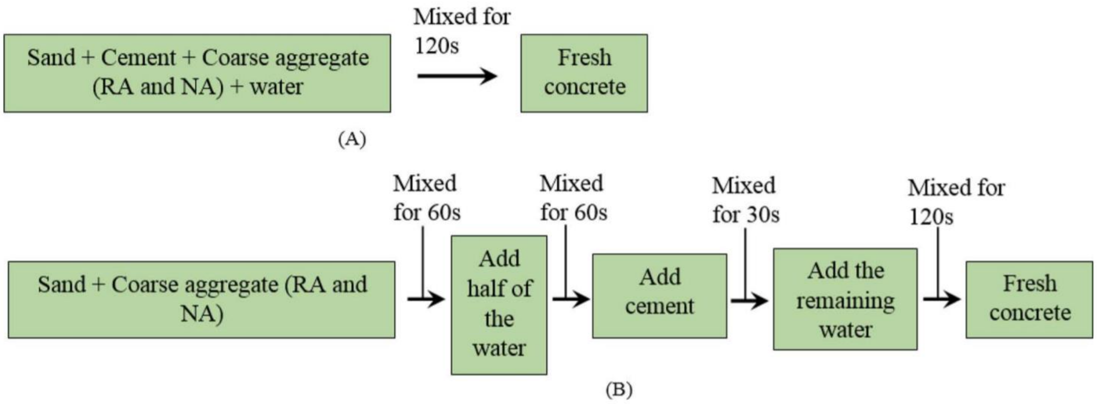

*Figure 14: (A) Normal mixing approach (B) TSMA (V. W. Y. Tam & Tam, 2007)*

Some modifications to this technique may also suggested, which incorporates SF, or a combination of SF with cement in the pre-mixing process (V. W. Y. Tam & Tam, 2007, 2008). This technique with SF will be abbreviated as TSMA$_S$, the one with SF and cement as TSMA$_{SC}$. Their production processes are shown in figures 15 and 16. A denser old cement mortar is developed by filling old pores and cracks with SF when the TSMA$_S$-technique is used. Since a certain amount of SF and cement are present in the mix, the TSMA$_{SC}$ -technique will ensure that the ITZ is further improved between the cement paste and the recycled aggregates. Due to the improved ITZ, the RCA concrete's compressive strength will be higher. A higher strength enhancement is observed with RCA concrete specimens made with the TSMA$_{SC}$ method compared to the specimens made with the TSMA$_S$ method. But still, the RCA concrete made with the two modified methods still give a much better performance than RCA concrete made with the original TSMA method. This only results in the conclusion that the two modification methods, TSMA$_S$ and TSMA$_{SC}$, are more effective in improving the strength of the concrete than the initial TSMA method (V. W. Y. Tam & Tam, 2008).

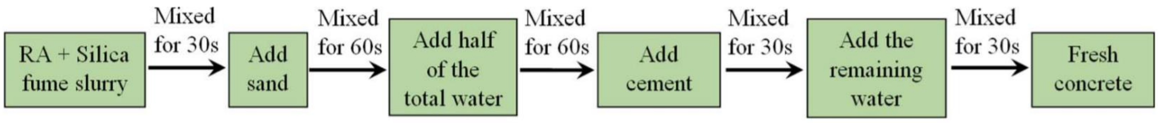

*Figure 15: Production process of TSMA$_S$ (V. W. Y. Tam & Tam, 2008)*

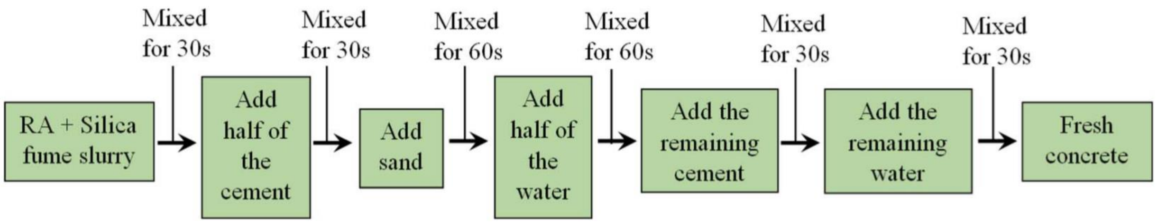

*Figure 16: Production process of TSMA$_{SC}$ (V. W. Y. Tam & Tam, 2008)*

### 4.3.8 Reducing the mortar content on RA

In previous sections it was already shown that the adhered mortar has no improving properties when making new concrete. Removing them is then a logical consequence in improving the result. The removal or reduction of the attached mortar to the aggregates shows improvement to the final product's quality (Committee, 2001; Verian et al., 2018). There are several options available to accomplish this:

- The RCA's adhered mortar concrete can be crushed into smaller sizes and subsequently washed off with water of the aggregates;
- The RAs could be submerged for five days in a sulphuric acid solution, then subsequently washed and sieved to remove the adhered mortar (Parthiban & Saravana Raja Mohan, 2017);
- The removal can also be done by submerging the RCA in a hydrochloric acid (HCl) solution for 24 hours (Katkhuda & Shatarat, 2017);
- If RCA is placed in a modified concrete mixer with a capacity of 8 m$^3$, water is added and it rotates for five hours at a speed of 10 rpm, the RCA particles will be fully submerged and it will remove the mortar (Dimitriou et al., 2018).
- Some more options are listed under the heading 4.3.16 Other RA treatment methods.

### 4.3.9 Mixture design modification

The use of RCA in concrete has been shown to change many properties of the concrete. To compensate for these changes, the mix of the concrete can be modified (Beltrán et al., 2014; M. Etxeberria, Vázquez, et al., 2007; Verian et al., 2018). To keep the workability the same but improve the compressive strength of the concrete with RCA, additional admixtures and cement are required. While keeping the amount of water the same, an additional amount of cement can be added to the mix to compensate for the decrease in the strength of the concrete with recycled aggregates (M. Etxeberria, Vázquez, et al., 2007).

### 4.3.10 Limiting the amount of RA in concrete mixture

With this method, it should be reported that not all sources agree on the limit of the amount of RCA that does not affect the compressive strength of the concrete. (S.-c. Kou, Poon, & Agrela, 2011) mentioned that the incorporation up to 50% of RCA did not influence the compressive strength of the RAC, while (Abd Elhakam et al., 2012) stated that using RCA up to 25% of total aggregates does not affect the compressive strength. Further, there is also a controversy in the use of the amount of coarse recycled aggregates. According to (Verian, 2012), there are similar to slightly better properties of RCA than NA if concrete pavement contains 30% of coarse RCA. But (M. C. Limbachiya, Leelawat, & Dhir, 2000) reported that an addition of coarse RCA up to 30% has no influence on the strength of the concrete. It can be debated that one speaks of properties and the other of strength, but it was shown earlier that one is closely related to the other. The essence, however, is why one would reduce the use of RCA in a mix. This is to minimize the alteration of the properties of the concrete that is caused by the insertion of RCA (Verian et al., 2018).

### 4.3.11 Self-healing RA

To obtain self-healing aggregates, the aggregates must be kept in water for 30 days (Gesoglu et al., 2015; Verian et al., 2018). This method will improve the recycled aggregate's quality as well as the concrete that incorporates these aggregate's quality (Abd Elhakam et al., 2012; Şahmaran, Keskin, Ozerkan, & Yaman, 2008; Zhong & Yao, 2008) et al.

### 4.3.12 Coating RA surface with pozzolanic powder

The pozzolanic powder will cover the surface of each particle of the RCAs in this method and will form a film layer. The process of the making is seen in figure 17. In comparison to the conventional concrete, this RCA concrete had a significant improvement in compressive and flexural strength, as in workability if the concrete was mixed with this technique.  During the initial stage of mixing, the pozzolanic powder film will limit the absorbed water on the surfaces of the RCAs (J. Li, Xiao, & Zhou, 2009; Verian et al., 2018).

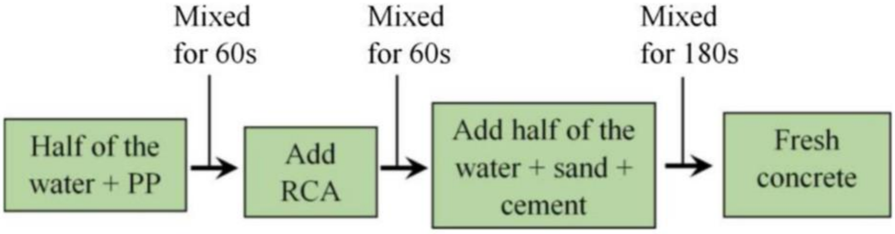

*Figure 17: Schematic process of coating RCA with pozzolanic powder (J. Li et al., 2009)*

### 4.3.13 Surface-modification technology

In this method, the surfaces of the aggregate particles will be covered with a coarse paste that contains an inorganic admixture. The surface-modification technology improves the performance of RCA with low quality. The method will provide an increase in both the compressive and tensile strength and in the shear strength of the RAC (Choi et al., 2016; Choi, Kitagaki, & Noguchi, 2014; Choi, Lim, Choi, Kitagaki, & Noguchi, 2014; Verian et al., 2018).

### 4.3.14 Using saturated aggregate

Before the batching process, saturating the RCA particles will enhance the performance of the concrete (A. S. Brand et al., 2015; M. B. Leite & Monteiro, 2016; Pickel, Tighe, & West, 2017; Verian et al., 2018). The RCA will be saturated if the aggregates are immersed for 24 hours in water (Ferreira et al., 2011). A disadvantage here may be that 100% saturation may however have a detrimental effect on the concrete. Research has shown that 90% saturation is an ideal level (Ferreira et al., 2011). In comparison to dry RCA is the ITZ for RAC between the paste and the aggregate particles denser. There is a possibility that moisture could be transported from the matrix of the aggregate to the bulk of the concrete due to the higher absorption capacity of the recycled aggregates compared to the natural aggregates (M. B. Leite & Monteiro, 2016). The advantage of this method over dry recycled aggregates can also be found in mortars where the compressive strength of specimens made with dry fine RCAs is lower than those made with saturated fine RCAs (Le et al., 2017).

### 4.3.15 Incorporating fiber into concrete mixture

Some of the disadvantages of using RCA in concrete can be offset by the use of fibers (Afroughsabet, Biolzi, & Ozbakkaloglu, 2017; Gao, Zhang, & Nokken, 2017; Katkhuda & Shatarat, 2017; Verian et al., 2018). There may be an increase in the splitting tensile and flexural strength compared to conventional concrete if the concrete is made with 20% treated recycled aggregates, 80% natural aggregates and 1% to 1,5% basalt fibers (Katkhuda & Shatarat, 2017). An increase of up to 60% in tensile strength and up to 88% in flexural strength in concrete made with RCA can be obtained after 28 days when using double hooked-end steel fiber. It is the better bonds between the RCA and the cement paste that provide the improvements. This is due to the rough surface of the RCA and the effect of the interlocking fibers and aggregates (Afroughsabet et al., 2017). An addition of up to 2% of the total volume of steel fibers can increase the shear strength (Gao et al., 2017). Another fiber, the synthetic macro-fibers can also improve the resulting concrete. The incorporation of these fibers up to 0,2% of the total volume can improve the concrete with 50% RCA's fracture properties in such a way that those are similar to that of concrete made with natural aggregates (Bordelon, Cervantes, & Roesler, 2009).

### 4.3.16 Other RA treatment methods

When the RA-treatment methods mentioned above, are applied to a large scale, this brings backdates to which its use remains limited, namely a difficult embodiment, further environmental problems and extra time and costs (Kazmi et al., 2020; Xuan, Zhan, & Poon, 2016; Xuan et al., 2017). If the example is taken from the removal of mortar, the challenges here are the high need for energy, the emission of $CO_2$, the large mountain of waste that is created and the increase in the amounts of sulfate and chloride in the RAs (Kazmi et al., 2020; Xuan et al., 2016, 2017). One of the solutions to improve the RAC's performance while owing to the ease of execution, the eco-friendly environment, the economy and the efficiency is RA immersing an acetic acid solution and RA's accelerated carbonation (L. Wang et al., 2017; Xuan et al., 2016, 2017). These were only two examples, in total there are five that are discussed here:

1. Immersion in acetic acid;
2. Immersion in acetic acid with rubbing;
3. Accelerated carbonation;
4. Immersion in acetic acid with accelerated carbonation;
5. Immersion in lime with accelerated carbonation.

The weakening and removal of the adhered old mortar to the surface of the RA is achieved by the solution of acetic acid, which will react with the calcium carbonate ($CaCO_3$) and the cement hydration products. It will also produce waste by-products, that can be used in the new concrete as an admixture (P. Chen et al., 2017; L. Wang et al., 2017). Enhanced mechanical performance and durability of the RAC is obtained by making the RA's surface denser. This can be done by carbonating RA under pressure in specially designed rooms that can cause accelerated carbonation, and in this way produce $CaCO_3$ in the pores, which in turn ensures this denser surface (Xiao, Li, & Poon, 2012; Xuan et al., 2016). The effectiveness of the RA's treatment with the accelerated carbonation is primarily dependent on the adhered mortar's number of reactive components (Zhan, Xuan, & Poon, 2018). A more enhanced water absorption capacity of concrete with carbonated RA can be noticed in comparison to that of RAC. For improving the performance of RAC, the accelerated carbonation and the immersion in acetic acid are the most effective and environment friendly methods (Kazmi et al., 2019b; L. Wang et al., 2017; Xuan et al., 2016). To remove the adhered old mortar on the surface of RA, the washed RA can be undercoated in a solution with 3% acetic acid for 24 hours (L. Wang et al., 2017). As a result, acetic acid immersed RA, or A-RA is formed. For a removal that is more effective, the A-RAs can be mechanically sanded against each other by putting them in a concrete mixer for 5 minutes and thus obtain acetic acid immersed and mechanically rubbed RA (AR-RA). In comparison to RAC samples, the AR-RAC ones showed a rise in the splitting tensile strength of 23% and in the flexural strength of 60% (L. Wang et al., 2017). To be able to calculate the amount of attached mortar, the RAs were also immersed in a solution of sodium sulfate and thereafter to seven freeze-thaw cycles exposed (A Abbas et al., 2008; Abdelgadir Abbas et al., 2009). To approve the effectiveness of RA's treatment with an accelerated carbonation, the amount of $CO_2$, that is used in the production of $CaCO_3$ in the pores of the attached mortar of RA, is an important parameter (Xuan et al., 2016). The RAC's compressive strength experiences a positive influence from the RA's treatment. The reason for this could be the combination of two methods. Firstly, the immersion of RA in acidic solution to remove the adhered old mortar (L. Wang et al., 2017) and secondly, the deposition of $CaCO_3$ after the accelerated carbonation to densify the old adhered mortar's pore-structure (Xuan et al., 2017; Zhan et al., 2018). The immersion in acidic solution-treatment and the accelerated carbonation-treatment makes the properties of RA enhance, and in turn increases the concrete's elastic modulus (S. Luo, Ye, Xiao, Zheng, & Zhu, 2018; L. Wang et al., 2017; Zhan et al., 2018). For concrete samples that contain treated RA's a rise in the splitting tensile and flexural strength can be observed. When using treated RA in concrete, a decrease can be noticed in the volume of the permeable voids. This is important since the reduction of those voids can support the overcoming of the inferior RAC's durability performance. For concrete that contains treated RA, an enhancement in the resistance to chloride can be observed compared to concrete with untreated RA. This can be due to the denser adhered mortar that was achieved by the accelerated carbonation, followed by the precipitation of CaCO3 of the mortar and the acid treatment (Xuan et al., 2017; Zhan et al., 2018; J Zhang et al., 2015), followed by the mortar removal (L. Wang et al., 2017). RAC containing treated RA will show an improved microstructure with denser ITZ in comparison to RAC with untreated RA. Green constructions can be achieved by overcoming the RAC's inferior durability properties, due to the AR-RA's and immersion in lime with the accelerated carbonation method.

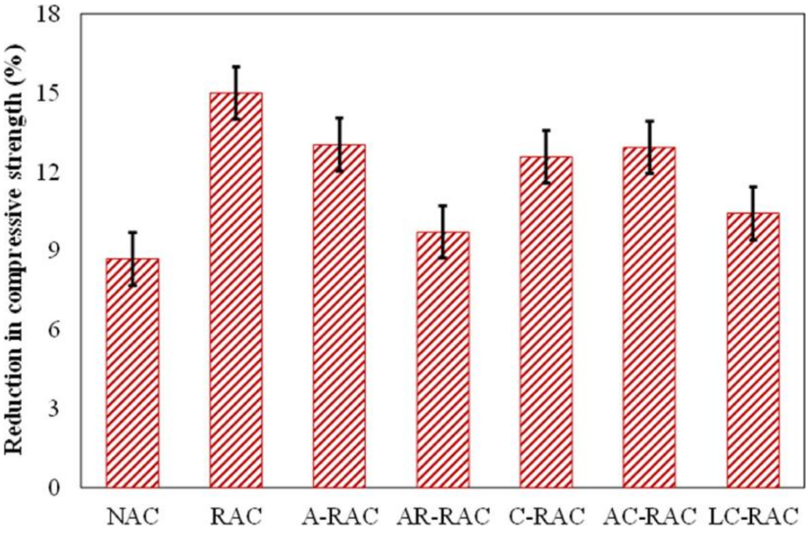

*Figure 18: Reduction of compressive strength of concrete with NA, untreated RA and RA after acid immersion (Kazmi et al., 2020)*

One of the main properties that is required in chemically aggressive environments is the concrete's resistance to acid. However, the resistance of current concrete to acid attacks is low (Bakharev, Sanjayan, & Cheng, 2003). When introducing RAs in the mix, this resistance drops even further. The graph in figure 18 shows the reduction of the NAC's and RAC's compressive strength when untreated and treated with acid immersion. The cause of this can be the high porosity or the absorption capacity of RAC, which facilitates the penetration of the acid, resulting in a decalcification of the C-S-H in the concrete (Alnahhal et al., 2018; K. J. Rao, Keerthi, & Vasam, 2018). An improvement can be noticed in concrete that contains treated RA, due to the lower water absorption capacity and porosity, which in turn results in a lower acid penetration in the RAC (L. Wang et al., 2017; Xuan et al., 2017). By treating the RA's by immersing them in lime with accelerated carbonation and the immersing in acetic acid with rubbing techniques, the resistance to acid can be enhanced when concrete is exposed to chemically aggressive environments. In this way cleaner and durable constructions can be produced. Concrete with treated RA also shows an increase in carbonation resistance compared to concrete with untreated RA. This can also be related to the porosity reduction. The technique that could be used to improve the resistance to carbonation of RAC are the immersion in lime with accelerated carbonation and the acetic acid with rubbing technique. From all this it can be concluded that in general treated RA will improve the physical properties RAC in comparison to untreated RA.

A lot of methods are developed to examine the effects of the treatment techniques on RA. X-ray diffraction analysis and thermogravimetric analysis can be used to study the techniques on mineralogical composition and the aggregate's thermal behavior. The X-ray diffraction patterns will show the enhanced chemical compositions of the RA's, while the thermogravimetric curve will show the decomposition of CaCO3. To study the impact of the methods on the pore-structure and the microstructure characteristics, the mercury intrusion porosimetry and scanning electron microscopy can be executed. They show the improved microstructure, the denser ITZ and enhanced porosity of the RAC that contains treated RA (S. Luo et al., 2018; Xuan et al., 2017). Going deeper into these methods would take the scope of this work too far and are therefore not furtherly addressed.

### 4.3.17 Conclusion

It is recommended to use SCMs (i.e., FA, SF, MK and GGBFS) since they have proven to enhance the RCA concrete's quality (Berndt, 2009; Verian et al., 2018; Verian et al., 2013) et al. The use of FA or a slag coating will react with the concrete's existing $Ca(OH)_2$ and form a secondary C-S-H product that will strengthen the ITZ layer and they will also enhance the RA's pore structure. If RA is modified with $CO_2$, it can produce $CaCO_3$ by reacting with the hydration products in the concrete. This will strengthen the micro pore structure of the concrete. For this reason, the use of pozzolanic materials and treating the aggregates with $CO_2$ previous to using them in concrete is suggested to have a RAC that is more durable (Guo et al., 2018). By coating the surface of the RA with SF (Amnon Katz, 2003), SCMs (J. Li et al., 2009) and an admixture of inorganic paste (Choi et al., 2016), the RAC will show an enhanced packing density and a better behavior in durability in comparison to concrete with RA that was not treated (Kazmi et al., 2020). The batched concrete's quality is influenced by the RCA's treatment prior to the mixing. If this is in combination with a good mix design and a good batching, the (partially) saturated RCA will show an enhancement in the performance of the concrete in comparison to concrete that contains dry RCA (Verian et al., 2018). The batching techniques that have been modified (i.e., TSMA, $TSMA_S$, $TSAM_{SC}$) have proven to enhance the RCA concrete's quality.

# 5 Laboratory

This part of the thesis is mainly about the lab tests that were performed in Norway by fellow students. This section starts with a summary of what to consider when making concrete. This was based on literature. After that, the various lab results are listed and links are made with the information seen in the literature.

## 5.1 How to prepare the best possible concrete using RA

### 5.1.1 Consistence

One of the primarily properties of the fresh concrete is the consistence or workability and several methods can be used to evaluate it, such as the slump test. For a given mix composition and size limit, several aggregate characteristics impact the concrete's consistence, such as the shape, surface texture, absorption and distribution of the particle size. The RAC will absorb significant amounts of mixing water, so the RA's high water absorption capacity significantly impacts the behavior of the fresh material.

When concrete is made with NA, the NAs have a water absorption capacity that is normally very low in the (semi-)dry state, therefore the water that is needed for compensating for the NA's absorption during the mixing process, is very little. However, when RAs are used in the production of concrete, one should pay attention to its higher water absorption, due to the microstructure that is porous ad the attached mortar or ceramic particles (Barra & Vázquez; Dhir Obe et al., 2019). Initially, it was suggested that the RAs in the SSD state should be used (T. C. Hansen, 1992). In this way the RA would be prevented from absorbing the mix's free water, that otherwise could reduce the RAC's workability excessively. Several studies have been released that describe the concrete's fresh properties under the influence of an increase in the content of RA. But only three of them have been used in the RAC's mix design while they maintained a consistence that was constant. Since the first method was used in the laboratory tests, this one will be explained in more detail.

