

Renan Sorato

Recycled aggregate concrete; an overview

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<p>The aim of this Bachelor's thesis was to investigate whether recycled materials can be incorporated into the production of concrete without compromising the compressive strength of the concrete produced. In order to shed light on the compressive strength of concrete made from recycled materials, the thesis reviewed studies in which waste materials are utilised as recycled aggregates in the composition of concrete and presented the results of this synthesis and analysis. It was found that some types of recycled aggregate can be used as a component in the production of concrete without undermining the compressive strength of the concrete produced.</p> <p>This thesis provided an insight into the current use of recycled aggregates in Finland. It was established that the current legislation in Finland imposes a heavy bureaucratic burden on the production of concrete using recycled aggregates.</p> <p>The research implicated that the possibility of utilising waste material in the production of concrete offers a compelling alternative to waste disposal and the preservation of natural resources. However, legislation that hinders the use of recycled aggregate in Finland should be re-evaluated in order for the construction industry to be able to utilise recycled aggregates on a larger scale.</p>	
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Definitions ¹

aggregate: inert granular material such as sand, gravel, crushed rock and clinker used as a main solid constituent in concrete, plaster, tarmacadam and asphalt.

bottom ash: bottom ash is part of the non-combustible residue of combustion in a furnace or incinerator. In an industrial context, it usually refers to coal combustion and comprises traces of combustibles embedded in forming clinkers and sticking to hot side walls of a coal-burning furnace during its operation. The portion of the ash that escapes up the chimney or stack is, however, referred to as fly ash.

coarse aggregate: aggregate which consists largely of particles over 5 mm in diameter.

conventional aggregate: (see aggregate)

end-of-waste: end-of-waste criteria specify when certain waste ceases to be waste and obtains a status of a product (or a secondary raw material).

fine aggregate: aggregate consisting largely of particles with a size range of 