- Prior to the mixing process, the RA is pre-saturated for a certain period of time.
  This method will prevent the absorption of excessive water and is capable of maintaining a constant consistence (Koulouris, Limbachiya, Fried, & Roberts, 2004; Topcu & Sengel, 2004; Y Kimura, 2004). This method has the disadvantages that in practice it is difficult to implement and the slump values can result unstable due to the RA's apparent SSD state. This condition ensures that the pores of the surface retain the

leftover water, resulting in mixtures with an increased degree of slump (Debieb & Kenai, 2008; Kutegeza & Alexander, 2004).

- To partly or fully compensate for the RA's absorbed water, extra water is added during the mixing;
- Maintaining a constant consistence and W/C ratio was achieved by adding superplasticizers in the RAC mix.

Data from several studies were put together and divided into four categories.

1. Contains all data from all studies. The only trend that could be derived here is that for a higher replacement level, the spread of values is greater. The upper and lower limit of 95% of the data show a range of -120mm and +140mm.

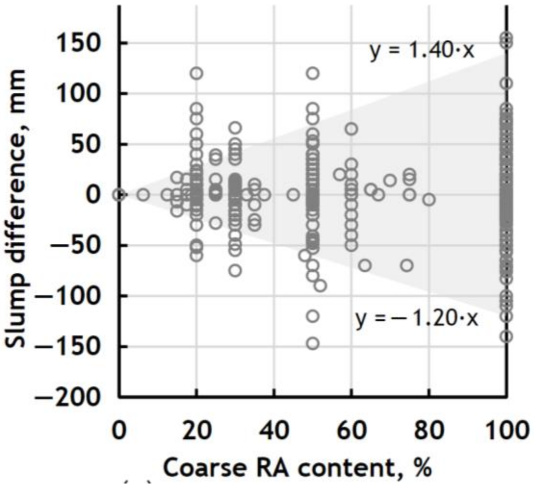

*Figure 19: The difference in slump with an increase in RA content - all mixes (Amorim et al., 2012; Butler et al., 2011; Buyle-Bodin & Zaharieva, 2002)et.al*

2. Contains only mixes with compensation for water, pre-saturation method inclusive and where the effective W/C ratio was equivalent. The range has been changed to -67mm to +150mm, which indicates that an extra water addition avoids a workability loss.

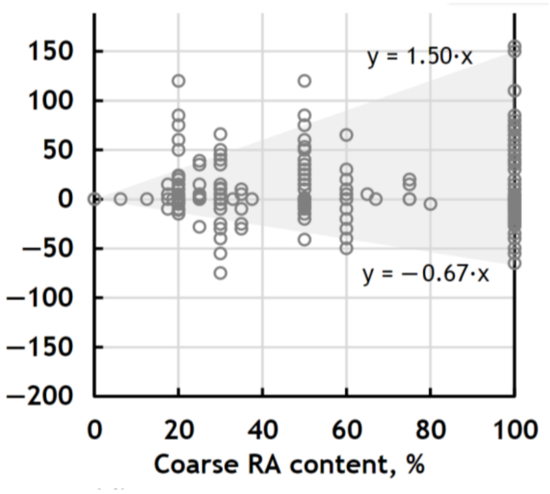

*Figure 20: The difference in slump with an increase in RA content - water-compensated mixes (Amorim et al., 2012; Butler et al., 2011; Buyle-Bodin & Zaharieva, 2002) et al.*

However, some loss in slump could occur (Kutegeza & Alexander, 2004) as a result of the increased RA's roughness ad shape index which increases the interparticle friction (Assaad & Daou, 2017; Mas et al., 2012; Radonjanin, Marinković, & Malešev, 2010) and the cleanliness level of the RAs (Montgomery; Wegen & Haverkort, 1998). Given the RA's higher water absorption, for RAC with a content of RA that increases, the slump values will yet be higher (S.-W. Kim & Yun, 2013; S. C. Kou & Poon, 2009; C. S. Poon & Kou, 2010). This can possibly occur due to the RCA's enhanced shape index in relation to that of NA (Pickel et al., 2017). But the slump variation will not be affected by this factor (Nealen & Rühl, 1997; Nealen & Schenk, 1998). The RA will be in an SSD state if it's first pre-saturated for 24 hours, after which it is air-dried for 1 hour before the mixing. However, that the surface will be really dry is hard to guarantee (Ferreira et al., 2011). Due to the surface pores of some treated RAs that contain a particular amount of water, the W/C ratio will be higher and thus the workability will increase

3. Contains the same data as in category 2 but without the studies that used the water compensating method with adding water corresponding to an SSD RA. This shows a slump variation with greatly smaller range.

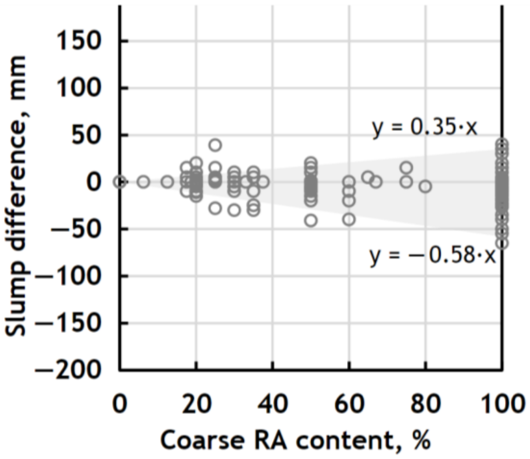

*Figure 21: The difference in slump with an increase in RA content - selected mixes (Amorim et al., 2012; Butler et al., 2011; Buyle-Bodin & Zaharieva, 2002) et al.*

The figure suggests that a replacement level of 100% has an interval between -57mm and +35mm. Mixes with a replacement level of 20% had a standard deviation that was higher than expected, namely more or less 8.5mm. With the assumption that there was a proper compensation for the water absorption of the RAs, the RA's greater roughness can be partly the cause of the slight decreasing trend with the increase in content of RA.

4. Shows RAC's slump loss for mixes with the same W/C ratio as the concrete with NA and thus concrete where the used RA has a high absorption for the mixing water.

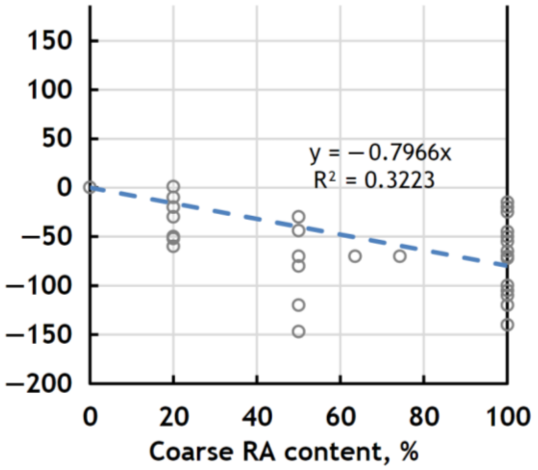

*Figure 22: The difference in slump with an increase in RA content - constand W/C factor (Amorim et al., 2012; Butler et al., 2011; Buyle-Bodin & Zaharieva, 2002) et al.*

With the increase of the content of RA, there was a significant slump loss. The increased content of RA usually progresses linearly with the slump difference. The addition of

> RA with a replacement level of 100% can suggest a slump loss between 30mm and 100m. The slump will be very dependent on the RA's water absorption capacity if the RAC mixes are uncompensated (Mefteh, Kebaïli, Oucief, Berredjem, & Arabi, 2013).

To maintain a workability that is comparable when using fine RA (Debieb & Kenai, 2008; L. Evangelista & de Brito, 2007, 2014) or the combined use of fine and coarse RA (D. J. Anderson, Smith, & Au, 2016; S. C. Kou & Poon, 2009; X.-b. Zhang et al., 2008), the amount of water that is required is higher than when fractions are used that are coarser. This amount will increase with the increasing replacement levels and this is due to the water absorption capacity that is typically higher with finer fractions of RA. Which in turn is due to the higher amount of attached mortar that is porous and the bigger surface area. The RAC mixes can present a workability that is similar to that of the mixes with natural aggregates if the content of water is correctly calculated and the RA has enough time to absorb the extra water, regardless of the RA's size, type and capacity of water absorption. For a study by (C. S. Poon, Shui, Lam, Fok, & Kou, 2004), the mixes contained RA in an oven dry-state and with extra water to compensate for what will be absorbed in time. This study showed that the initial mix's lump increased as the content that was replaced by RA increased. From this it can be concluded that to be able to absorb the extra water, the coarse RCA had been given too little time. In a study by (Carro-López et al., 2015), the results claimed that the identification of the time between mixing and casting is needed. How this conclusion was reached is left out of this work.

To determine the RA's effects on the concrete's workability, the compaction factor can be used. These tests suggest that the measurement will decrease for a constant W/C factor as the content of RA increases (Ray & Venkateswarlu, 1991).

The distribution of the particle size that varies and the lower quality of RA that has a more irregular shape will require an extra amount of water (Yang et al., 2008) that differs from the water that is needed to compensate. This will make the effective W/C factor increase. When RCA comes from products that have a strength class that is different, the shape will not likely be affected, so the extra amount of water is only dependable on the capacity of the water absorption and the content of attached mortar (Otsuki et al., 2003). RA from a lower quality can be highly contaminated with constituents that are unwanted which will affect the concrete's hardened performance.

### 5.1.2 Rheology

The rheology is the study of the matter's flow. Rheological characteristics are influenced by parameters that are related to the constituent materials of the mix (i.e., the particle size distribution of the RA, the moisture state, the shape, and the roughness of the surface due to the attached mortar). For concrete mixes that are made in an increasing content of coarse RCA a different state of moisture and a W/C factor of 0.60, the figure below stages its yield stress (a) and plastic viscosity (b).

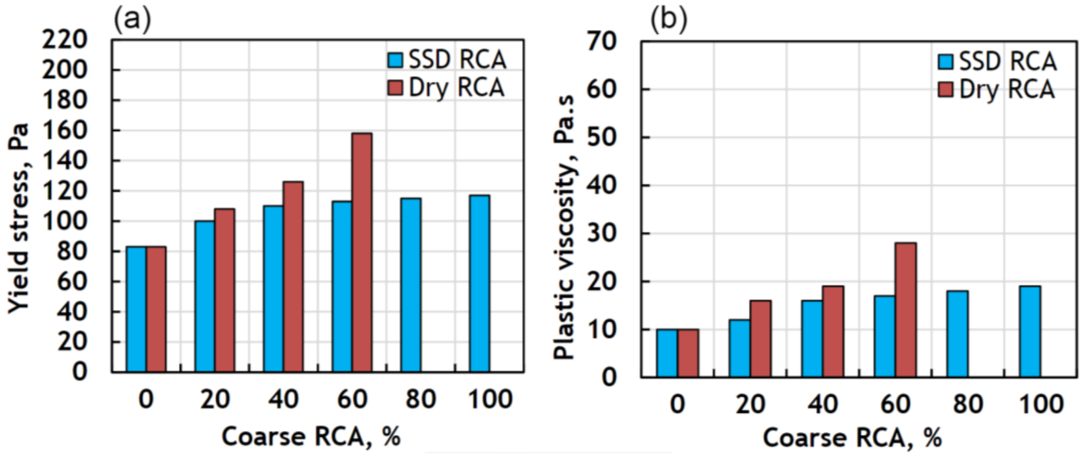

*Figure 23: (a) Yield stress and (b) Plastic viscosity with an increase in dry/SSD RCA for a W/C factor of 0.60 (Ait Mohamed Amer et al., 2016)*

From this figure, it can be deduced that the yield stress and plastic viscosity will increase when the amount of RCA in an SSD state increases (Ait Mohamed Amer et al., 2016; Barra Bizinotto, Faleschini, Jiménez Fernández, & Aponte Hernández, 2017; Dhir Obe et al., 2019; Faleschini et al., 2014). For mixes with a reduction in water content, this is a common outcome (Dhir Obe et al., 2019; Newman & Choo, 2003). Another study by (Dhir Obe et al., 2019; K. Kim, Shin, & Cha, 2013) found a lower yield stress when adding coarse RCA in an SSD state. With an increasing level of replacement there was a large increase in slump, allowing for a more regular form of RCA compared to NA, or an accidental addition of mixing water through the SSD state of the coarse RCA. The two parameters will further increase for the addition of coarse RCA at a dry state that increases. Which suggests a mix that is stiffer and more viscous to the point where it was impossible to evaluate the mixes when the content of RCA was 80% and 100% (Ait Mohamed Amer et al., 2016; Dhir Obe et al., 2019). For this reason, it's suggested that in the SCC production there is no use of RA in a dry state (Dhir Obe et al., 2019; Kebaïli, Mouret, Arabi, & Cassagnabere, 2015).

In figure 24 are the yield stress and plastic viscosity presented for an increasing content of SSD RCA and a decreasing W/C ratio.

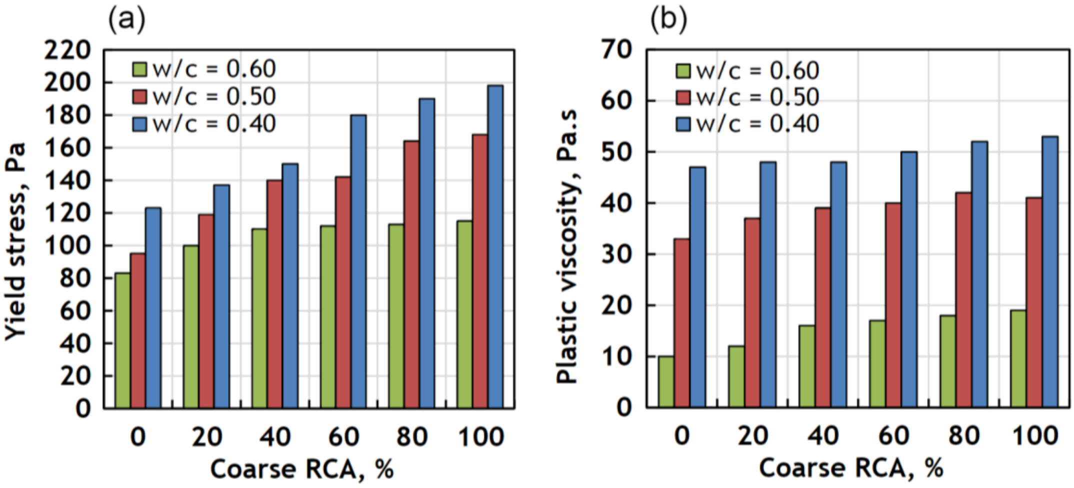

*Figure 24: (a) Yield stress (b) Plastic viscosity wint increasing SSD RCA and different ratios for W/C factor(Ait Mohamed Amer et al., 2016)*

As the W/C ratio decreases, both properties increase significantly and further increase with the content of RCA that increases. The surface that is rougher with the SSD RCA that is incorporated has a greater enhancement as the content of the effective water decreases (Dhir Obe et al., 2019; Güneyisi, Gesoglu, Algın, & Yazıcı, 2016; Iris, Belen, Fernando, & Diego, 2017). Part of the increasing yield stress of concretes with dry coarse RCA can be compensated for by adding high-range water-reducing admixtures but it won't do anything for the plastic viscosity (Ait Mohamed Amer et al., 2016; Dhir Obe et al., 2019). All these previous conclusions were drawn when concrete was still in its fresh state, however when looking at the state after 15 minutes, there is little variation. This suggests an equivalent effective content of water and as the time proceeded, an increase in the plastic viscosity and yield stress was observed due to the absorption of the mixing water by the fine RCAs.

### 5.1.3 Stability

Freshly mixed concrete must always be stable in addition to having good workability. This is necessary so that all constituent materials remain a uniform whole while the concrete sets. Segregation of the constituents and bleeding are two stable-related challenges that can crop up. They can both influence the performance of the concrete in both the mechanical and durability properties, as well as the performance in its cured state. With an increase in the content of RA, it was found by (Dhir Obe et al., 2019; Koulouris et al., 2004; Kutegeza & Alexander, 2004; Yanagibashi, Yonezawa, Arakawa, & Yamada, 2002) that bleeding was lower of equivalent as with concrete with NA. Magnitude will appear to decrease as the RA’s water uptake increases (Dhir Obe et al., 2019; Yang et al., 2008). An enhanced stability could be noticed when the content of RA increased, as the segregation decreased. This was promoted by the use of FA and is more likely to arise in SCC (Carro-López et al., 2015; Dhir Obe et al., 2019; Dhir et al., 1999; S. C. Kou & Poon, 2009). But partially replacing NA with RA has also been observed to reduce the stability (Debieb & Kenai, 2008; Dhir Obe et al., 2019; M C Limbachiya, Leelawat, & Dhir, 1998; C. S. Poon, Kou, & Lam, 2007). The moisture state of the RA is partly the cause of this. (Dhir Obe et al., 2019; Ismail & Ramli, 2014; M C Limbachiya et al., 1998; C. S. Poon et al., 2007) observed that in the presence of SSD RA bleeding can occur, which can lead to a feeble mechanical bond, caused by the increase of the W/C factor in the ITZ between the cement paste and the RA. This can take place when a compensation for water is used during the mixing, where the total absorption capacity of RA is compensated for. A more or less 25% increase in the rate of bleeding was observed under these circumstances when mixes were used with a replacement level of 100% of coarse RCA due to the little time RA was given to absorb this compensating water (Dhir Obe et al., 2019; C. S. Poon et al., 2007). This led to a W/C ratio that was initially higher and effective. With passing time, this greater bleeding was compensated for to a point at with there was insignificant difference between the concrete with RCA and that with NA. Although many studies show that the absorption of the mixing water can be prevented by using RA in a SSD state, only a portion of that absorption capacity of the RAs will be compensated (Dhir Obe et al., 2019; Miren Etxeberria, Gonzalez-Corominas, & Pardo, 2016). This water content should actually be equal to that what RA absorbs until the casting process to ensure an adequate workability.

### 5.1.4 Air content

To measure the fresh concrete mixes’ air content, a method is used that is performed on vibrated samples that also allow an assessment of the potential porosity of the cementitious concrete. When it comes to the impact of the addition of coarse RA on the concrete’s air content, the findings are somewhat contradictory (Assaad & Daou, 2017; Dhir Obe et al., 2019). With an increase in the content of RA, many noticed a slight increase (Andal et al., 2016; Mohammed Seddik & Ryoichi, 2010; A. Rao et al., 2007) et al., while few others observed a decrease in the air content (Casuccio, Torrijos, Giaccio, & Zerbino, 2008; Ferreira et al., 2011; Radonjanin et al., 2010; K. K. Sagoe-Crentsil, Brown, & Taylor, 2001). From the literature, it could be deduced that in the production of RAC with the addition of oven-dry RA a slightly higher amount of air is trapped than for the concrete that is made with NA. If concrete has to be tested that contains more porous aggregates, the test method to determine the amount of air will be less adequate (Dhir Obe et al., 2019; Holm & Bremner, 2000). The attached mortar on the RCAs can also be a factor that potentiates the entrapped air. Higher contents of air were reported for mixes that contained RCAs that came from multiple recycling stages (Dhir Obe et al., 2019; S. B. Huda & Alam, 2014). The RCA's progressively increased roughness can lead to an increased content of entrapped air during the RAC's compaction process. An increase in the content of air can be noticed for mixes that contain an increased content of fine RA (Dhir Obe et al., 2019; L. Evangelista & de Brito, 2007; Jacobsen, Rommetvedt, & Gjengstø; Amnon Katz, 2003; Wegen & Haverkort, 1998). With the addition of coarse RA fractions, the air content could increase even further, whereas the content of air was 8.2%-8.5% when completely replacing both of the natural size fractions (Dhir Obe et al., 2019; Jacobsen et al.). This was due to the fine RA's higher porosity and angularity compared to that of NA, where the latter provides a decrease in the vibrated fresh concrete's packing density and triggers a larger entrapment of air. Concrete exposed to freeze-thaw cycles often have air-entrained additives, studies conducted on the use of these additives in the production of concrete with RAs found that the presence of RA did not affect their effect (Dhir Obe et al., 2019).

### 5.1.5 Fresh density

The density of the concrete will decrease as the content of RCA in the concrete increases (Dhir Obe et al., 2019; M. Etxeberria, Vázquez, et al., 2007; Verian et al., 2018). A greater decrease of this property is seen when both the fine and coarse natural aggregates are replaced with RA (Dhir Obe et al., 2019; Jacobsen et al.; S. C. Kou & Poon, 2009). It is the result of the relative lighter attached mortar that is present of material that is porous and ceramic (Dhir Obe et al., 2019; T. C. Hansen, 1992; Nixon, 1978). When RCA has a lower specific gravity, the concrete containing RCA will have lower density (Verian et al., 2018). But if the replacement level for NA is up to 50%, the density of the concrete will not be significantly affected (Marinković et al., 2010; Verian et al., 2018). If that replacement level is increased to 100% coarse RA, the concrete will have a density that is 1% to 7% lower than the concrete with natural aggregates, with an average of 4% (Dhir Obe et al., 2019).

### 5.1.6 Moisture content

Since the water absorption of natural aggregates is often low, the moisture content is usually ignored. However, this should be taken into account when using RA as they do have a potential impact on the concrete's fresh and hardened properties. The moisture content is dependent on the constituent material's porosity, which for RCA is amplified by the content of the attached mortar. If RCA is used in the SSD state, the mixing water's excessive absorption can be avoided and reasonable workability can be maintained (Dhir Obe et al., 2019; T. C. Hansen, 1992). (Dhir Obe et al., 2019; Ferreira et al., 2011) did a comparison of mixes with RAs that were pre-saturated and mixes where the water compensation approach was used. Making mixes with RCA that hade more predictable levels of workability and slight improved mechanical behavior can be possible when using the latter method in comparison to the former one. Two factors explain this enhancement. Firstly, the surface and pores of the RAs have a greater envelopment which improves the mechanical bond in the ITZ. Secondly, the water absorption capacity of the aggregates is not fully compensated for, which means that the mixes, with passing time, have a slightly lower effective W/C factor. Several studies by Tam (V. W. Y. Tam et al., 2005; V. W. Y. Tam & Tam, 2007, 2008) evaluated another perspective of mixing. The mixing procedure was divided into two different stages, causing to benefit the RAC's mechanical performance. Dividing the mixing process into two stages (TSMA) happened as follows: along with part of the mixing water the aggregates are introduced first, this will ensure that some of that water is absorbed by the aggregates, cement is then added after a certain period along with the rest of the mixing water. This resulted in mixes where the absorption capacity of the RAs is partly or fully compensated for. Furthermore, the surface of the RAs will be more enveloped effectively with the cement paste, which provides an improved ITZ and a lower loss of compressive strength, or in the study by (Guneyisi et al., 2014) even a gain in strength. If the binder would be introduced at a later time in the mixing procedure, after aggregates have absorbed the water it would then envelop them end thus act as a pore sealant (M B Leite, 2001; A. M. Neville, 1995). The RA's moisture state at the start of the mixing process, even when the total content of water is the same, will have a significant impact on the concrete's mechanical performance. The comparison made by (C. S. Poon, Shui, Lam, et al., 2004) between the use of air-dried RCA and SSD RCA stated that there was some bleeding around the particles for SSD RCA, and therefor decreased the mechanical bond in the ITZ. In some cases, the mechanical performance could be enhanced by increasing the level of the RA replacement, according to (Dhir Obe et al., 2019; N Y Ho, 2013; Ridzuan, Ibrahim, Ismail, & Diah, 2005). The partly dry RA reduces the effective W/C ratio, and this in turn causes this compressive strength increase for mixes where the content of initial free water is the same as that of the conventional concrete. The free mix water will over time be absorbed by the uncompensated RA, leading to a cementitious matrix with a lower effective W/C factor, which in turn leads to a better release of temperature during the hydration in the concrete (Koenders, Pepe, & Martinelli, 2014), a porous microstructure that is finer (García-González, Rodríguez-Robles, Juan-Valdés, Pozo, & Guerra-Romero, 2015; Gonzalez-Corominas & Etxeberria, 2016) and a compressive strength that is higher (J A Carneiro, 2014).

## 5.2 Lab tests

### 5.2.1 Mix design

#### 5.2.1.1 Mix design of the concrete

In order to be able to judge the results of the tests, the properties of the concrete and aggregates must be reviewed. The literature study of this work has already clearly shown that the properties determine the concrete. The mix design that was used for these lab tests can be seen in Table 1.

*Table 1: Mix design lab tests*

| Concrete mix design | | | |
|---|---|---|---|
| Design specifications | | Material properties | |
| Exposure class | M60 | Binder [kg/m³] | 346 |
| Strength class | C30/37 | Free water [kg/m³] | 156 |
| Slump class | S4-200mm | Air [%] | 2,00 |
| Air entrainer | No | Water/binder ratio | 0,45 |

The binder that was used, was Norcem standard FA. This is standard cement that has FA incorporated. This cement is fully adapted to the climate conditions of Norway. Given the geographical location and the known weather conditions, the lab tests that are carried out in Norway have to be done differently than in Belgium. As an example, in Norway, the freeze-thaw cycles must be taken more into account. The concrete is always protected with foils during the curing process.

A fixed W/B ratio was established in advance and the amount of free water was calculated on the basis of this.

#### 5.2.1.2 Bland in % of RCA and NA

In order to investigate the influence of the recycled aggregates on the concrete, samples were made with 3 different amounts of those aggregates. To make comparisons with common concrete, the first replacement level was set at 0%. Thus, the concrete contains 100% natural aggregates. The second type of samples were made with a replacement level of 5% to 20% recycled aggregates. And finally, the samples with the greatest number of recycled aggregates contain a replacement level of 20% to 60%. All tests further described in this section are divided into these three categories of aggregate quantity.

### 5.2.2 concrete properties

#### 5.2.2.1 Density

In the literature study that was previously discussed, it could be noted that the density of the concrete samples can say a lot about the performance of the concrete. There are many properties that influence this density. For samples that were used to measure the compressive strength, the calculation of the sample's density is shown in annex 1. The density can be calculated using the following formula: $density\ \left[\frac{kg}{m^3}\right] = \frac{mass\ [kg]}{volume\ [m^3]}$

The arrows next to the values indicate the comparison with the control concrete where no use was made of recycled concrete aggregates. It indicates whether the value has increased or decreased compared to the control concrete. The development of the density after 3 and 28 days can be seen in the figures 25 and 26.

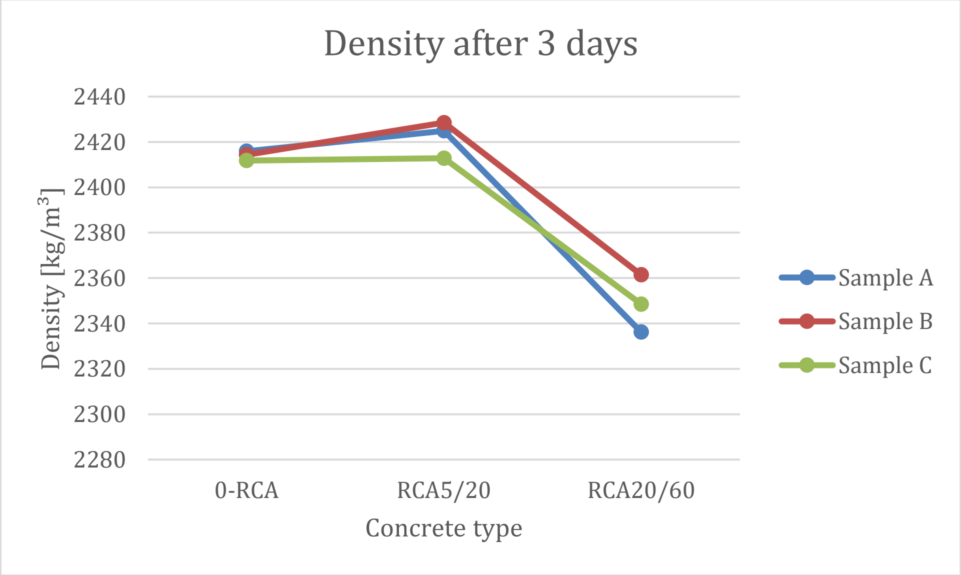

*Figure 25: Correlation between density and amount of recycled aggregates after 3 days*

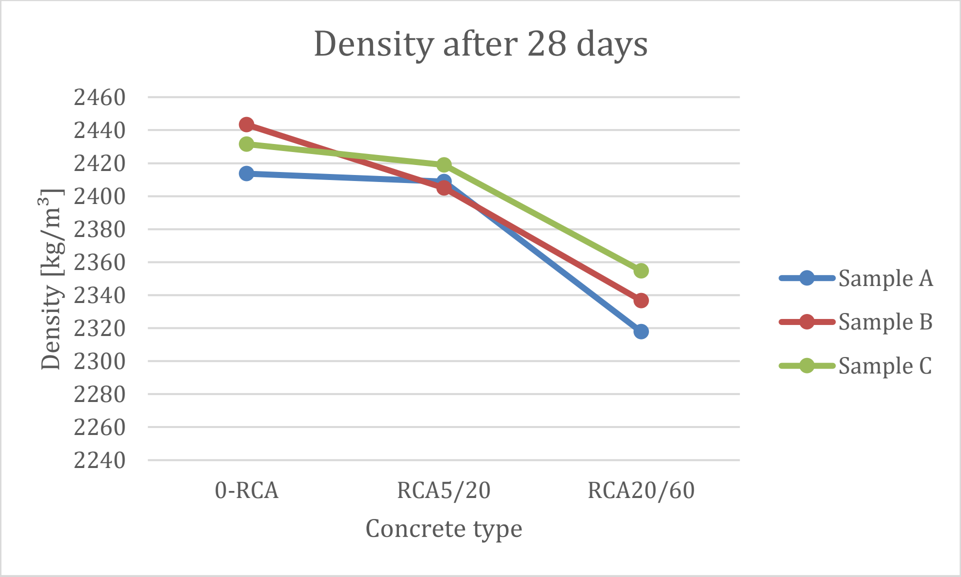

*Figure 26: Correlation between density and amount of recycled aggregates after 28 days*

For the concrete that contained 5% to 20% RCA, the density first increased, whereafter it decreased. The concrete with 20% to 60% RCA showed an immediate decrease of the density. From this it can be deduced that the density thus decreases with time and the number of recycled aggregates. It has already been stated in section 5.1.5 that the increase in RCAs will cause a decrease in density and this is thus confirmed here. The statement that was made in section 5.1.5 that a replacement level of 50% of coarse RCA will not significantly affect the density is invalidated. There was also a statement that said that the loss of density for concrete containing 100% RCA would have an average value of 4%. If the losses are calculated for this lab test for concrete with the maximum amount of RCA, the average is:

After 3 days: $\frac{3{,}3+2{,}2+2{,}62}{3} = 2{,}71\ kg/m^3$

After 28 days: $\frac{3{,}97+4{,}36+3{,}16}{3} = 3{,}83\ kg/m^3$

The big difference between the two is probably that the concrete takes time to reach its final properties. It is known from the literature study that the use of FA also ensures that the properties need more time to develop. The value after 28 days is very close to the average value indicated in the study that was done in the literature, where a replacement level of 100% was used instead of a maximum of 60%.

When observing the shrinkage of the concrete, which will be discussed later, the density of the concrete was also measured. The development of the density in time for the three categories can be seen in the figures 27 to 29, the results can be found in annex 3.

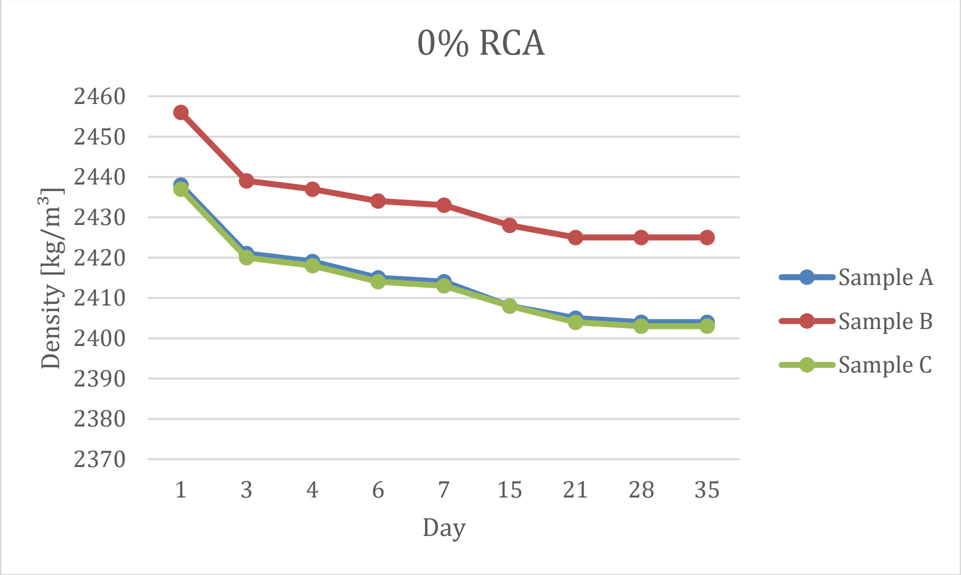

*Figure 27: Development of density in time for concrete with a replacement level of 0%*

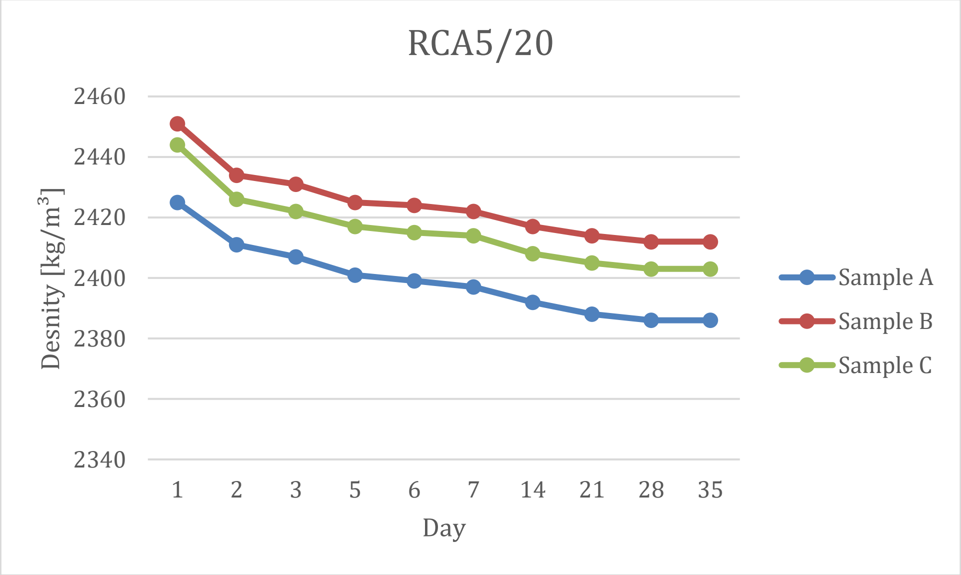

*Figure 28: Development of density in time for concrete with a replacement level of 5% - 20%*

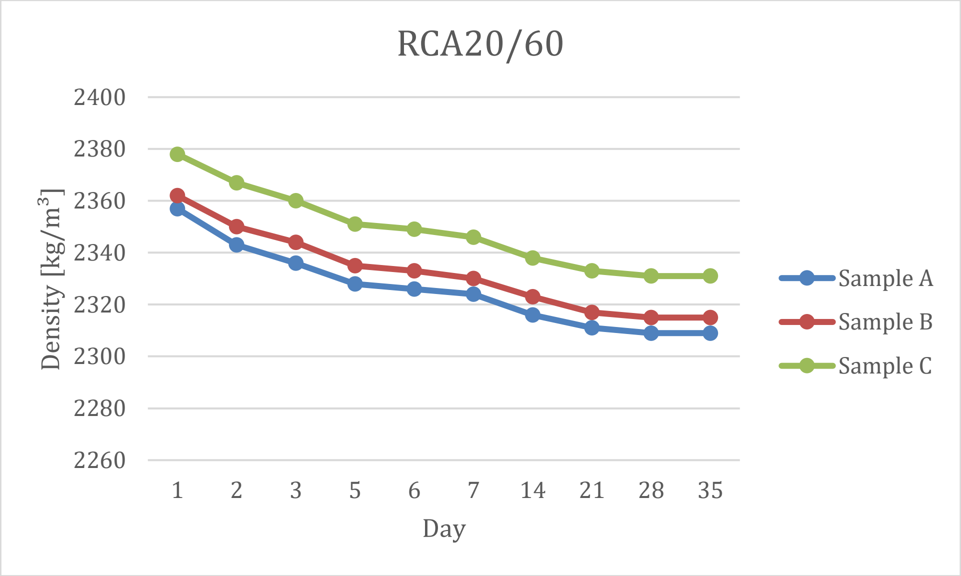

*Figure 29: Development of density in time for concrete with a replacement level of 20% - 60%*

It can be deduced from these figures that the decrease in densit accelerates with the increase in the amount of recycled aggregates. This is in line with the findings from the literature.

#### 5.2.2.2 Compressive strength

The compressive strength of the samples was tested at 3 days and 28 days. The values that were observed are summarized in figure 30 and the exact results can be found in annex 2. The concrete's compressive strength is strongly influenced by the mix design since it is dependent on the properties of the used aggregates. It can be noted from the table that the compressive strength values decrease as the amount RCA increases. The decrease of the strength will be more pronounced for mixes with a W/C ratio that is lower. As mentioned in section 4.2.2, the compressive strength of concrete with RCA will have a development rate that is higher than concrete with a replacement level of 0%. The values in the table do not confirm this.

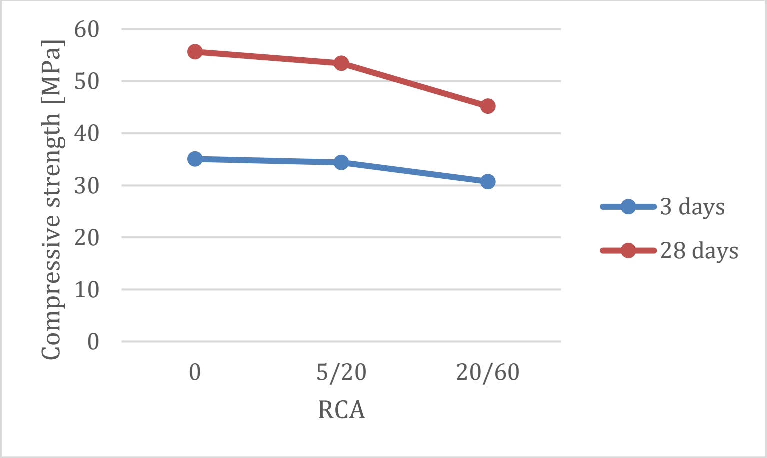

*Figure 30: Development of the compressive strength after (red) 3 days (bleu) 28 days in relation to the content of RCA*

The concrete with an RCA amount of 0% has an average increase of 20.59 MPa after 25 days. According to the statement of the literature, the difference between compressive strengths for an increase in the amount of RCA should be bigger. The strength difference for the concrete with 5% - 20% RCA is 19,07 MPa and is less than for the first one. If the development rate was higher, this difference should be bigger. For a replacement level of 20% - 60%, this difference is even less, namely 14,46 MPa. This shows the complete opposite of the statement.

The overall performance of the RAC will decrease as the amount of RA increases. If 28 days was effectively the day on which all concrete reached its highest strength, these values are in line with that. But since FA is used in the cement, the final strength is not reached until later. The concrete can now only be judged on the rate of development, which is less here instead of more.

The inferior properties of RCA are the main cause of the lower strength. A blend of SF and MK can compensate this because they can improve the microstructure's refinement of the pore size. The quality of the RCA's has a huge impact on the compressive strength. This could be another option to improve these values. Changing the mixing process to a TSMA could also help to enhance the values of these tests.

### 5.2.2.3 Chloride migration

To test the penetration of the chloride, the TCP was measured for the different samples. The observed values can be found in Table 2.

*Table 2: Chloride migration test*

| | | Coulomb [Q] | Chloride penetration [mm] |
|---|---|---|---|
| REF RCA 0% | A | 1431 | 12,2 |
| | B | 2158 | 12,6 |
| | C | 2255 | 14,5 |
| Ref RCA 5% - 20% | A | 1783 (↑) | 9,6 (↓) |
| | B | 2642 (↑) | 16,8 (↑) |
| | C | 2814 (↑) | 17,6 (↑) |
| Ref RCA 20% - 60% | A | 3107 (↑) | 21,0 (↑) |
| | B | 3931 (↑) | 22,1 (↑) |
| | C | 3907 (↑) | 27,1 (↑) |

Section 4.2.12 mentioned that the chloride penetration depth increases with RAC in comparison to NAC. The values in Table 2 confirm this. The graph that was used to indicate the relation between the TCP and the coarse RA content is repeated in figure 31.

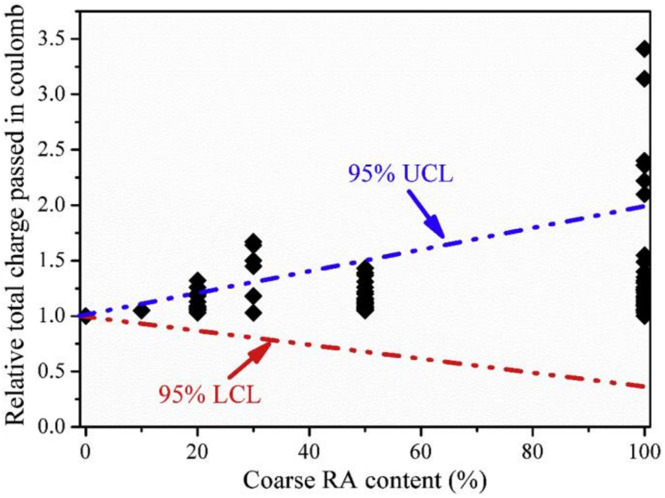

*Figure 31: The total charge passed in relation to the content of coarse RA (Andreu & Miren, 2014; Kapoor, Singh, & Singh, 2016; Matias, Brito, Rosa, & Pedro, 2014) et al.*

When the values in Table 2 are compared with the above figure, it can be concluded that the values from the table are clearly higher than 95% UCL from figure 31. Section 4.2.12 mentioned that the resistance to chloride penetration of the RAC decreases when the W/C factor increases. In order to continue with the same concrete mix but to obtain a higher value for the resistance, the W/C ratio can be reduced. But the curing age of the concrete should be taken into account. The chloride resistance improves with the concrete's curing age. Another way to improve these values is to use RAs with a parent concrete that has a higher strength, due to the water absorption capacity that is lower. Also, mineral admixtures could be used to improve the chloride penetration resistance. The last option is to use the $CO_2$ treatment that is very effective to improve this property because it will reduce the water absorption capacity.

#### 5.2.2.4 Shrinkage

For the shrinkage test, different samples with different degrees of RCA amounts were made. The shrinkage was measured regularly. The different values can be found in annex 3 a to b. How fast the shrinkage increased can be derived in the figures 32 to 34.

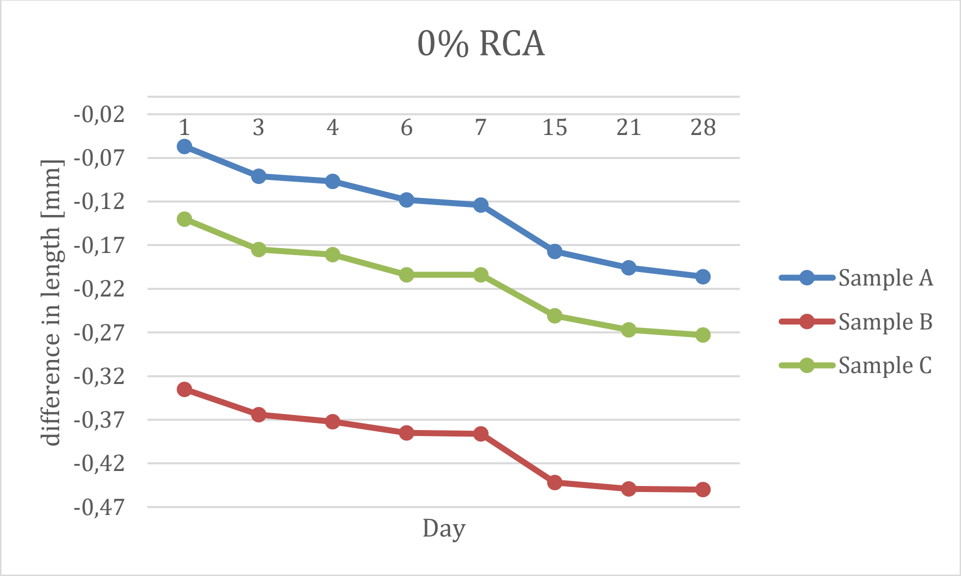

*Figure 32: Increase in shrinkage with time for concrete with a replacement level of 0%*

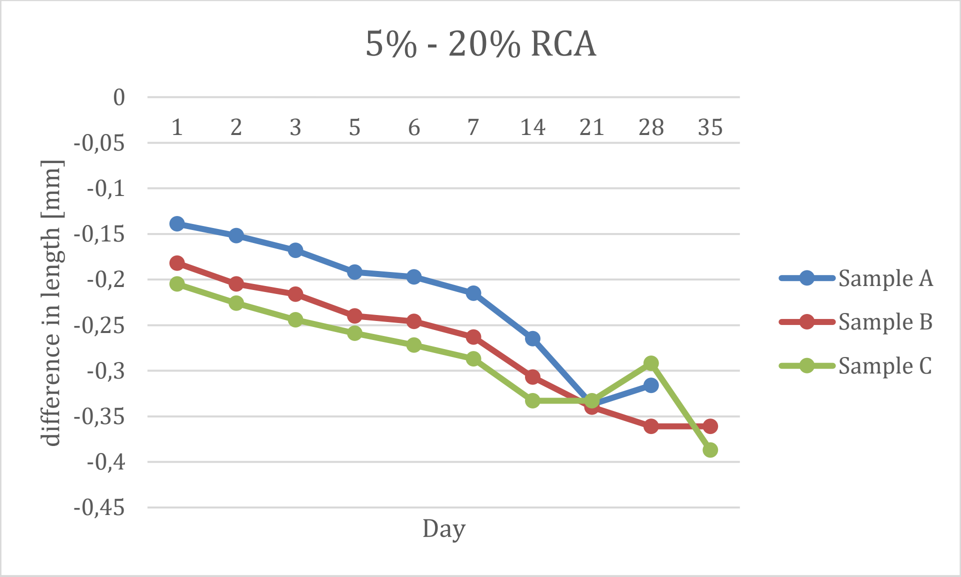

*Figure 33: Increase in shrinkage with time for concrete with a replacement level of 5% - 20%*

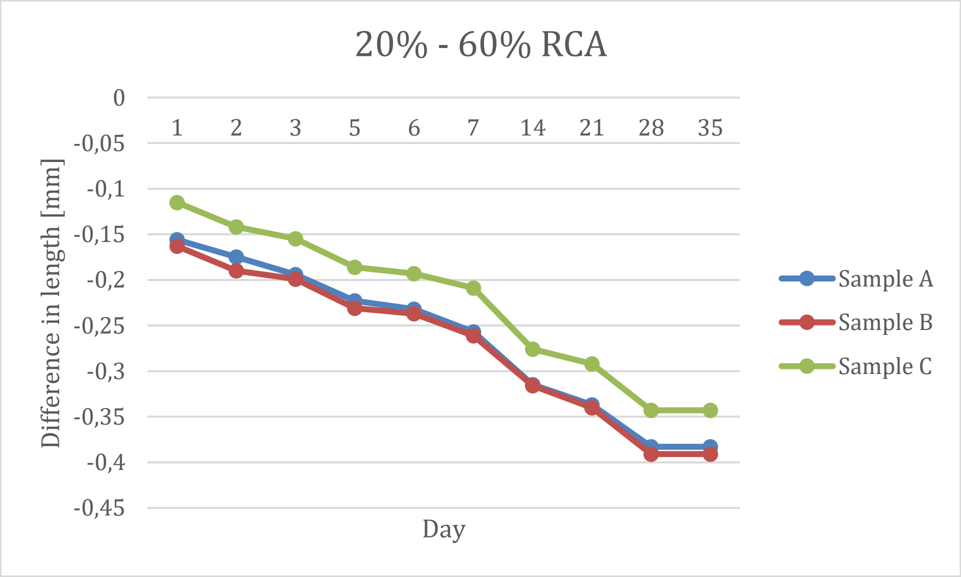

*Figure 34: Increase in shrinkage with time for concrete with a replacement level of 20% - 60%*

The overall shrinkage between two measurements will be greater when more RCA is used. As mentioned in section 4.2.16, shrinkage is time dependent and will increase as the time goes by. A statement in this section reported that a replacement level of 20% would not significantly influence the shrinkage. But the values of annex 3 show an increase in shrinkage development.

Shrinkage is influenced by the aggregates rock type, the particle size distribution, etc. This is an aspect that can easily been changed in these lab tests.

## 5.3 Future research

In section 5.1.1 three methods were discussed to improve the workability of the concrete. Since the first one was used in the lab tests, an idea for lab tests in the future might be to try the other two.

The first one is the water compensation during the process of mixing. Water is added into the mix with the amount that RA absorbs until the mixing process is completed. This amount is thus dependent on the RA's water absorption capacity. This means that the water will only compensate for a certain part of the total water absorption capacity and it will not put RA in an SSD state. It is suggested that the mixing is done in a TSMA way so that before the rest of the constituents is added, the water absorption can take place. It is a practical and effective method that reaches the level of workability similar to concrete with natural aggregate without the W/C ratio that needs to be altered. The bond between the hardened cement and the RA's will be enhanced with this method.

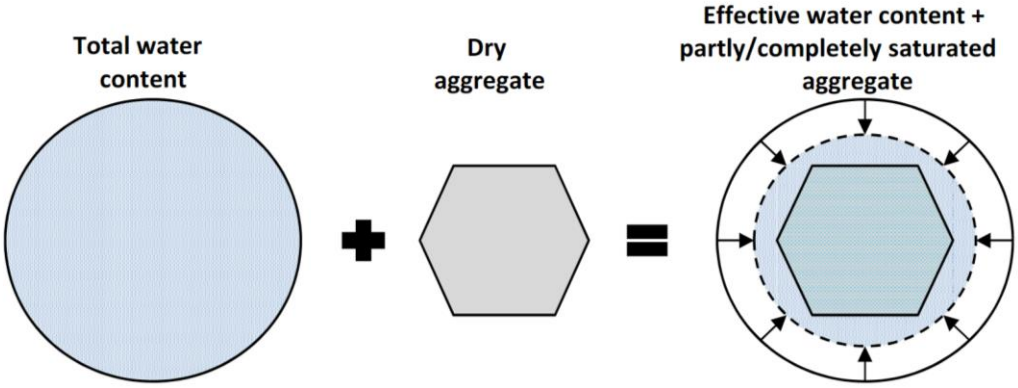

*Figure 35: Effective water content (Dhir Obe et al., 2019)*

The second method uses superplasticisers where the mix has a constant W/C factor. From a point of view for the mechanical performance, this method has encouraging outcomes in studies that were done. However, due to the RA's water absorption, the SPs can lose their effectiveness. Figure 35 shows the behaviour of the content of water in in concrete. Dependent on the time they are in the water and the water absorption capacity, the (partly) dry RAs will absorb part of the water. A reduction over time in the W/C ratio can be observed if (semi-)dry RA is added into the mix, it will also reduce the concrete's consistence. That is why there is an addition of extra water to increase the W/C ratio and so improve the consistence. This method will lead to a possible enhanced mechanical behaviour and a lower level of porosity of the hardened concrete.

The high workability losses in the initial phase of mixtures with large amounts of (partly) dry RA can be compensated with SPs, but this cannot be done so much over a longer period of time. Therefore, it is recommended from a practical point of view that a water compensation approach should be used.

# 6 Conclusion

This thesis starts with the following research question: Why would we use recycled aggregates in concrete instead of natural aggregates? It begins with a very extensive literature study in which the advantages and disadvantages are first investigated. Due to the insufficient recycling procedures of the CDW recycling plants, a wide range of RAs are produced that sometimes even have an unknown composition. Because of this, the physical properties of the RA often show great variation and inconsistency, which makes them considered low quality and are therefore used less.

This work continues with a useful source of information on properties of recycled aggregates that decide the durability of the concrete. Here we could find strong relations between the compressive strength of the concrete and the coarse aggregate's water absorption capacity and its porosity, between the splitting tensile strength of the concrete and the coarse aggregate's porosity and between the concrete's flexural strength and the coarse aggregate's crushing value, porosity and attached mortar. However, different studies do not always agree with each other about the fracture properties. It can be stated that all the concrete's mechanical properties have a strong relationship with the durability properties.

The following section provided opportunities that could improve and sometimes remove the challenges that the use of recycled aggregates in concrete causes. Supplementary cementitious materials such as fly ash, silica fume and metakaolin are recommended to be used since they have proven to enhance the RCA concrete's quality. By coating the surface of the RA with SF, SCMs and an admixture of inorganic paste, the RAC will show an enhanced packing density and a better behavior in durability in comparison to concrete with RA that was not treated. The batched concrete's quality is influenced by the RCA's treatment prior to the mixing.

This thesis ends with a discussion of the lab results that were obtained from the students from the Arctic University of Norway.

The effective widespread use of recycled aggregates is still a long way off and many studies still need to be undertaken to bring a consistent concrete to the market. Further research is definitely needed to improve the quality so that it may become the norm in the future.

# Annex

1. Density

| 0% RCA | | | | | | |
|---|---|---|---|---|---|---|
| | **3 days** | | | **28 days** | | |
| | A | B | C | A | B | C |
| Volume [cm³] | 3413,86 | 3440,45 | 3409,96 | 3395,64 | 3396,86 | 3408,17 |
| Mass [g] | 8247,4 | 8306,6 | 8224,3 | 8195,8 | 8299,8 | 8287,1 |
| Density [kg/m³] | 2415,86 | 2414,4 | 2411,84 | 2413,63 | 2443,37 | 2431,54 |
| RCA5/20 | | | | | | |
| | **3 days** | | | **28 days** | | |
| | A | B | C | A | B | C |
| Volume [cm³] | 3396,67 | 3398,16 | 3392,35 | 3427,18 | 3396,83 | 3415,64 |
| Mass [g] | 8236,6 | 8252,5 | 8185,2 | 8255,3 | 8169,3 | 8262,1 |
| Density [kg/m³] | 2424,90(↑) | 2428,52(↑) | 2412,84(↑) | 2408,77(↓) | 2404,98(↓) | 2418,90(↓) |
| RCA20/60 | | | | | | |
| | **3 days** | | | **28 days** | | |
| | A | B | C | A | B | C |
| Volume [cm³] | 3388,28 | 3354,57 | 3402,59 | 3419,39 | 3381,50 | 3375,65 |
| Mass [g] | 7915,6 | 7921,5 | 7991,1 | 7925,5 | 7901,8 | 7949 |
| Density [kg/m³] | 2336,17(↓) | 2361,41(↓) | 2348,53(↓) | 2317,81(↓) | 2336,77(↓) | 2354,81(↓) |

2. Compressive strength

| | | Sample A | Sample B | Sample C | average |
|---|---|---|---|---|---|
| 0% RCA | 3 days | 34,66 MPa | 35,48 MPa | 35,06 MPa | 35,07 MPa |
| | 28 days | 55,21 MPa | 56,42 MPa | 55,36 MPa | 55,66 MPa |
| 5% - 20% RCA | 3 days | 33,33 MPa | 35,46 MPa | 34,39 MPa | 34,39 MPa (↓) |
| | 28 days | 54,2 MPa | 52,71 MPa | 53,48 MPa | 53,46 MPa (↓) |
| 20% - 60% RCA | 3 days | 30,76 MPa | 30,35 MPa | 31,12 MPa | 30,74 MPa (↓) |
| | 28 days | 45,06 MPa | 44,66 MPa | 45,88 MPa | 45,2 MPa (↓) |

## 3. Shrinkage

### a. 0% RCA

| Day/ Sample | | A | Δ | B | Δ | C | Δ |
|---|---|---|---|---|---|---|---|
| **0** | Density [kg/m$^3$] | 2438 | | 2456 | | 2437 | |
| **1** | Density [kg/m$^3$] | 2438 | 0 | 2456 | 0 | 2437 | 0 |
| | $\Delta l$ [mm] | -0.057 | | -0.335 | | -0.14 | |
| **3** | Density [kg/m$^3$] | 2421 | 17 | 2439 | 17 | 2420 | 17 |
| | $\Delta l$ [mm] | -0.091 | 0.034 | -0.364 | 0.029 | -0.175 | 0.035 |
| **4** | Density [kg/m$^3$] | 2419 | 2 | 2437 | 2 | 2418 | 2 |
| | $\Delta l$ [mm] | -0.097 | 0.006 | -0.372 | 0.008 | -0.181 | 0.006 |
| **6** | Density [kg/m$^3$] | 2415 | 4 | 2434 | 3 | 2414 | 4 |
| | $\Delta l$ [mm] | -0.118 | 0.021 | -0.385 | 0.013 | -0.204 | 0.023 |
| **7** | Density [kg/m$^3$] | 2414 | 1 | 2433 | 1 | 2413 | 1 |
| | $\Delta l$ [mm] | -0.124 | 0.006 | -0.386 | 0.001 | -0.204 | 0 |
| **15** | Density [kg/m$^3$] | 2408 | 6 | 2428 | 5 | 2408 | 5 |
| | $\Delta l$ [mm] | -0.177 | 0.053 | -0.442 | 0.056 | -0.251 | 0.047 |
| **21** | Density [kg/m$^3$] | 2405 | 3 | 2425 | 3 | 2404 | 4 |
| | $\Delta l$ [mm] | -0.196 | 0.019 | -0.449 | 0.007 | -0.267 | 0.016 |
| **28** | Density [kg/m$^3$] | 2404 | 1 | 2425 | 0 | 2403 | 1 |
| | $\Delta l$ [mm] | -0.206 | 0.010 | -0.45 | 0.001 | -0.273 | 0.006 |
| **35** | Density [kg/m$^3$] | 2404 | 0 | 2425 | 0 | 2403 | 0 |
| | $\Delta l$ [mm] | -0.206 | 0 | -0.45 | 0 | -0.273 | 0 |

b. 5% - 20% RCA

| **Day/ Sample** | | **A** | **Δ** | **B** | **Δ** | **C** | **Δ** |
|---|---|---|---|---|---|---|---|
| **0** | Density [kg/m³] | 2425 | | 2451 | | 2444 | |
| **1** | Density [kg/m³] | 2425 | 0 | 2451 | 0 | 2444 | 0 |
| | Δl [mm] | -0,139 | | -0,182 | | -0,205 | |
| **2** | Density [kg/m³] | 2411 | 14 | 2434 | 17 | 2426 | 18 |
| | Δl [mm] | -0.152 | 0.013 | -0.205 | 0.023 | -0.226 | 0.021 |
| **3** | Density [kg/m³] | 2407 | 4 | 2431 | 3 | 2422 | 4 |
| | Δl [mm] | -0.168 | 0.016 | -0.216 | 0.011 | -0.244 | 0.018 |
| **5** | Density [kg/m³] | 2401 | 6 | 2425 | 6 | 2417 | 5 |
| | Δl [mm] | -0.192 | 0.024 | -0.240 | 0.024 | -0.259 | 0.015 |
| **6** | Density [kg/m³] | 2399 | 2 | 2424 | 1 | 2415 | 2 |
| | Δl [mm] | -0.197 | 0.005 | -0.246 | 0.006 | -0.272 | 0.013 |
| **7** | Density [kg/m³] | 2397 | 2 | 2422 | 2 | 2414 | 1 |
| | Δl [mm] | -0.215 | 0.018 | -0.263 | 0.017 | -0.287 | 0.015 |
| **14** | Density [kg/m³] | 2392 | 5 | 2417 | 5 | 2408 | 6 |
| | Δl [mm] | -0.265 | 0.050 | -0.307 | 0.044 | -0.333 | 0.046 |
| **21** | Density [kg/m³] | 2388 | 4 | 2414 | 3 | 2405 | 3 |
| | Δl [mm] | -0.337 | 0.072 | -0.340 | 0.033 | -0.292 | -0.041 |
| **28** | Density [kg/m³] | 2386 | 2 | 2412 | 2 | 2403 | 2 |
| | Δl [mm] | -0.316 | -0.021 | -0.361 | 0.021 | -0.387 | 0.095 |
| **35** | Density [kg/m³] | 2386 | 0 | 2412 | 0 | 2403 | 0 |
| | Δl [mm] | -0.316 | 0 | -0.361 | 0 | -0.387 | 0 |

c. 20% - 60% RCA

| **Day/ Sample** | | **A** | **Δ** | **B** | **Δ** | **C** | **Δ** |
|---|---|---|---|---|---|---|---|
| **0** | Density [kg/m³] | 2357 | | 2362 | | 2378 | |
| **1** | Density [kg/m³] | 2357 | 0 | 2362 | 0 | 2378 | 0 |
| | Δl [mm] | -0.156 | | -0.163 | | -0.115 | |
| **2** | Density [kg/m³] | 2343 | 14 | 2350 | 12 | 2367 | 11 |
| | Δl [mm] | -0.175 | 0.019 | -0.190 | 0.027 | -0.142 | 0.027 |
| **3** | Density [kg/m³] | 2336 | 7 | 2344 | 6 | 2360 | 7 |
| | Δl [mm] | -0.194 | 0.019 | -0.199 | 0.009 | -0.155 | 0.013 |
| **5** | Density [kg/m³] | 2328 | 8 | 2335 | 9 | 2351 | 9 |
| | Δl [mm] | -0.223 | 0.029 | -0.231 | 0.032 | -0.186 | 0.031 |
| **6** | Density [kg/m³] | 2326 | 2 | 2333 | 2 | 2349 | 2 |
| | Δl [mm] | -0.232 | 0.009 | -0.237 | 0.006 | -0.193 | 0.007 |
| **7** | Density [kg/m³] | 2324 | 2 | 2330 | 3 | 2346 | 3 |
| | Δl [mm] | -0.257 | 0.025 | -0.261 | 0.024 | -0.209 | 0.016 |
| **14** | Density [kg/m³] | 2316 | 8 | 2323 | 7 | 2338 | 8 |
| | Δl [mm] | -0.315 | 0.058 | -0.316 | 0.055 | -0.276 | 0.067 |
| **21** | Density [kg/m³] | 2311 | 5 | 2317 | 6 | 2333 | 5 |
| | Δl [mm] | -0.337 | 0.022 | -0.340 | 0.024 | -0.292 | 0.016 |
| **28** | Density [kg/m³] | 2309 | 2 | 2315 | 2 | 2331 | 2 |
| | Δl [mm] | -0.383 | 0.046 | -0.391 | 0.051 | -0.343 | 0.051 |
| **35** | Density [kg/m³] | 2309 | 0 | 2315 | 0 | 2331 | 0 |
| | Δl [mm] | -0.383 | 0 | -0.391 | 0 | -0.343 | 0 |

# Abbreviations

| | | | |
|---|---|---|---|
| ASR | Alkali-silica reaction | CDW | Construction & demolition waste |
| C-S-H | Calcium silicate hydrate | CTE | Coefficient of thermal expansion |
| FA | Fly ash | GGBFS | Ground granulated blast furnace |
| ITZ | Interfacial transition zone | LA | Los Angeles |
| MK | Metakaolin | MRA | Mixed recycled aggregate |
| NA | Natural aggregate | NAC | Natural aggregate concrete |
| NVC | Normally vibrated concrete | OPC | Ordinary Portland cement |
| PC | Portland cement | RA | Recycled aggregate |
| RAC | Recycled aggregate concrete | RCA | Recycled concrete aggregate |
| RH | Relative humidity | RMA | Recycled masonry aggregate |
| RMC | Reclaimed mortar content | SCC | Self-compacting concrete |
| SCM | Supplementary cementitious materials | SF | Silica fume |
| TCP | Total charge passed | TSMA | Two stage mixing approach |
| VMA | Viscosity modifying agent | WA | Water absorption |

# Works cited

Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A., Fournier, B., & Foo, S. (2008). proposed method for determining the residual mortar content of recycled concrete aggretes. *ASTM, int 5*, 1-12.

Abbas, A., Fathifazl, G., Isgor, O. B., Razaqpur, A. G., Fournier, B., & Foo, S. (2009). Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cement & concrete composites, 31*(8), 555-563. doi:10.1016/j.cemconcomp.2009.02.012

Abd Elhakam, A., Mohamed, A. E., & Awad, E. (2012). Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete. *Construction & building materials, 35*, 421-427. doi:10.1016/j.conbuildmat.2012.04.013

Abdulla, N. A. (2015). Effect of recycled coarse aggregate type on concrete *Journal of Materials in Civil Engineering, 27*. Retrieved from https://ascelibrary.org/doi/full/10.1061/%28ASCE%29MT.1943-5533.0001247?casa_token=ja3LjYXZlXAAAAAA%3AqzXLgTRaRRmQEFczHxYNl29GDHl8o7fmezjqBS5lp5QTCSscE-vrhg6dAJLuZpHM5qftWE95nJIA

ACPA. (2009). Recycling Concrete Pavements. *Engineering Bulletin*.

Adams, M. P., Fu, T., Cabrera, A. G., Morales, M., Ideker, J. H., & Isgor, O. B. (2016). Cracking susceptibility of concrete made with coarse recycled concrete aggregates. *Construction & building materials, 102*, 802-810. doi:10.1016/j.conbuildmat.2015.11.022

Afroughsabet, V., Biolzi, L., & Ozbakkaloglu, T. (2017). Influence of double hooked-end steel fibers and slag on mechanical and durability properties of high performance recycled aggregate concrete. *Composite structures, 181*, 273-284. doi:10.1016/j.compstruct.2017.08.086

Ait Mohamed Amer, A., Ezziane, K., Bougara, A., & Adjoudj, M. H. (2016). Rheological and mechanical behavior of concrete made with pre-saturated and dried recycled concrete aggregates. *Construction & building materials, 123*, 300-308. doi:10.1016/j.conbuildmat.2016.06.107

Ajdukiewicz, A. B., & Kliszczewicz, A. T. (2002). Influence of recycled aggregates on mechanical properties of HS/HPC. *Cement & concrete composites, 24*(2), 269-279. doi:10.1016/S0958-9465(01)00012-9

Ajdukiewicz, A. B., & Kliszczewicz, A. T. (2007). Comparative Tests of Beams and Columns Made of Recycled Aggregate Concrete and Natural Aggregate Concrete. *ACT, 5*(2), 259-273. doi:10.3151/jact.5.259

Akbarnezhad, A., Ong, K. C. G., Zhang, M. H., Tam, C. T., & Foo, T. W. J. (2011). Microwave-assisted beneficiation of recycled concrete aggregates. *Construction and Building Materials, 25*(8), 3469-3479. doi:https://doi.org/10.1016/j.conbuildmat.2011.03.038

Alnahhal, M. F., Alengaram, U. J., Jumaat, M. Z., Alsubari, B., Alqedra, M. A., & Mo, K. H. (2018). Effect of aggressive chemicals on durability and microstructure properties of concrete containing crushed new concrete aggregate and non-traditional supplementary cementitious materials. *Construction & building materials, 163*, 482-495. doi:10.1016/j.conbuildmat.2017.12.106

Amin, A., Hasnat, A., Khan, A. H., & Ashiquzzaman, M. (2016). Residual cementing property in recycled fines and coarse aggregates: occurrence and quantification. *Journal of Materials in Civil Engineering, 28*, 11.

Amirkhanian, A. N. (2012). Properties of functionally graded concrete slabs. *M.S. THESIS*, 100.

Amorim, P., Brito, J. d., & Evangelista, L. (2012). Concrete Made with Coarse Concrete Aggregate: Influence of Curing on Durability. *ACI materials journal, 109*(2), 195. doi:10.14359/51683706

Anastasiou, E., Georgiadis Filikas, K., & Stefanidou, M. (2014). Utilization of fine recycled aggregates in concrete with fly ash and steel slag. *Construction & building materials, 50*, 154-161. doi:10.1016/j.conbuildmat.2013.09.037

Andal, J., Shehata, M., & Zacarias, P. (2016). Properties of concrete containing recycled concrete aggregate of preserved quality. *Construction & building materials, 125*, 842-855. doi:10.1016/j.conbuildmat.2016.08.110

Anderson, D. J., Smith, S. T., & Au, F. T. K. (2016). Mechanical properties of concrete utilising waste ceramic as coarse aggregate. *Construction & building materials, 117*, 20-28. doi:10.1016/j.conbuildmat.2016.04.153

Anderson, K. W., Uhlmeyer, J. S., & Russell, M. (2009). Use of Recycled Concrete Aggregate in PCCP: Literature Search. *Washington State Department of Transportation* Retrieved from https://trid.trb.org/view/902140

Andreu, G., & Miren, E. (2014). Experimental analysis of properties of high performance recycled aggregate concrete. *Construction & building materials, 52*, 227-235. doi:10.1016/j.conbuildmat.2013.11.054

Angulo, S. C., Ulsen, C., Carrijo, P. M., Silva, R. M., Jogn, V. M., & Kahn, H. (2004). Characterization of Brazilian construction and demolition waste coarse recycled aggregate. *International RILEM Conference on the Use of Recycled Materials in Building and Structures*, 87-96.

Asensio, E., Medina, C., Frías, M., & de Rojas, M. I. S. (2016). Characterization of Ceramic-Based Construction and Demolition Waste: Use as Pozzolan in Cements. *J. Am. Ceram. Soc, 99*(12), 4121-4127. doi:10.1111/jace.14437

Aslani, F., Ma, G., Yim Wan, D. L., & Muselin, G. (2018). Development of high-performance self-compacting concrete using waste recycled concrete aggregates and rubber granules. *Journal of cleaner production, 182*, 553-566. doi:10.1016/j.jclepro.2018.02.074

Assaad, J., & Daou, Y. (2017). Behavior of structural polymer-modified concrete containing recycled aggregates. *Journal of adhesion science and technology, 31*(8), 874-896. doi:10.1080/01694243.2016.1235750

ASTM. (2016). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.

Bakharev, T., Sanjayan, J. G., & Cheng, Y. B. (2003). Resistance of alkali-activated slag concrete to acid attack. *Cement and concrete research, 33*(10), 1607-1611. doi:10.1016/S0008-8846(03)00125-X

Barbudo, A., Agrela, F., Ayuso, J., Jiménez, J. R., & Poon, C. S. (2012). Statistical analysis of recycled aggregates derived from different sources for sub-base applications. *Construction & building materials, 28*(1), 129-138. doi:10.1016/j.conbuildmat.2011.07.035

Barra Bizinotto, M., Faleschini, F., Jiménez Fernández, C. G., & Aponte Hernández, D. F. (2017). Effects of chemical admixtures on the rheology of fresh recycled aggregate concretes. *Construction & building materials, 151*, 353-362. doi:10.1016/j.conbuildmat.2017.06.111

Barra, M., & Vázquez, E. PROPERTIES OF CONCRETES WITH RECYCLED AGGREGATES: INFLUENCE OF PROPERTIES OF THE AGGREGATES AND THEIR INTERPRETATION. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 18-30).

Basheer, L., Basheer, P. A. M., & Long, A. E. (2005). Influence of coarse aggregate on the permeation, durability and the microstructure characteristics of ordinary Portland cement concrete. *Construction & building materials, 19*(9), 682-690. doi:10.1016/j.conbuildmat.2005.02.022

Bassani, M., Diaz Garcia, J. C., Meloni, F., Volpatti, G., & Zampini, D. (2019). Recycled coarse aggregates from pelletized unused concrete for a more sustainable concrete production. *Journal of cleaner production, 219*, 424-432. doi:10.1016/j.jclepro.2019.01.338

Bazaz, J. B., Khayati, M., & Akrami, N. (2006). Performance of Concrete Produced with Crushed Bricks as the Coarse and Fine Aggregate. *The Geological Society of London*, 10.

Beltrán, M. G., Barbudo, A., Agrela, F., Galvín, A. P., & Jiménez, J. R. (2014). Effect of cement addition on the properties of recycled concretes to reach control concretes strengths. *Journal of cleaner production, 79*, 124-133. doi:10.1016/j.jclepro.2014.05.053

Bendimerad, A. Z., Rozière, E., & Loukili, A. (2016). Plastic shrinkage and cracking risk of recycled aggregates concrete. *Construction & building materials, 121*, 733-745. doi:10.1016/j.conbuildmat.2016.06.056

Berndt, M. L. (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction & building materials, 23*(7), 2606-2613. doi:10.1016/j.conbuildmat.2009.02.011

Bhikshma, V., & Divya, K. (2012). Study on the permeability of the recycled aggregate concrete using fly ash. *37th conference on our world in concrete and structures*.

Bogas, J. A., Brito, J. d., & Ramos, D. (2016). Freeze-thaw resistance of concrete produced with fine recycled concrete aggregates. *J. Clean. Prod., 115*, 294-306.

Bordelon, A., Cervantes, V., & Roesler, J. R. (2009). Fracture properties of concrete containing recycled concrete aggregates. *Magazine of Concrete Research, 61*(9), 665-670. doi:10.1680/macr.2008.61.9.665

Bovea, M. D., & Powell, J. C. (2016). Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. *Waste Manag, 50*, 151-172. doi:10.1016/j.wasman.2016.01.036

Braga, A. M., Silvestre, J. D., & de Brito, J. (2017). Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *Journal of cleaner production, 162*, 529-543. doi:10.1016/j.jclepro.2017.06.057

Brand, A., Amirkhanian, A., & Roesler, J. (2014). Flexural capacity of full-depth and two-lift concrete slabs with recycled aggregates. *Transp. Res. Rec. J. Transp. Res. , Board 2456*, 64-72.

Brand, A. S., Roesler, J. R., & Salas, A. (2015). Initial moisture and mixing effects on higher quality recycled coarse aggregate concrete. *Construction & building materials, 79*, 83-89. doi:10.1016/j.conbuildmat.2015.01.047

Bravo, M., de Brito, J., Pontes, J., & Evangelista, L. (2015a). Durability performance of concrete with recycled aggregates from construction and demolition waste plants. *Construction & building materials, 77*, 357-369. doi:10.1016/j.conbuildmat.2014.12.103

Bravo, M., de Brito, J., Pontes, J., & Evangelista, L. (2015b). Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. *Journal of cleaner production, 99*, 59-74. doi:10.1016/j.jclepro.2015.03.012

Brito, J. D., Gonçalves, A. P., & Santos, R. (2006). Recycled aggregates in concrete production - multiple recycling of concrete coarse aggregates. *Revista Ingeniería de Construcción, 21*, 33-40.

Butler, L., West, J. S., & Tighe, S. L. (2011). The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement. *Cement and concrete research, 41*(10), 1037-1049. doi:10.1016/j.cemconres.2011.06.004

Buyle-Bodin, F., & Zaharieva, R. (2002). Influence of industrially produced recycled aggregates on flow properties of concrete. *Materials and structures, 35*(8), 504-509. doi:10.1007/BF02483138

C.-S. Poon, Kou, S. C., & Chan, D. (2006). Influence of steam curing on hardened properties of recycled aggregate concrete. *Magazine of Concrete Research, 58*(5), 289-299. doi:10.1680/macr.2006.58.5.289

Cakir, O. (2014). Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. *Construction & building materials, 68*, 17-25. doi:10.1016/j.conbuildmat.2014.06.032

Cakir, O., & Sofyanli, O. O. (2015). Influence of silica fume on mechanical and physical properties of recycled aggregate concrete. *HBRC journal, 11*(2), 157-166. doi:10.1016/j.hbrcj.2014.06.002

Carro-López, D., González-Fonteboa, B., de Brito, J., Martínez-Abella, F., González-Taboada, I., & Silva, P. (2015). Study of the rheology of self-compacting concrete with fine recycled concrete aggregates. *Construction and Building Materials, 96*, 491-501. doi:https://doi.org/10.1016/j.conbuildmat.2015.08.091

Casuccio, M., Torrijos, M. C., Giaccio, G., & Zerbino, R. (2008). Failure mechanism of recycled aggregate concrete. *Construction & building materials, 22*(7), 1500-1506. doi:10.1016/j.conbuildmat.2007.03.032

CCANZ. (2011). Best Practice Guide for the Use of Recycled Aggregates in New Concrete. *Cement and Concrete Association of New Zealand*, 49.

Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011a). Behaviour of recycled aggregate concrete under drop weight impact load. *Construction & building materials, 25*(1), 69-80. doi:10.1016/j.conbuildmat.2010.06.055

Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011b). Influence of field recycled coarse aggregate on properties of concrete. *Materials and structures, 44*(1), 205-220. doi:10.1617/s11527-010-9620-x

Chandra, S. (2004). IMPLICATIONS OF USING RECYCLED CONSTRUCTION DEMOLITION WASTE AS AGGREGATE IN CONCRETE. In *Sustainable Waste Management and Recycling: Construction Demolition Waste* (pp. 104-114).

Chen, A. J., Wang, J., & Ma, Y. (2015). Test of frost resistance for steel fiber rubber recycled concrete. *Acta Mater. Compos. , 32*, 933-941.

Chen, G. M., He, Y. H., Yang, H., Chen, J. F., & Guo, Y. C. (2014). Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures. *Construction & building materials, 71*, 1-15. doi:10.1016/j.conbuildmat.2014.08.012

Chen, P., Wang, J., Wang, L., Xu, Y., Qian, X., & Ma, H. (2017). Producing vaterite by CO2 sequestration in the waste solution of chemical treatment of recycled concrete aggregates. *Cleaner Prod., 149*, 735-742. Retrieved from https://pdf.sciencedirectassets.com/271750/1-s2.0-S0959652617X00085/1-s2.0-S0959652617303748/Peiyuan_Chen_waste_treatment_solution_2017.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEAoaCXVzLWVhc3QtMSJIMEYCIQDNrFZor%2FyyxgUX1R0xzKASmbaD0P5gZEvzomffRwHS7QIhAO5iqmL799AFSsn0ydRMKgAZ1fnZnfe8I05xlFadQmhDKr0DCKP%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEQAxoMMDU5MDAzNTQ2ODY1IgyUQD2SQdl3VD4R3XIqkQMlDBYzJT3hwhOjkgdqcaTi0d4fKovj5%2B7qGsHZvgH8uDDwvLtI5x1fpm%2FsfllNsEonSRc34VnaZ5wxpJ48RnyvlTXORcK8ffGaUwkeAsUyO1q1aebTbNPMxBH7QwAQcuVl8s%2FSW%2BlEpwOCxvdAuSD31YhdQctALEuqL%2FOo4UmD%2Bc5ZUe98X2TLYPEgWrlaUMCy1HDBFj%2BheQmGNlD85g7mydE%2FuSI5pdX5KkRLB%2BL7nSwGixs5 mdelqq1xtfJfN8miYFbLf%2B%2B%2BGNYrepXFLbVZaf7YsKEkDFy3hH6P7hJlB0AO1QcMzkJdwtWUEF8LaQ58StkHG%2Bmmnp95OMpaejJLWwVWodRpe3KeXJy7jhCHBzFp8fAa35wEstxTfihy5JTDTB1D00vwMe01jn%2BqDmBekzzZa%2F6Y%2BDA2qyaoKbg0vOW4DKgQHi53UMHGigIWgug7KFQrVpsLyEFmYP2D4uLIUwstU28g30vV5nv%2BOqG3raORv5T%2Bzs90zlrUOViX0if9p8Qhb%2BcApx4g6m4XWkXTeDD3iJ6FBjrqAZXlAbFy2eqn8JDvnpKpD3UYm%2F%2FcsDTpsi%2BFQKP0LSOzhVv1UyIbcIx4vmjDrp%2B3ErbAYFWjr%2FfhC2rUHniZGS%2BPPo2f%2BvLazBWxIXgz4m767Pzw5Eabm7njwNFkE1LheKEMKy1e4Sh3LtXfHF3LfCCgPi1jj3gDsRrR5ZzDwHyLvA9migBPJ1mO4mQFrjfdmlWrJpP%2BAlfg3XN8zSydMgH3tCLEDK5oxgqEXor5XOAF2pOyvWg7JX5mWfVNNWghndWQsWKoNM7ETYVKQkkSmDPDD9aiC%2F7YRzcrJV62EhVhDfysCBUnYjLHcA%3D%3D&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Date=20210521T101528Z&X-Amz-SignedHeaders=host&X-Amz-Expires=300&X-Amz-Credential=ASIAQ3PHCVTYTSSOCXO5%2F20210521%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Signature=72dc889655da4e3d4dcb5073209c3b4a38a205d4dbc1fba2483ef6ec59fd3e1e&hash=67c0d1c8ef06a1c8304f7ef96dfcc23a97e3f502f4ab747bbbc2ad95f53e8098&host=68042c943591013ac2b2430a89b270f6af2c76d8dfd086a07176afe7c76c2c61&pii=S0959652617303748&tid=pdf-7887d803-5dab-4bea-b549-4efe27fafe4b&sid=e2ff65da246a364264098d6-7b9875caa4f2gxrqb&type=client

Choi, H., Choi, H., Lim, M., Inoue, M., Kitagaki, R., & Noguchi, T. (2016). Evaluation on the Mechanical Performance of Low-Quality Recycled Aggregate Through Interface Enhancement Between Cement Matrix and Coarse Aggregate by Surface Modification Technology. *International journal of concrete structures and materials, 10*(1), 87-97. doi:10.1007/s40069-015-0124-5

Choi, H., Kitagaki, R., & Noguchi, T. (2014). Effective Recycling of Surface Modification Aggregate using Microwave Heating. *ACT, 12*(2), 34-45. doi:10.3151/jact.12.34

Choi, H., Lim, M., Choi, H., Kitagaki, R., & Noguchi, T. (2014). Using Microwave Heating to Completely Recycle Concrete. *Journal of environmental protection (Irvine, Calif.), 5*(7), 583-596. doi:10.4236/jep.2014.57060

Coelho, A., & Brito, J. d. (2013). Environmental analysis of a construction and demolition waste recycling plant in Portugal – Part I: Energy consumption and CO2 emissions. *Waste Manag, 33*(5), 1258-1267. doi:10.1016/j.wasman.2013.01.025

Coelho, A., & de Brito, J. (2011). Economic analysis of conventional versus selective demolition—A case study. *Resources, conservation and recycling, 55*(3), 382-392. doi:10.1016/j.resconrec.2010.11.003

Coelho, A., & de Brito, J. (2012). Influence of construction and demolition waste management on the environmental impact of buildings. *Waste Manag, 32*(3), 532-541. doi:10.1016/j.wasman.2011.11.011

Coelho, A., & de Brito, J. (2013a). Economic viability analysis of a construction and demolition waste recycling plant in Portugal – part I: location, materials, technology and economic analysis. *Journal of cleaner production, 39*, 338-352. doi:10.1016/j.jclepro.2012.08.024

Coelho, A., & de Brito, J. (2013b). Economic viability analysis of a construction and demolition waste recycling plant in Portugal – part II: economic sensitivity analysis. *Journal of cleaner production, 39*, 329-337. doi:10.1016/j.jclepro.2012.05.006

Coelho, A., & de Brito, J. (2013c). Environmental analysis of a construction and demolition waste recycling plant in Portugal – Part II: Environmental sensitivity analysis. *Waste Manag, 33*(1), 147-161. doi:10.1016/j.wasman.2012.09.004

Committee, A. (2001). Removal and Reuse of hardened Concrete. 1-26. Retrieved from http://civilwares.free.fr/ACI/MCP04/555r_01.pdf

Constructor, T. Clasification of Aggregates as pers Size and Shape - Coarse and Fine Aggregates. Retrieved from https://theconstructor.org/building/classification-of-aggregates-size-shape/12339/

Corinaldesi, V., Monosi, S., & Moriconi, G. (2007). Effect of different recycled aggregates on mortar performance. *Sustainable Construction Materials and Tecnologies*, 59-62.

Corinaldesi, V., & Moriconi, G. (2009). Behaviour of cementitious mortars containing different kinds of recycled aggregate. *Construction & building materials, 23*(1), 289-294. doi:10.1016/j.conbuildmat.2007.12.006

Corinaldesi, V., & Moriconi, G. (2011). The role of industrial by-products in self-compacting concrete. *Construction & building materials, 25*(8), 3181-3186. doi:10.1016/j.conbuildmat.2011.03.001

Corinaldesi, V., Orlandi, G., & Moriconi, G. (2002). Self-compacting concrete incorporating recycled aggregate. *Proceedings of the International Conference on Innovations and Developments in Concrete Materials and Construction* 454-464. Retrieved from https://books.google.be/books?hl=nl&lr=&id=OQisnyS5vN0C&oi=fnd&pg=PA455&dq=self-compacting+concrete+incorporating+recycled+aggregate+Corinaldesi&ots=UUqGe_qVuL&sig=Tu5DtJO63ZaOnFOiMf5cNPfeOKc#v=onepage&q=self-compacting%20concrete%20incorporating%20recycled%20aggregate%20Corinaldesi&f=false

Correia, J. R., de Brito, J., & Pereira, A. S. (2006). Effects on concrete durability of using recycled ceramic aggregates. *Materials and structures, 39*(2), 169-177. doi:10.1617/s11527-005-9014-7

Cuenca-Moyano, G. M., Martín-Morales, M., Valverde-Palacios, I., Valverde-Espinosa, I., & Zamorano, M. (2014). Influence of pre-soaked recycled fine aggregate on the properties of masonry mortar. *Construction & building materials, 70*, 71-79. doi:10.1016/j.conbuildmat.2014.07.098

Cui, Z. L., Ohaga, Y. K., Kitatsuji, M. H., & Tanaka, R. J. (2007). Experimental research on freezing-thawing cycle of recycled aggregate concrete. *J. Build. Mater., 10*, 534-537.

de Brito, J., & Alves, F. (2010). Concrete with recycled aggregates: the Portuguese experimental research. *Materials and structures, 43*(S1), 35-51. doi:10.1617/s11527-010-9595-7

De Brito, J., & Silva, R. (2016). Current status on the use of recycled aggregates in concrete: Where do we go from here? *RILEM Technical Letters, 1*, 1. doi:10.21809/rilemtechlett.v1.3

de Juan, M. S., & Gutiérrez, P. A. (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction & building materials, 23*(2), 872-877. doi:10.1016/j.conbuildmat.2008.04.012

Debieb, F., & Kenai, S. (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction & building materials, 22*(5), 886-893. doi:10.1016/j.conbuildmat.2006.12.013

Desmyter, J., Vrijders, J., & Boehme, L. (2010). Recycling of C&D Waste in Belgium: Ongoing research and relevant developments. In: Grada Publihing.

DETR. (2000). Controlling the Environmental Effects of Recycled and Secondary Aggregates Production *Good Practice Guidance,* 143. Retrieved from https://www.thenbs.com/PublicationIndex/documents/details?Pub=DETR&DocID=252471

Dhir Obe, R. K., Brito, J. d., Silva, R. V., & Lye, C. Q. (2019). *Sustainable Construction Materials: Recycled Aggregates*. Kent: Kent: Elsevier Science & Technology.

Dhir, R. K., Limbachiya, M. C., Leelawat, T., BS, & 882, B. (1999). SUITABILITY OF RECYCLED CONCRETE AGGREGATE FOR USE IN BS 5328 DESIGNATED MIXES. *Proceedings of the Institution of Civil Engineers - Structures and Buildings, 134*(3), 257-274. doi:10.1680/istbu.1999.31568

Dhir, R. K., & Paine, K. A. (2004). Suitability and practicality of using coarse RCA in normal and high strength concrete. *1st International Conference on Sustainable Construction: Waste Management*, 108-123.

Dhir, R. K., & Paine, K. A. (2007). Performance Related Approach to the Use of Recycled Aggregates. 77.

Dhir, R. K., Paine, K. A., & Halliday, J. E. (2008). facilitating the Wider Use of Coarse and Fine RA from Washing Plants WRAP Technical Report No AGG 105-003. *Waste and Research Action Programme*.

Dimitriou, G., Savva, P., & Petrou, M. F. (2018). Enhancing mechanical and durability properties of recycled aggregate concrete. *Construction & building materials, 158*, 228-235. doi:10.1016/j.conbuildmat.2017.09.137

Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction & building materials, 23*(7), 2545-2553. doi:10.1016/j.conbuildmat.2009.02.018

Domingo, A., Lázaro, C., Gayarre, F. L., Serrano, M. A., & López-Colina, C. (2010). Long term deformations by creep and shrinkage in recycled aggregate concrete. *Materials and structures, 43*(8), 1147-1160. doi:10.1617/s11527-009-9573-0

Dong, H., Cao, W., Bian, J., & Zhang, J. (2014). The Fire Resistance Performance of Recycled Aggregate Concrete Columns with Different Concrete Compressive Strengths. *Materials (Basel), 7*(12), 7843-7860. doi:10.3390/ma7127843

Dong, J. F., Wang, Q. Y., & Guan, Z. W. (2013). Structural behaviour of recycled aggregate concrete filled steel tube columns strengthened by CFRP. *Engineering structures, 48*, 532-542. doi:10.1016/j.engstruct.2012.11.006

Duan, Z. H., & Poon, C. S. (2014). Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. *Materials in engineering, 58*, 19-29. doi:10.1016/j.matdes.2014.01.044

EC. (2016). EU Construction & Demolition Waste Management Protocol. *European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs*, 52. Retrieved from https://ec.europa.eu/growth/content/eu-construction-and-demolition-waste-protocol-0_en

Eckert, E., & Oliveira, M. (2015). Risk of plastic shrinkage cracking in recycled aggregate concrete. *International Journal of civil and Environmental Engineering, 9*, 931-937.

EN-1992-1-1. (2008). Eurocode 2 - Design of Concrete Structures. *General Rules and Rules for Buildings, Part 1-1*, 259.

Etxeberria, M., Gonzalez-Corominas, A., & Pardo, P. (2016). Influence of seawater and blast furnace cement employment on recycled aggregate concretes' properties. *Construction & building materials, 115*, 496-505. doi:10.1016/j.conbuildmat.2016.04.064

Etxeberria, M., Marí, A. R., & Vázquez, E. (2007). Recycled aggregate concrete as structural material. *Materials and structures, 40*(5), 529-541. doi:10.1617/s11527-006-9161-5

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and concrete research, 37*(5), 735-742. doi:10.1016/j.cemconres.2007.02.002

Eurostat. (2017). Waste Statistics in Europe. Retrieved from epp.eurostat.ec.europa.eu

Evangelista, A. C. J., Tam, V. W. Y., & Santos, J. (2017). Recycled Ceramic Fine Aggregate for Masonry Mortar Production. In (pp. 1141-1148). Singapore: Singapore: Springer Singapore.

Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement & concrete composites, 29*(5), 397-401. doi:10.1016/j.cemconcomp.2006.12.004

Evangelista, L., & de Brito, J. (2010). Durability performance of concrete made with fine recycled concrete aggregates. *Cement & concrete composites, 32*(1), 9-14. doi:10.1016/j.cemconcomp.2009.09.005

Evangelista, L., & de Brito, J. (2014). Concrete with fine recycled aggregates: a review. *European journal of environmental and civil engineering, 18*(2), 129-172. doi:10.1080/19648189.2013.851038

Evangelista, L., Guedes, M., de Brito, J., Ferro, A. C., & Pereira, M. F. (2015). Physical, chemical and mineralogical properties of fine recycled aggregates made from concrete waste. *Construction & building materials, 86*, 178-188. doi:10.1016/j.conbuildmat.2015.03.112

Faella, C., Lima, C., Martinelli, E., Pepe, M., & Realfonzo, R. (2016). Mechanical and durability performance of sustainable structural concretes: An experimental study. *Cement & concrete composites, 71*, 85-96. doi:10.1016/j.cemconcomp.2016.05.009

Faleschini, F., Jiménez, C., Barra, M., Aponte, D., Vázquez, E., & Pellegrino, C. (2014). Rheology of fresh concretes with recycled aggregates. *Construction & building materials, 73*, 407-416. doi:10.1016/j.conbuildmat.2014.09.068

Faleschini, F., Zanini, M. A., Pellegrino, C., & Pasinato, S. (2016). Sustainable management and supply of natural and recycled aggregates in a medium-size integrated plant. *Waste Manag, 49*, 146-155. doi:10.1016/j.wasman.2016.01.013

Fan, C.-C., Huang, R., Hwang, H., & Chao, S.-J. (2015). The Effects of Different Fine Recycled Concrete Aggregates on the Properties of Mortar. *Materials, 8*(5), 2658-2672. doi:10.3390/ma8052658

Fan, C.-C., Huang, R., Hwang, H., & Chao, S.-J. (2016). Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. *Construction & building materials, 112*, 708-715. doi:10.1016/j.conbuildmat.2016.02.154

Ferreira, L., Brito, J. d., & Barra, M. (2011). Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Magazine of Concrete Research, 63*(8), 617-627. doi:10.1680/macr.2011.63.8.617

Folino, P., & Xargay, H. (2014). Recycled aggregate concrete – Mechanical behavior under uniaxial and triaxial compression. *Construction & building materials, 56*, 21-31. doi:10.1016/j.conbuildmat.2014.01.073

Freedonia. (2012). World Construction Aggregates. *The Freedonia Group*, 334.

Gao, D., Zhang, L., & Nokken, M. (2017). Mechanical behavior of recycled coarse aggregate concrete reinforced with steel fibers under direct shear. *Cement & concrete composites, 79*, 1-8. doi:10.1016/j.cemconcomp.2017.01.006

García-González, J., Rodríguez-Robles, D., Juan-Valdés, A., Pozo, J. M. M.-d., & Guerra-Romero, M. I. (2015). Porosity and pore size distribution in recycled concrete. *Magazine of Concrete Research, 67*(22), 1214-1221. doi:10.1680/macr.14.00218

Geng, J., & Sun, J. (2013). Characteristics of the carbonation resistance of recycled fine aggregate concrete. *Construction & building materials, 49*, 814-820. doi:10.1016/j.conbuildmat.2013.08.090

Gesoglu, M., Guneyisi, E., Oz, H. O., Taha, I., & Yasemin, M. T. (2015). Failure characteristics of self-compacting concretes made with recycled aggregates. *Construction & building materials, 98*, 334-344. doi:10.1016/j.conbuildmat.2015.08.036

Goel, S., Singh, S. P., & Kaushik, S. K. (2012). Prediction of mean and design fatigue lives of self compacting concrete beams in flexure. *J. Inst. Eng. Ser. A, 93*, 55-61.

Goel, S., Singh, S. P., & Singh, P. (2012). Flexural fatigue analysis of self-compacting concrete beams. *Proceedings of the Institution of Civil Engineers - Construction Materials, 165*(6), 367-376. doi:10.1680/coma.11.00016

Gokce, A., Nagataki, S., Saeki, T., & Hisada, M. (2004). Freezing and thawing resistance of air-entrained concrete incorporating recycled coarse aggregate: The role of air content in demolished concrete. *Cement and concrete research, 34*(5), 799-806. doi:10.1016/j.cemconres.2003.09.014

Gokce, A., Nagataki, S., Saeki, T., & Hisada, M. (2011). Identification of frost-susceptible recycled concrete aggregates for durability of concrete. *Construction & building materials, 25*(5), 2426-2431. doi:10.1016/j.conbuildmat.2010.11.054

Gomes, M., & de Brito, J. (2009). Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. *Materials and structures, 42*(5), 663-675. doi:10.1617/s11527-008-9411-9

Gómez-Soberón, J. M. V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. *Cement and concrete research, 32*(8), 1301-1311. doi:10.1016/S0008-8846(02)00795-0

Gonzalez-Corominas, A., & Etxeberria, M. (2016). Effects of using recycled concrete aggregates on the shrinkage of high performance concrete. *Construction & building materials, 115*, 32-41. doi:10.1016/j.conbuildmat.2016.04.031

González-Taboada, I., González-Fonteboa, B., Martínez-Abella, F., & Seara-Paz, S. (2017). Analysis of rheological behaviour of self-compacting concrete made with recycled aggregates. *Construction & building materials, 157*, 18-25. doi:10.1016/j.conbuildmat.2017.09.076

Grabiec, A. M., Klama, J., Zawal, D., & Krupa, D. (2012). Modification of recycled concrete aggregate by calcium carbonate biodeposition. *Construction & building materials, 34*(1), 145-150. doi:10.1016/j.conbuildmat.2012.02.027

Guadalupe Cabrera-Covarrubias, F., Manuel Gomez-Soberon, J., Luis Almaral-Sanchez, J., Corral-Higuera, R., & Consolacion Gomez-Soberon, M. (2017). Implementation of Interaction Diagram of the Properties in Fresh for Mortars with Ceramic Aggregates. *Periodica polytechnica. Civil engineering. Bauingenieurwesen, 61*(2), 335-340. doi:10.3311/PPci.9651

Guneyisi, E., Gesoglu, M., Algin, Z., & Yazici, H. (2014). Effect of surface treatment methods on the properties of self-compacting concrete with recycled aggregates. *Construction & building materials, 64*, 172-183. doi:10.1016/j.conbuildmat.2014.04.090

Güneyisi, E., Gesoglu, M., Algın, Z., & Yazıcı, H. (2016). Rheological and fresh properties of self-compacting concretes containing coarse and fine recycled concrete aggregates. *Construction & building materials, 113*, 622-630. doi:10.1016/j.conbuildmat.2016.03.073

Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T.-C., . . . Wang, Y. (2018). Durability of recycled aggregate concrete – A review. *Cement & concrete composites, 89*, 251-259. doi:10.1016/j.cemconcomp.2018.03.008

Hachemi, S., & Ounis, A. (2015). Performance of concrete containing crushed brick aggregate exposed to different fire temperatures. *European journal of environmental and civil engineering, 19*(7), 805-824. doi:10.1080/19648189.2014.973535

Haitao, Y., & Shizhu, T. (2015). Preparation and properties of high-strength recycled concrete in cold areas. *Materiales de construcción (Madrid), 65*(318), e050-e050. doi:10.3989/mc.2015.03214

Hansen, T. C. (1986). Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. *Materials and structures, 19*(3), 201-246. doi:10.1007/BF02472036

Hansen, T. C. (1992). *Recycling of Demolished Concrete and Masonry*: CRC Press.

Holm, T., & Bremner, T. (2000). State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments.

Hossain, M. U., Poon, C. S., Lo, I. M. C., & Cheng, J. C. P. (2016). Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, conservation and recycling, 109*, 67-77. doi:10.1016/j.resconrec.2016.02.009

Hosseini Zadeh, A., Mamirov, M., Kim, S., & Hu, J. (2021). CO2-treatment of recycled concrete aggregates to improve mechanical and environmental properties for unbound applications. *Construction & building materials, 275*, 122180. doi:10.1016/j.conbuildmat.2020.122180

Huda, S., & Alam, M. S. (2015). Mechanical and freeze-thaw durability properties of recycled aggregate concrete made with recycled coarse aggregate. *Journal of Materials in Civil Engineering, 27*, 1-9.

Huda, S. B., & Alam, M. S. (2014). Mechanical behavior of three generations of 100% repeated recycled coarse aggregate concrete. *Construction & building materials, 65*, 574-582. doi:10.1016/j.conbuildmat.2014.05.010

Hurley, J. W., McGrath, C., Fletcher, S. L., & Bowes, H. M. (2001). Deconstruction and Reuse of Construction Materials. *British Research Establishment, BRE Report* 33. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.115.882&rep=rep1&type=pdf#page=102

Ignjatovic, I. S., Marinkovic, S. B., & Tosic, N. (2017). Shear behaviour of recycled aggregate concrete beams with and without shear reinforcement. *Engineering structures, 141*, 386-401. doi:10.1016/j.engstruct.2017.03.026

Iris, G.-T., Belen, G.-F., Fernando, M.-A., & Diego, C.-L. (2017). Self-compacting recycled concrete: Relationships between empirical and rheological parameters and proposal of a workability box. *Construction & building materials, 143*, 537-546. doi:10.1016/j.conbuildmat.2017.03.156

Ismail, S., & Ramli, M. (2014). Mechanical strength and drying shrinkage properties of concrete containing treated coarse recycled concrete aggregates. *Construction & building materials, 68*, 726-739. doi:10.1016/j.conbuildmat.2014.06.058

J A Carneiro, P. R. L. L., M B Leite and R D Toledo. (2014). Compressive stress-strain behavior of steel fiber reinforced-recycled aggregate concrete. *Cement and Concrete Composites*, 65-72.

Jacobsen, S., Rommetvedt, O. W., & Gjengstø, K. T. PROPERTIES AND FROST DURABILITY OF RECYCLED AGGREGATE FROM OSLO, NORWAY. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 189-196).

Jalal, M., Pouladkhan, A., Harandi, O. F., & Jafari, D. (2015). Comparative study on effects of Class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete. *Construction & building materials, 94*, 90-104. doi:10.1016/j.conbuildmat.2015.07.001

James W. Mack, C. E. S., Geralt F. Voigt. (1993). Recycling Concrete Pavements.pdf. Retrieved from https://www.concreteconstruction.net/projects/repair-rehab/recycling-concrete-pavements_o

Jiménez, J. R., Agrela, F., Ayuso, J., & López, M. (2011). A comparative study of recycled aggregates from concrete and mixed debris as material for unbound road sub-base. *Materiales de construcción (Madrid), 61*(302), 289-302. doi:10.3989/mc.2010.54009

Johnson, R., & Shehata, M. H. (2016). The efficacy of accelerated test methods to evaluate Alkali Silica Reactivity of Recycled Concrete Aggregates. *Construction & building materials, 112*, 518-528. doi:10.1016/j.conbuildmat.2016.02.155

Kapoor, K., Singh, S. P., & Singh, B. (2016). Durability of self-compacting concrete made with Recycled Concrete Aggregates and mineral admixtures. *Construction & building materials, 128*, 67-76. doi:10.1016/j.conbuildmat.2016.10.026

Kasai, Y. (2004). Recent trends in recycling of concrete waste and use of recycled aggregate concrete in Japan. *Recycling Concrete and Other Materials for Sustainable Development*, 11-33.

Katkhuda, H., & Shatarat, N. (2016). Shear behavior of reinforced concrete beams using treated recycled concrete aggregate. *Construction & building materials, 125*, 63-71. doi:10.1016/j.conbuildmat.2016.08.034

Katkhuda, H., & Shatarat, N. (2017). Improving the mechanical properties of recycled concrete aggregate using chopped basalt fibers and acid treatment. *Construction & building materials, 140*, 328-335. doi:10.1016/j.conbuildmat.2017.02.128

Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and concrete research, 33*(5), 703-711. doi:10.1016/S0008-8846(02)01033-5

Katz, A. (2004). Treatments for the improvement of recycled aggregate. *J Mater. Civ. Eng., 16*, 597-603. Retrieved from https://ascelibrary.org/doi/abs/10.1061/(ASCE)0899-1561(2004)16:6(597)?casa_token=JMQdv5FGUesAAAAA:bwkfjwSqLk3XWXH5ciZhikw71IxwNMUOcj0ihhsYHooAusVTuqqixiY8YyHtwVplXnjSagJAV-li

Kazmi, S. M. S., Munir, M. J., Wu, Y.-F., Patnaikuni, I., Zhou, Y., & Xing, F. (2019a). Axial stress-strain behavior of macro-synthetic fiber reinforced recycled aggregate concrete. *Cement & concrete composites, 97*, 341-356. doi:10.1016/j.cemconcomp.2019.01.005

Kazmi, S. M. S., Munir, M. J., Wu, Y.-F., Patnaikuni, I., Zhou, Y., & Xing, F. (2019b). Influence of different treatment methods on the mechanical behavior of recycled aggregate concrete: A comparative study. *Cement & concrete composites, 104*, 103398. doi:10.1016/j.cemconcomp.2019.103398

Kazmi, S. M. S., Munir, M. J., Wu, Y.-F., Patnaikuni, I., Zhou, Y., & Xing, F. (2020). Effect of recycled aggregate treatment techniques on the durability of concrete: A comparative evaluation. *Construction & building materials, 264*, 120284. doi:10.1016/j.conbuildmat.2020.120284

Kebaïli, O., Mouret, M., Arabi, N., & Cassagnabere, F. (2015). Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: evidence and analysis through an example. *Journal of cleaner production, 87*, 752-761. doi:10.1016/j.jclepro.2014.10.077

Khalaf, F. M. (2006). Using crushed clay brick as coarse aggregate in concrete. *Journal of Materials in Civil Engineering, 18*, 518-526.

Khalaf, F. M., & DeVenny, A. S. (2004a). Performance of brick aggregate concrete at high temperatures. *Journal of Materials in Civil Engineering, 16*, 556-565.

Khalaf, F. M., & DeVenny, A. S. (2004b). Recycling of demolished masonry rubble as coarse aggregate in concrete: Review. *Journal of Materials in Civil Engineering, 16*, 331-340.

Khalaf, F. M., & DeVenny, A. S. (2005). Properties of new and recycled clay brick aggregates for use in concrete: Review. *Journal of Materials in Civil Engineering, 17*, 456-464.

Khatib, J. M. (2005). Properties of concrete incorporating fine recycled aggregate. *Cement and concrete research, 35*(4), 763-769. doi:10.1016/j.cemconres.2004.06.017

Khodair, Y., & Luqman. (2017). Self-compacting concrete using recycled asphalt pavement and recycled concrete aggregate. *Journal of Building Engineering, 12*, 282-287. doi:10.1016/j.jobe.2017.06.007

Kikuchi, M., Dosho, Y., Miura, T., & Narikawa, M. (1998). Application of recycled aggregate concrete for structural concrete: Part 1 - experimental study on the quality of recycled aggregate and recycled aggregate concrete *Proceedings of the International Symposium on Sustainable Construction: Use of Recycled Concrete Aggregate*, 55-68.

Kim, H., & Bentz, D. (2008). Internal curing with crushed returned concrete aggregates for high performance concrete. *Concrete Technology Forum, Focus on Sustainable Development*, 12.

Kim, J., Nam, B., Behring, Z., & Muhit, B. A. (2014). Evaluation of recementation reactivity of recycled concrete aggregate fines. *Transportation Research Record*, 44-51.

Kim, K., Shin, M., & Cha, S. (2013). Combined effects of recycled aggregate and fly ash towards concrete sustainability. *Construction & building materials, 48*, 499-507. doi:10.1016/j.conbuildmat.2013.07.014

Kim, S.-W., & Yun, H.-D. (2013). Influence of recycled coarse aggregates on the bond behavior of deformed bars in concrete. *Engineering structures, 48*, 133-143. doi:10.1016/j.engstruct.2012.10.009

Kim, Y.-J. (2017). Quality properties of self-consolidating concrete mixed with waste concrete powder. *Construction & building materials, 135*, 177-185. doi:10.1016/j.conbuildmat.2016.12.174

Kim, Y., Hanif, A., Kazmi, S. M. S., Munir, M. J., & Park, C. (2018). Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates – Comparative assessment of assorted techniques. *Journal of cleaner production, 191*, 339-349. doi:10.1016/j.jclepro.2018.04.192

Kisku, N., Joshi, H., Ansari, M., Panda, S. K., Nayak, S., & Dutta, S. C. (2017). A critical review and assessment for usage of recycled aggregate as sustainable construction material. *Construction & building materials, 131*, 721-740. doi:10.1016/j.conbuildmat.2016.11.029

Knoeri, C., Binder, C. R., & Althaus, H.-J. (2011). Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, conservation and recycling, 55*(11), 1039-1050. doi:10.1016/j.resconrec.2011.05.018

Knoeri, C., Nikolic, I., Althaus, H.-J., & Binder, C. R. (2014). Enhancing Recycling of Construction Materials: An Agent Based Model with Empirically Based Decision Parameters. In: University of Surrey, Department of Sociology.

Koenders, E. A. B., Pepe, M., & Martinelli, E. (2014). Compressive strength and hydration processes of concrete with recycled aggregates. *Cement and concrete research, 56*, 203-212. doi:10.1016/j.cemconres.2013.11.012

Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., & Jiang, J. (2010). Effect and mechanism of surface-coating pozzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. *Construction & building materials, 24*(5), 701-708. doi:10.1016/j.conbuildmat.2009.10.038

Kou, S.-C., & Poon, C.-S. (2010). Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. *Cement & concrete composites, 32*(8), 649-654. doi:10.1016/j.cemconcomp.2010.05.003

Kou, S.-C., & Poon, C.-S. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement & concrete composites, 37*, 12-19. doi:10.1016/j.cemconcomp.2012.12.011

Kou, S.-c., & Poon, C.-s. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction & building materials, 77*, 501-508. doi:10.1016/j.conbuildmat.2014.12.035

Kou, S.-c., Poon, C.-s., & Agrela, F. (2011). Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. *Cement & concrete composites, 33*(8), 788-795. doi:10.1016/j.cemconcomp.2011.05.009

Kou, S.-C., Poon, C.-S., & Etxeberria, M. (2011). Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. *Cement & concrete composites, 33*(2), 286-291. doi:10.1016/j.cemconcomp.2010.10.003

Kou, S.-C., Zhan, B.-j., & Poon, C.-S. (2014). Use of a CO2 curing step to improve the properties of concrete prepared with recycled aggregates. *Cement & concrete composites, 45*, 22-28. doi:10.1016/j.cemconcomp.2013.09.008

Kou, S. (2006). Reusing recycled aggregates in structural concrete. In: ProQuest Dissertations Publishing.

Kou, S. C., & Poon, C. S. (2009). Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. *Cement and Concrete Composites, 31*(9), 622-627. doi:https://doi.org/10.1016/j.cemconcomp.2009.06.005

Kou, S. C., & Poon, C. S. (2012). Enhancing the durability properties of concrete prepared with coarse recycled aggregate. *Construction & building materials, 35*, 69-76. doi:10.1016/j.conbuildmat.2012.02.032

Kou, S. C., Poon, C. S., & Chan, D. (2007). Influence of fly ash as cement replacement on the properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering, 19*, 709-717. Retrieved from https://ascelibrary.org/doi/full/10.1061/%28ASCE%290899-1561%282007%2919%3A9%28709%29?casa_token=sWdRU405-zQAAAAA%3AwJOIP_U9aNzMjOWqytR7r6bKqaYkUedH9x5kMEYRq8WYCNiQY85d6VN8dP59ifQNRzvuqW33-EZy

Koulouris, A., Limbachiya, M. C., Fried, A. N., & Roberts, J. J. (2004). USE OF RECYCLED AGGREGATE IN CONCRETE APPLICATION: CASE STUDIES. In *Sustainable Waste Management and Recycling: Construction Demolition Waste* (pp. 245-257).

Kurad, R., Silvestre, J. D., de Brito, J., & Ahmed, H. (2017). Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete. *Journal of cleaner production, 166*, 485-502. doi:10.1016/j.jclepro.2017.07.236

Kurda, R., de Brito, J., & Silvestre, J. D. (2017a). Combined influence of recycled concrete aggregates and high contents of fly ash on concrete properties. *Construction & building materials, 157*, 554-572. doi:10.1016/j.conbuildmat.2017.09.128

Kurda, R., de Brito, J., & Silvestre, J. D. (2017b). Influence of recycled aggregates and high contents of fly ash on concrete fresh properties. *Cement & concrete composites, 84*, 198-213. doi:10.1016/j.cemconcomp.2017.09.009

Kutegeza, B., & Alexander, M. G. (2004). THE PERFORMANCE OF CONCRETE MADE WITH COMMERCIALLY PRODUCED RECYCLED COARSE AND FINE AGGREGATES IN THE WESTERN CAPE. In *Sustainable Waste Management and Recycling: Construction Demolition Waste* (pp. 235-244).

Kwan, W. H., Ramli, M., Kam, K. J., & Sulieman, M. Z. (2012). Influence of the amount of recycled coarse aggregate in concrete design and durability properties. *Construction & building materials, 26*(1), 565-573. doi:10.1016/j.conbuildmat.2011.06.059

Le, T., Le Saout, G., Garcia-Diaz, E., Betrancourt, D., & Rémond, S. (2017). Hardened behavior of mortar based on recycled aggregate: Influence of saturation state at macroand microscopic scales. *Construction & building materials, 141*, 479-490. doi:10.1016/j.conbuildmat.2017.02.035

Lei, B., & Xiao, J. Z. (2008). Research on carbonation resistance of recycled aggregate concrete. *J. Build. Mater., 11*, 605-611.

Leite, M. B. (2001). Evaluation of the Mechanical Poreprties of Concrete produced with Recycled Aggregates from Construction and Demolition Wastes. Retrieved from https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/reference/ReferencesPapers.aspx?ReferenceID=1577644

Leite, M. B., Lima, P. R., & Santos, A. C. (2009). Study of the consistence and mechanical behaviour of recycled mortars. *2nd International RILEM Conference on Progress of Reccling in the Built Environment*, 223-229. Retrieved from https://www.researchgate.net/profile/Monica-Leite/publication/282366692_STUDY_OF_THE_CONSISTENCE_AND_MECHANICAL_BEHAVIOR_OF_RECYCLED_MORTARS/links/560ee03f08aec422d112cfef/STUDY-OF-THE-CONSISTENCE-AND-MECHANICAL-BEHAVIOR-OF-RECYCLED-MORTARS.pdf

Leite, M. B., & Monteiro, P. J. M. (2016). Microstructural analysis of recycled concrete using X-ray microtomography. *Cement and concrete research, 81*, 38-48. doi:https://doi.org/10.1016/j.cemconres.2015.11.010

Leng, F., Feng, N., & Lu, X. (2000). An experimental study on the properties of resistance to diffusion of chloride ions of fly ash and blast furnace slag concrete. *Cement and concrete research, 30*(6), 989-992. doi:10.1016/S0008-8846(00)00250-7

Levy, S. M., & Helene, P. (2004). Durability of recycled aggregates concrete: a safe way to sustainable development. *Cement and concrete research, 34*(11), 1975-1980. doi:10.1016/j.cemconres.2004.02.009

Li, J., Xiao, H., & Zhou, Y. (2009). Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete. *Construction & building materials, 23*(3), 1287-1291. doi:10.1016/j.conbuildmat.2008.07.019

Li, L., Xiao, J., & Poon, C. S. (2016). Dynamic compressive behavior of recycled aggregate concrete. *Materials and structures, 49*(11), 4451-4462. doi:10.1617/s11527-016-0800-1

Li, Q., Li, Z., & Yuan, G. (2012). Effects of elevated temperatures on properties of concrete containing ground granulated blast furnace slag as cementitious material. *Construction & building materials, 35*, 687-692. doi:10.1016/j.conbuildmat.2012.04.103

Li, T., Xiao, J., & Zhu, C. (2016). Hydration process modeling of ITZ between new and old cement paste. *Construction & building materials, 109*, 120-127. doi:10.1016/j.conbuildmat.2016.01.053

Limbachiya, M., Meddah, M. S., & Ouchagour, Y. (2012). Use of recycled concrete aggregate in fly-ash concrete. *Construction & building materials, 27*(1), 439-449. doi:10.1016/j.conbuildmat.2011.07.023

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (1998). RCA CONCRETE: A STUDY OF PROPERTIES IN THE FRESH STATE, STRENGTH DEVELOPMENT AND DURABILITY. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 227-237).

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and structures, 33*(9), 574-580. doi:10.1007/BF02480538

Liu, K., Yan, J., Hu, Q., Sun, Y., & Zou, C. (2016). Effects of parent concrete and mixing method on the resistance to freezing and thawing of air-entrained recycled aggregate concrete. *Construction & building materials, 106*, 264-273. doi:10.1016/j.conbuildmat.2015.12.074

Liu, Q., Xiao, J., & Sun, Z. (2011). Experimental study on the failure mechanism of recycled concrete. *Cement and concrete research, 41*(10), 1050-1057. doi:10.1016/j.cemconres.2011.06.007

Liu, Y., Ji, H., Zhang, J., Wang, W., & Chen, Y. F. (2016). Mechanical properties of thermal insulation concrete with recycled coarse aggregates after elevated temperature exposure. *Materials Testing, 58*(7-8), 669-677. doi:doi:10.3139/120.110902

Liu, Y., Wang, W., Chen, Y. F., & Ji, H. (2016). Residual stress-strain relationship for thermal insulation concrete with recycled aggregate after high temperature exposure. *Construction & building materials, 129*, 37-47. doi:10.1016/j.conbuildmat.2016.11.006

Lopez Gayarre, F., Gonzalez Perez, J., Lopez-Colina Perez, C., Serrano Lopez, M., & Lopez Martinez, A. (2016). Life cycle assessment for concrete kerbs manufactured with recycled aggregates. *Journal of cleaner production, 113*, 41-53. doi:10.1016/j.jclepro.2015.11.093

Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. *Cement and concrete research, 41*(12), 1244-1256. doi:https://doi.org/10.1016/j.cemconres.2010.12.001

Lübeck, A., Gastaldini, A. L. G., Barin, D. S., & Siqueira, H. C. (2012). Compressive strength and electrical properties of concrete with white Portland cement and blast-furnace slag. *Cement & concrete composites, 34*(3), 392-399. doi:10.1016/j.cemconcomp.2011.11.017

Luo, S., Ye, S., Xiao, J., Zheng, J., & Zhu, Y. (2018). Carbonated recycled coarse aggregate and uniaxial compressive stress-strain relation of recycled aggregate concrete. *Construction & building materials, 188*, 956-965. doi:10.1016/j.conbuildmat.2018.08.159

Luo, W. H., Wei, J., & Luo, X. (2006). Physics relation between concrete deterioration and harmful pore. *J. Huazhong Univ. Sci. Technol., Nat. Sci. Ed.*, 94-96.

Lye, C. Q., Dhir, R. K., & Ghataora, G. S. (2016). Elastic modulus of concrete made with recycled aggregates. *Proceedings of Institution of Civil Engineers, Structures and Buildings*, 314-339.

Maeda, S., Shigeishi, M., Namihira, T., Ohtsu, M., & Akiyama, H. (2008). Recycling technology for concrete aggregate using underwater electric pulse discharge. *Proceedings of the International Conference on the Role for Concrete in Global Development*, 325-336.

Majhi, R. K., Nayak, A. N., & Mukharjee, B. B. (2018). Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag. *Construction & building materials, 159*, 417-430. doi:10.1016/j.conbuildmat.2017.10.118

Mália, M., de Brito, J., Pinheiro, M. D., & Bravo, M. (2013). Construction and demolition waste indicators. *Waste Management & Research, 31*(3), 241-255. doi:10.1177/0734242X12471707

Marinkovic, S., Dragas, J., Ignjatovic, I., & Tosic, N. (2017). Environmental assessment of green concretes for structural use. *Journal of cleaner production, 154*, 633-649. doi:10.1016/j.jclepro.2017.04.015

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag, 30*(11), 2255-2264. doi:10.1016/j.wasman.2010.04.012

Martín-Pérez, B., Zibara, H., Hooton, R. D., & Thomas, M. D. A. (2000). A study of the effect of chloride binding on service life predictions. *Cement and concrete research, 30*(8), 1215-1223. doi:10.1016/S0008-8846(00)00339-2

Martínez-Lage, I., Martínez-Abella, F., Vázquez-Herrero, C., & Pérez-Ordóñez, J. L. (2012). Properties of plain concrete made with mixed recycled coarse aggregate. *Construction & building materials, 37*, 171-176. doi:10.1016/j.conbuildmat.2012.07.045

Martins, D. J., Correia, J. R., & de Brito, J. (2016). The effect of high temperature on the residual mechanical performance of concrete made with recycled ceramic coarse aggregates. *Fire Mater, 40*(2), 289-304. doi:10.1002/fam.2287

Maruyama, I., & Sato, R. (2005). A trial of reducing autogenous shrinkage by recycled aggregate. *4th International Seminar on Self-desiccation and its Importance in Concrete Technology*, 8. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.558.1163&rep=rep1&type=pdf

Mas, B., Cladera, A., Olmo, T. d., & Pitarch, F. (2012). Influence of the amount of mixed recycled aggregates on the properties of concrete for non-structural use. *Construction & building materials, 27*(1), 612-622. doi:10.1016/j.conbuildmat.2011.06.073

Matias, D., Brito, J. d., Rosa, A., & Pedro, D. (2014). Durability of concrete with recycled coarse aggregates: influence of superplasticizers Retrieved from https://ascelibrary.org/doi/full/10.1061/%28ASCE%29MT.1943-5533.0000961

McCarthy, M. J., Csetenyi, L. J., Halliday, J. E., & Dhir, R. K. (2015). Evaluating the effect of recycled aggregate on damaging AAR in concrete. *Magazine of Concrete Research, 67*(11), 598-610. doi:10.1680/macr.14.00260

Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., & Arabi, N. (2013). Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. *Journal of cleaner production, 54*, 282-288. doi:10.1016/j.jclepro.2013.05.009

Mohammed Seddik, M., & Ryoichi, S. (2010). Effect of Curing Methods on Autogenous Shrinkage and Self-Induced Stress of High-Performance Concrete. *ACI materials journal, 107*(1), 65. doi:10.14359/51663467

Montgomery, D. G. WORKABILITY AND COMPRESSIVE STRENGTH PROPERTIES OF CONCRETE CONTAINING RECYCLED CONCRETE AGGREGATE. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 287-296).

Mukharjee, B. B., & Barai, S. V. (2015a). Characteristics of sustainable concrete incorporating recycled coarse aggregates and colloidal nano-silica. *Advances in Concrete Construction, 3*, 187-202. Retrieved from http://www.techno-press.org/content/?page=article&journal=acc&volume=3&num=3&ordernum=2

Mukharjee, B. B., & Barai, S. V. (2015b). Development of construction materials using nano-silica and aggregates recycled from construction and demolition waste. *Waste Management & Research, 33*, 515-523.

Mukharjee, B. B., & Barai, S. V. (2017). Mechanical and microstructural characterization of recycled aggregate concrete containing silica nanoparticles. *Journal of Sustainable Cement-Based Materials, 6*(1), 37-53. doi:10.1080/21650373.2016.1230899

Mukhopadhyay, G. (2013). An Effective Approach to Utilize Recycled Aggregates (RAs) from Alkali-Silica Reaction (ASR) Affected Portland Cement Concrete. In (pp. 555-568).

Müller, A., & Winkler, A. (1998). Characteristics of processed concrete rubble. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 109-119).

Munir, M. J., Kazmi, S. M. S., Wu, Y.-F., Patnaikuni, I., Wang, J., & Wang, Q. (2020). Development of a unified model to predict the axial stress–strain behavior of recycled aggregate concrete confined through spiral reinforcement. *Engineering structures, 218*, 110851. doi:10.1016/j.engstruct.2020.110851

Munir, M. J., Kazmi, S. M. S., Wu, Y.-F., Patnaikuni, I., Zhou, Y., & Xing, F. (2020). Stress strain performance of steel spiral confined recycled aggregate concrete. *Cement & concrete composites, 108*, 103535. doi:10.1016/j.cemconcomp.2020.103535

N Y Ho, Y. P. K. L., W F Lim, T Zayed, KC Chew, G L Low, S K Ting. (2013). efficient utilization of recycled concrete aggregate in structural concrete. *Journal of Materials in Civil Engineering* 318 - 327.

N.F.E.N. (2011). Tests for Mechanical and Physical Properties of Aggregates - Part 2: Methods for the Determination of Resistance to Fragmentation. *AFNOR*.

Nagataki, S., Gokce, A., Saeki, T., & Hisada, M. (2004). Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and concrete research, 34*(6), 965-971. doi:10.1016/j.cemconres.2003.11.008

Narahara, S., Namihira, T., Nakashima, K., Inoue, S., Iizasa, S., Maeda, S., . . . Akiyama, H. (2007). Evaluation of concrete made from recycled coarse aggregates by pulsed power discharge. In (Vol. 1, pp. 748-751): IEEE.

Nazarimofrad, E., Shaikh, F. U. A., & Nili, M. (2017). Effects of steel fibre and silica fume on impact behaviour of recycled aggregate concrete. *Journal of Sustainable Cement-Based Materials, 6*, 54-68.

Nealen, A., & Rühl, M. (1997). Consistency aspects in the production of concrete using aggregates from recycled demolition material. *Darmstadt Concrete, 12,5*.

Nealen, A., & Schenk, S. (1998). The influence of recycled aggregate core moisture on freshly mixed and hardened concrete properties. *Darmstadt Concrete, 13,5*.

Neville, A. M. (1995). *Properties of concrete* (4th and final ed. ed.). Harlow: Longman.

Neville, A. M., & Brooks, J. J. (2010). *Concrete Technology*: Prentice Hall.

Neville, A. M., Dilger, W. H., & Brooks, J. J. (1983). Creep of Plain and Structural Concrete. *Construction Press*.

Newman, J., & Choo, B. S. (2003). *Advanced Concrete Technology*: Butterworth-Heinemann.

Nie, S., Hu, S., Wang, F., Hu, C., Li, X., & Zhu, Y. (2017). Pozzolanic reaction of lightweight fine aggregate and its influence on the hydration of cement. *Construction & building materials, 153*, 165-173. doi:10.1016/j.conbuildmat.2017.07.111

Nixon, P. J. (1978). Recycled concrete as an aggregate for concrete—a review. *Matériaux et Construction, 11*(5), 371. doi:10.1007/BF02473878

Noguchi, T., Park, W.-J., & Kitagaki, R. (2015). Risk evaluation for recycled aggregate according to deleterious impurity content considering deconstruction scenarios and production methods. *Resources, conservation and recycling, 104*, 405-416. doi:10.1016/j.resconrec.2015.08.002

Obla, K., Kim, H., & Lobo, C. (2007). Crushed Returned Concrete as Aggregates for New Concrete.

Ollivier, J. P., Maso, J. C., & Bourdette, B. (1995). Interfacial transition zone in concrete. *Advanced Cement Based Materials, 2*(1), 30-38. doi:10.1016/1065-7355(95)90037-3

Omary, S., Ghorbel, E., & Wardeh, G. (2016). Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties. *Construction & building materials, 108*, 163-174. doi:10.1016/j.conbuildmat.2016.01.042

Otsuki, N., Miyazato, S., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and crbonation of concrete. *Journal of Materials in Civil Engineering, 15*, 443-451. Retrieved from https://ascelibrary.org/doi/abs/10.1061/(ASCE)0899-1561(2003)15:5(443)

Ozbakkaloglu, T., Gholampour, A., & Xie, T. (2018). Mechanical and Durability Properties of Recycled Aggregate Concrete: Effect of Recycled Aggregate Properties and Content. *J. Mater. Civ. Eng., 30*. Retrieved from https://ascelibrary.org/doi/full/10.1061/(ASCE)MT.1943-5533.0002142

P, B., Chisholm, D., J, G., & Harrison, T. (2008). *Properties of Concrete for use in Eurocode 2*.

Padmini, A. K., Ramamurthy, K., & Mathews, M. S. (2009). Influence of parent concrete on the properties of recycled aggregate concrete. *Construction & building materials, 23*(2), 829-836. doi:10.1016/j.conbuildmat.2008.03.006

Paleti Siva Sai Krishna, C. (2011). Workability and air void related problems in plain and fly ash cementitious systems. In: ProQuest Dissertations Publishing.

Parthiban, K., & Saravana Raja Mohan, K. (2017). Influence of recycled concrete aggregates on the engineering and durability properties of alkali activated slag concrete. *Construction & building materials, 133*, 65-72. doi:10.1016/j.conbuildmat.2016.12.050

Pedro, D., de Brito, J., & Evangelista, L. (2015). Performance of concrete made with aggregates recycled from precasting industry waste: influence of the crushing process. *Materials and structures, 48*(12), 3965-3978. doi:10.1617/s11527-014-0456-7

Pedro, D., de Brito, J., & Evangelista, L. (2017). Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement. *Construction & building materials, 147*, 803-814. doi:10.1016/j.conbuildmat.2017.05.007

Peng, Y., Chu, H., & Pu, J. (2016). Numerical Simulation of Recycled Concrete Using Convex Aggregate Model and Base Force Element Method. *Advances in materials science and engineering, 2016*, 1-10. doi:10.1155/2016/5075109

Perdikou, S., & Nicholaides, D. (2014). Weather effects on recycled concrete used as a paving material for roads. *Natural Hazards, 72*(1), 109-117. doi:10.1007/s11069-013-0561-x

Pereira, P., Evangelista, L., & de Brito, J. (2012a). The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates. *Construction & building materials, 28*(1), 722-729. doi:10.1016/j.conbuildmat.2011.10.050

Pereira, P., Evangelista, L., & de Brito, J. (2012b). The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates. *Cement & concrete composites, 34*(9), 1044-1052. doi:10.1016/j.cemconcomp.2012.06.009

Piaw, C. Y. (2006). *Basic Research Statistics*

Pickel, D., Tighe, S., & West, J. S. (2017). Assessing benefits of pre-soaked recycled concrete aggregate on variably cured concrete. *Construction & building materials, 141*, 245-252. doi:10.1016/j.conbuildmat.2017.02.140

Poon, C.-S., & Chan, D. (2007). Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. *Construction & building materials, 21*(1), 164-175. doi:10.1016/j.conbuildmat.2005.06.031

Poon, C.-S., Kou, S.-c., Wan, H.-w., & Etxeberria, M. (2009). Properties of concrete blocks prepared with low grade recycled aggregates. *Waste Manag, 29*(8), 2369-2377. doi:10.1016/j.wasman.2009.02.018

Poon, C. S., & Chan, D. (2006a). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction & building materials, 20*(8), 578-585. doi:10.1016/j.conbuildmat.2005.01.045

Poon, C. S., & Chan, D. (2006b). Paving blocks made with recycled concrete aggregate and crushed clay brick. *Construction & building materials, 20*(8), 569-577. doi:10.1016/j.conbuildmat.2005.01.044

Poon, C. S., & Kou, S. C. (2010). *EFFECTS OF FLY ASH ON MECHANICAL PROPERTIES OF 10-YEAR-OLD CONCRETE PREPARED WITH RECYCLED CONCRETE AGGREGATES.*

Poon, C. S., Kou, S. C., & Lam, L. (2006). Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. *Construction & building materials, 20*(10), 858-865. doi:10.1016/j.conbuildmat.2005.07.001

Poon, C. S., Kou, S. C., & Lam, L. (2007). Influence of recycled aggregate on slump and bleeding of fresh concrete. *Materials and structures, 40*(9), 981-988. doi:10.1617/s11527-006-9192-y

Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Construction & building materials, 18*(6), 461-468. doi:10.1016/j.conbuildmat.2004.03.005

Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and concrete research, 34*(1), 31-36. doi:https://doi.org/10.1016/S0008-8846(03)00186-8

Popovics, S., & Ujhelyi, J. (2008). Contribution to the concrete strength versus water-cement ratio relationship. *J. Mater. Civ. Eng., 20*, 459-463.

Prakash, K. B., & Krishnaswamy, K. T. (1998). Suitability of superplasticized recycled aggregate concrete in road construction. *8th International Symposium on Concrete Roads*, 25-31.

Radonjanin, V., Malešev, M., Marinković, S., & Al Malty, A. E. S. (2013). Green recycled aggregate concrete. *Construction & building materials, 47*, 1503-1511. doi:10.1016/j.conbuildmat.2013.06.076

Radonjanin, V., Marinković, S., & Malešev, M. (2010). Recycled Concrete as Aggregate for Structural Concrete Production. *Sustainability (Basel, Switzerland), 2*(5), 1204-1225. doi:10.3390/su2051204

Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. *Building and environment, 42*(1), 407-415. doi:10.1016/j.buildenv.2005.07.033

Rao, A., Jha, K. N., & Misra, S. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources, conservation and recycling, 50*(1), 71-81. doi:10.1016/j.resconrec.2006.05.010

Rao, K. J., Keerthi, K., & Vasam, S. (2018). Acid resistance of quaternary blended recycled aggregate concrete. *Case Studies in Construction Materials, 8*, 423-433. doi:10.1016/j.cscm.2018.03.005

Ravindrarajah, S. R., & Tam, C. T. (1987). Recycled concrete as fine aggregate in concrete. *Magazine of Concrete Research, 39*, 214-220.

Ray, S. P., & Venkateswarlu, B. (1991). Recycled aggregate concrete. *Journal of Structural Engineering, 18*, 67-75.

Ridzuan, A. R. M., Ibrahim, A., Ismail, A. M. M., & Diah, A. B. M. (2005). DURABLITY PERFORMANCE OF RECYCLED AGGREGATE CONCRETE. In *Achieving Sustainability in Construction* (pp. 193-202).

Rodrigues, F., Carvalho, M. T., Evangelista, L., & de Brito, J. (2013). Physical–chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants. *Journal of cleaner production, 52*, 438-445. doi:10.1016/j.jclepro.2013.02.023

Roesler, J., Lange, D., Salas, A., Brand, A., & Arboleda, C. (2013). Properties of Recycled Concrete Aggregates for Airfield Rigid Pavements. *Center of Excellence for Airport Technology (CEAT), CEO Report No. 34*. Retrieved from http://hdl.handle.net/2142/45894

Rohi M. Salem, E. G. B., & Jackson, N. M. (2003). Resistance to Freezing and Thawing of Recycled Aggregate Concrete. *ACI materials journal, 100*(3). doi:10.14359/12622

Sáez del Bosque, I. F., Zhu, W., Howind, T., Matías, A., Sánchez de Rojas, M. I., & Medina, C. (2017). Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate. *Cement & concrete composites, 81*, 25-34. doi:10.1016/j.cemconcomp.2017.04.011

Sagoe-Crentsil, K., & Brown, T. (1998). Guide for specification of Recycled Concrete Aggregates (RCA) for concrete production. *CSIRO, Building, Construction and Engineering*.

Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and concrete research, 31*(5), 707-712. doi:10.1016/S0008-8846(00)00476-2

Şahmaran, M., Keskin, S. B., Ozerkan, G., & Yaman, I. O. (2008). Self-healing of mechanically-loaded self consolidating concretes with high volumes of fly ash. *Cement & concrete composites, 30*(10), 872-879. doi:10.1016/j.cemconcomp.2008.07.001

Saini, B. S., & Singh, S. P. (2020). Flexural fatigue strength prediction of self compacting concrete made with recycled concrete aggregates and blended cements. *Construction & building materials, 264*, 120233. doi:10.1016/j.conbuildmat.2020.120233

Salem, R. M., & Burdette, E. G. (1998). Role of chemical and admixtures on physical and frost resistance of recycled aggregate concrete. *ACI Mater. J, 95*, 558-563.

Salgues, M., Souche, J. C., Devillers, P., & Garcia-Diaz, E. (2018). Influence of initial saturation degree of recycled aggregates on fresh cement paste characteristics: consequences on recycled concrete properties. *European journal of environmental and civil engineering, 22*(9), 1146-1160. doi:10.1080/19648189.2016.1245630

Salomon, L., & Paulo, H. (2007). Durability of concrete mixed with fine recycled aggregates. *Exacta, 5*(1), 25-34.

Santos, S., da Silva, P. R., & de Brito, J. (2019). Self-compacting concrete with recycled aggregates – A literature review. *Journal of Building Engineering, 22*, 349-371. doi:10.1016/j.jobe.2019.01.001

Sasanipour, H., & Aslani, F. (2020a). Durability assessment of concrete containing surface pretreated coarse recycled concrete aggregates. *Construction & building materials, 264*, 120203. doi:10.1016/j.conbuildmat.2020.120203

Sasanipour, H., & Aslani, F. (2020b). Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates. *Construction & building materials, 236*, 117540. doi:10.1016/j.conbuildmat.2019.117540

Sasanipour, H., Aslani, F., & Taherinezhad, J. (2019). Effect of silica fume on durability of self-compacting concrete made with waste recycled concrete aggregates. *Construction & building materials, 227*, 116598. doi:10.1016/j.conbuildmat.2019.07.324

Seara-Paz, S., González-Fonteboa, B., Martínez-Abella, F., & González-Taboada, I. (2016). Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage. *Construction & building materials, 122*, 95-109. doi:10.1016/j.conbuildmat.2016.06.050

Šeps, K., Fládr, J., & Broukalová, I. (2016). Resistance of Recycled Aggregate Concrete to Freeze-thaw and Deicing Salts. *Procedia engineering, 151*, 329-336. doi:10.1016/j.proeng.2016.07.367

Shaikh, F. U. A. (2016). Effect of ultrafine fly ash on the properties of concretes containing construction and demolition wastes as coarse aggregates. *Structural concrete : journal of the FIB, 17*(1), 116-122. doi:10.1002/suco.201500030

Shehata, M. H., Christidis, C., Mikhaiel, W., Rogers, C., & Lachemi, M. (2010). Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali–silica reaction. *Cement and concrete research, 40*(4), 575-582. doi:10.1016/j.cemconres.2009.08.008

Shi, C., Li, Y., Zhang, J., Li, W., Chong, L., & Xie, Z. (2016). Performance enhancement of recycled concrete aggregate – A review. *Journal of cleaner production, 112*, 466-472. doi:10.1016/j.jclepro.2015.08.057

Shi, C., Wu, Z., Cao, Z., Ling, T. C., & Zheng, J. (2018). Performance of mortar prepared with recycled concrete aggregate enhanced by CO2 and pozzolan slurry. *Cement & concrete composites, 86*, 130-138. doi:10.1016/j.cemconcomp.2017.10.013

Shi, C. J., Cao, Z. J., & Xie, Z. B. (2016). Research progress in the mechanical properties of recycled aggregate concrete. *Mater. Rev., A 30*, 96 - 103.

Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction & building materials, 65*, 201-217. doi:10.1016/j.conbuildmat.2014.04.117

Silva, R. V., de Brito, J., & Dhir, R. K. (2015a). Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete. *Engineering structures, 100*, 31-42. doi:10.1016/j.engstruct.2015.06.004

Silva, R. V., de Brito, J., & Dhir, R. K. (2015b). The influence of the use of recycled aggregates on the compressive strength of concrete: a review. *European journal of environmental and civil engineering, 19*(7), 825-849. doi:10.1080/19648189.2014.974831

Silva, R. V., de Brito, J., & Dhir, R. K. (2015c). Tensile strength behaviour of recycled aggregate concrete. *Construction & building materials, 83*, 108-118. doi:10.1016/j.conbuildmat.2015.03.034

Silva, R. V., Neves, R., de Brito, J., & Dhir, R. K. (2015). Carbonation behaviour of recycled aggregate concrete. *Cement & concrete composites, 62*, 22-32. doi:10.1016/j.cemconcomp.2015.04.017

Silva, Y. F., Robayo, R. A., Mattey, P. E., & Delvasto, S. (2016). Properties of self-compacting concrete on fresh and hardened with residue of masonry and recycled concrete. *Construction and Building Materials, 124*, 639-644. doi:https://doi.org/10.1016/j.conbuildmat.2016.07.057

Singh, N., M, M., & Arya, S. (2019). Utilization of coal bottom ash in recycled concrete aggregates based self compacting concrete blended with metakaolin. *Resources, conservation and recycling, 144*, 240-251. doi:10.1016/j.resconrec.2019.01.044

Singh, N., & Singh, S. P. (2016). Carbonation resistance and microstructural analysis of Low and High Volume Fly Ash Self Compacting Concrete containing Recycled Concrete Aggregates. *Construction & building materials, 127*, 828-842. doi:10.1016/j.conbuildmat.2016.10.067

Singh, N., & Singh, S. P. (2018). Evaluating the performance of self compacting concretes made with recycled coarse and fine aggregates using non destructive testing techniques. *Construction & building materials, 181*, 73-84. doi:10.1016/j.conbuildmat.2018.06.039

Singh, R. B., & Singh, B. (2018). Rheological behaviour of different grades of self-compacting concrete containing recycled aggregates. *Construction & building materials, 161*, 354-364. doi:10.1016/j.conbuildmat.2017.11.118

Smith, J. T. (2018). Recycled Concrete Aggregate-a Viable Aggregate Source for Concrete Pavements. *Ph D Dissertation*, 206.

Snyder, M. B., Vandenbossche, J. M., Smith, K. D., & Wade, M. (1994). Synthesis on Recycled Concrete Aggregate. *Interim Report - Task A.*

Somna, R., Jaturapitakkul, C., & Amde, A. M. (2012). Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete. *Cement & concrete composites, 34*(7), 848-854. doi:10.1016/j.cemconcomp.2012.03.003

Souche, J.-C., Bendimerad, A. Z., Roziere, E., Salgues, M., Devillers, P., Garcia-Diaz, E., & Loukili, A. (2017). Early age behaviour of recycled concrete aggregates under normal and severe drying conditions. *Journal of Building Engineering, 13*, 244-253. doi:10.1016/j.jobe.2017.08.007

Sturtevant, J. R. (2007). Performance of rigid pavements containing recycled concrete aggregates. In: ProQuest Dissertations Publishing.

Sun, H., Wang, P. M., & Sun, J. Y. (2006). Study on the gas anti-permeability and carbonation resistance of recycled concrete. *J. Build. Mater.*, *9*, 86-91.

Sun, J. Y., & Geng, J. (2012). Effect of particle size and content of recycled fine aggregate on frost resistance of concret. *J. Build. Mater.*, *15*, 382-385.

Tabsh, S. W., & Abdelfatah, A. S. (2009). Influence of recycled concrete aggregates on strength properties of concrete. *Construction & building materials, 23*(2), 1163-1167. doi:10.1016/j.conbuildmat.2008.06.007

Tam, V. W.-Y., Gao, X.-F., & Tam, C. M. (2006). Comparing performance of modified two-stage mixing approach for producing recycled aggregate concrete. *Magazine of Concrete Research, 58*(7), 477-484. doi:10.1680/macr.2006.58.7.477

Tam, V. W. Y., Gao, X. F., & Tam, C. M. (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and concrete research, 35*(6), 1195-1203. doi:10.1016/j.cemconres.2004.10.025

Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction & building materials, 172*, 272-292. doi:10.1016/j.conbuildmat.2018.03.240

Tam, V. W. Y., & Tam, C. M. (2007). Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach. *Journal of materials science, 42*(10), 3592-3602. doi:10.1007/s10853-006-0379-y

Tam, V. W. Y., & Tam, C. M. (2008). Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc. *Construction & building materials, 22*(10), 2068-2077. doi:10.1016/j.conbuildmat.2007.07.024

Tam, V. W. Y., & Tam, C. M. (2009). Parameters for assessing recycled aggregate and their correlation. *Waste Management & Research, 27*(1), 52-58. doi:10.1177/0734242x07079875

Tam, V. W. Y., Tam, C. M., & Wang, Y. (2007). Optimization on proportion for recycled aggregate in concrete using two-stage mixing approach. *Construction & building materials, 21*(10), 1928-1939. doi:10.1016/j.conbuildmat.2006.05.040

Thomas, C., Setién, J., Polanco, J. A., Alaejos, P., & Sánchez de Juan, M. (2013). Durability of recycled aggregate concrete. *Construction & building materials, 40*, 1054-1065. doi:10.1016/j.conbuildmat.2012.11.106

Topcu, I. B., & Sengel, S. (2004). Properties of concretes produced with waste concrete aggregate. *Cement and concrete research, 34*(8), 1307-1312. doi:10.1016/j.cemconres.2003.12.019

Tosic, N., Marinkovic, S., & Ignjatovic, I. (2016). A database on flexural and shear strength of reinforced recycled aggregate concrete beams and comparison to Eurocode 2 predictions. *Construction & building materials, 127*, 932-944. doi:10.1016/j.conbuildmat.2016.10.058

Tsujino, M., Noguchi, T., Tamura, M., Kanematsu, M., & Maruyama, I. (2007). Application of Conventionally Recycled Coarse Aggregate to Concrete Structure by Surface Modification Treatment. *ACT, 5*(1), 13-25. doi:10.3151/jact.5.13

Tuyan, M., Mardani-Aghabaglou, A., & Ramyar, K. (2014). Freeze–thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate. *Materials in engineering, 53*, 983-991. doi:10.1016/j.matdes.2013.07.100

USEPA. (2016). Construction and Demolition Debris Generation in the United States. 23. Retrieved from https://www.epa.gov/sites/production/files/2018-

09/documents/construction_and_demolition_debris_generation_in_the_united_states_2015_final.pdf

USGS. (2000). Recycled Aggregates-profitable Resource Conservation. Retrieved from https://pubs.usgs.gov/fs/fs-0181-99/fs-0181-99so.pdf

Van Praagh, M., Modin, H., & Trygg, J. (2015). Organic compounds in concrete from demolition works. *Waste Manag, 45*(Online 09 July 2015), 186-193. doi:10.1016/j.wasman.2015.06.037

Vázquez, E., Barra, M., Aponte, D., Jiménez, C., & Valls, S. (2014). Improvement of the durability of concrete with recycled aggregates in chloride exposed environment. *Construction & building materials, 67*, 61-67. doi:10.1016/j.conbuildmat.2013.11.028

Veiga, M. R. (1997). Performance of Rendering Mortars in Walls - Contribution to the Study of Their Resistance to Cracking. *Ph.D. thesis, Faculty of Engineering of the Porto University* 552.

Verian, K. P. (2012). Using recycled concrete as coarse aggregate in pavement concrete. In: ProQuest Dissertations Publishing.

Verian, K. P. (2015). influence of Air-cooled blast furnace slag coarse aggregate on properties of pavement concrete exposed to freezing-thawing and wetting-drying conditions *Ph.D Dissertation*, 206.

Verian, K. P., Ashraf, W., & Cao, Y. (2018). Properties of recycled concrete aggregate and their influence in new concrete production. *Resources, conservation and recycling, 133*, 30-49. doi:10.1016/j.resconrec.2018.02.005

Verian, K. P., Whiting, N. M., Jitendra, J., Olek, J., & Snyder, J. (2013). Using recycled concrete as aggregate in concrete pavements to reduce materials cost. *joint transportation research program*.

Vieira, J. P. B., Correia, J. R., & de Brito, J. (2011). Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. *Cement and concrete research, 41*(5), 533-541. doi:10.1016/j.cemconres.2011.02.002

Vieira, T., Alves, A., de Brito, J., Correia, J. R., & Silva, R. V. (2016). Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware. *Materials & design, 90*, 767-776. doi:10.1016/j.matdes.2015.11.023

Vinay Kumar, B. M., Ananthan, H., & Balaji, K. V. A. (2017). Experimental studies on utilization of coarse and finer fractions of recycled concrete aggregates in self compacting concrete mixes. *Journal of Building Engineering, 9*, 100-108. doi:10.1016/j.jobe.2016.11.013

Wang, J., Vandevyvere, B., Vanhessche, S., Schoon, J., Boon, N., & De Belie, N. (2017). Microbial carbonate precipitation for the improvement of quality of recycled aggregates. *Journal of cleaner production, 156*, 355-366. doi:10.1016/j.jclepro.2017.04.051

Wang, L., Wang, J., Qian, X., Chen, P., Xu, Y., & Guo, J. (2017). An environmentally friendly method to improve the quality of recycled concrete aggregates. *Construction & building materials, 144*, 432-441. doi:10.1016/j.conbuildmat.2017.03.191

Wang, Q., Yan, P., Yang, J., & Zhang, B. (2013). Influence of steel slag on mechanical properties and durability of concrete. *Construction & building materials, 47*, 1414-1420. doi:10.1016/j.conbuildmat.2013.06.044

Wardeh, G., Ghorbel, E., & Gomart, H. (2015). Mix Design and Properties of Recycled Aggregate Concretes: Applicability of Eurocode 2. *International journal of concrete structures and materials, 9*(1), 1-20. doi:10.1007/s40069-014-0087-y

Wegen, G. v. d., & Haverkort, R. (1998). RECYCLED CONSTRUCTION AND DEMOLITION WASTES AS A FINE AGGREGATE FOR CONCRETE. In *Sustainable Construction: Use of Recycled Concrete Aggregate* (pp. 333-345).

Wild, S., Khatib, J., Sabir, B., & Addis, S. D. (1996). The potential of fired brick clay as a partial cement replacement material. *Proceedings of the international conference of concrete in the service of mankind*, 685-696.

Wu, J., Jing, X., & Wang, Z. (2017). Uni-axial compressive stress-strain relation of recycled coarse aggregate concrete after freezing and thawing cycles. *Construction & building materials, 134*, 210-219. doi:10.1016/j.conbuildmat.2016.12.142

Xiao, J., Li, J., & Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and concrete research, 35*(6), 1187-1194. doi:https://doi.org/10.1016/j.cemconres.2004.09.020

Xiao, J., Li, L., Shen, L., & Poon, C. S. (2015). Compressive behaviour of recycled aggregate concrete under impact loading. *Cement and concrete research, 71*, 46-55. doi:10.1016/j.cemconres.2015.01.014

Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction & building materials, 31*(1), 364-383. doi:10.1016/j.conbuildmat.2011.12.074

Xiao, J., Li, W., & Poon, C. (2012). Recent studies on mechanical properties of recycled aggregate concrete in China—A review. *Science China. Technological sciences, 55*(6), 1463-1480. doi:10.1007/s11431-012-4786-9

Xuan, D., Zhan, B., & Poon, C. S. (2016). Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cement & concrete composites, 65*, 67-74. doi:10.1016/j.cemconcomp.2015.10.018

Xuan, D., Zhan, B., & Poon, C. S. (2017). Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates. *Cement & concrete composites, 84*, 214-221. doi:10.1016/j.cemconcomp.2017.09.015

Y Kimura, K. I., M Nagayama and H Tamura. (2004). High quality recycled aggregate concrete (HiRAC) processed by decompression and rapid release. *international RILEM Symposium on Environment-Conscious Materials and Systems for Sustainable Development*, 163-170.

Yanagibashi, K., Yonezawa, T., Arakawa, K., & Yamada, M. (2002). A NEW CONCRETE RECYCLING TECHNIQUE FOR COARSE AGGREGATE REGENERATION PROCESS. In *Challenges of Concrete Construction: Volume 5, Sustainable Concrete Construction* (pp. 511-522).

Yang, K.-H., Chung, H.-S., & Ashour, A. F. (2008). Influence of type and replacement level of recycled aggregates on concrete properties. *ACI materials journal, 105*(3), 289-296. doi:10.14359/19826

Yaragal, S. C., Teja, D. C., & Shaffi, M. (2016). Performance studies on concrete with recycled coarse aggregates. *Advances in Concrete Construction, 4*, 263-281. Retrieved from http://www.techno-press.org/content/?page=article&journal=acc&volume=4&num=4&ordernum=3

Yildirim, S. T., Meyer, C., & Herfellner, S. (2015). Effects of internal curing on the strength, drying shrinkage and freeze–thaw resistance of concrete containing recycled concrete aggregates. *Construction & building materials, 91*, 288-296. doi:10.1016/j.conbuildmat.2015.05.045

Younis, K. H., & Pilakoutas, K. (2013). Strength prediction model and methods for improving recycled aggregate concrete. *Construction & building materials, 49*, 688-701. doi:10.1016/j.conbuildmat.2013.09.003

Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., & Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement & concrete composites, 25*(2), 223-232. doi:10.1016/S0958-9465(02)00010-0

Zaharieva, R., Buyle-Bodin, F., & Wirquin, E. (2004). Frost resistance of recycled aggregate concrete. *Cement and concrete research, 34*(10), 1927-1932. doi:10.1016/j.cemconres.2004.02.025

Zega, C. J., & Maio, A. A. D. (2006). Recycled concrete exposed to high temperatures. *Magazine of Concrete Research, 58*, 675-682.

Zega, C. J., Villagran-Zaccardi, Y. A., & Di Maio, A. A. (2010). Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. *Materials and structures, 43*(1-2), 195-202. doi:10.1617/s11527-009-9480-4

Zhan, B. J., Poon, C. S., & Shi, C. J. (2016). Materials characteristics affecting CO2 curing of concrete blocks containing recycled aggregates. *Cement & concrete composites, 67*, 50-59. doi:10.1016/j.cemconcomp.2015.12.003

Zhan, B. J., Xuan, D. X., & Poon, C. S. (2018). Enhancement of recycled aggregate properties by accelerated CO2 curing coupled with limewater soaking process. *Cement & concrete composites, 89*, 230-237. doi:10.1016/j.cemconcomp.2018.03.011

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C.-S., & Xie, Z. (2015). Influence of carbonated recycled concrete aggregate on properties of cement mortar. *Construction & building materials, 98*, 1-7. doi:10.1016/j.conbuildmat.2015.08.087

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C.-S., & Xie, Z. (2015). Performance Enhancement of Recycled Concrete Aggregates through Carbonation. *J Mater. Civ. Eng., 27*. Retrieved from https://ascelibrary.org/doi/full/10.1061/%28ASCE%29MT.1943-5533.0001296?casa_token=fFgmCJ6G-EIAAAAA%3AQavWdYzGzSxltBmyCwNhVU-e0hJPlDsf7pX1ZRGWWtbDEP2nfri_HyYfiAn5hOtLcP7gpEQiH4Lk

Zhang, J., Taylor, P. C., & Shi, C. (2015). Investigation of Approaches for Improving Interfacial Transition Zone-Related Freezing-and-Thawing Resistance in Concrete Pavements. *ACI materials journal, 112*(5), 613-617. doi:10.14359/51687902

Zhang, X.-b., 张学兵, Fang, Z., 方, 志., 邓寿昌, Deng, S.-c., . . . 覃银辉. (2008). Additional water use influencing strength and fluidity of recycled concrete. *Journal of Central South University of Technology. Science & technology of mining and metallurgy, 15*(S1), 221-224. doi:10.1007/s11771-008-0350-y

Zhang, X., & Wu, K. R. (2002). Mechanism and key technique of mineral admixture. *J. Tongii Univ. Nat. Sci. Ed., 32*, 494-498.

Zhong, W., & Yao, W. (2008). Influence of damage degree on self-healing of concrete. *Construction & building materials, 22*(6), 1137-1142. doi:10.1016/j.conbuildmat.2007.02.006

Zhou, C., & Chen, Z. (2017). Mechanical properties of recycled concrete made with different types of coarse aggregate. *Construction & building materials, 134*, 497-506. doi:10.1016/j.conbuildmat.2016.12.163

Zhu, Y.-G., Kou, S.-C., Poon, C.-S., Dai, J.-G., & Li, Q.-Y. (2013). Influence of silane-based water repellent on the durability properties of recycled aggregate concrete. *Cement & concrete composites, 35*(1), 32-38. doi:10.1016/j.cemconcomp.2012.08.008

陈宝璠, & Chen, B. (2013). Basic mechanical properties and microstructural analysis of recycled concrete. *Journal of Wuhan University of Technology. Materials science edition, 28*(1), 104-109. doi:10.1007/s11595-013-0649-x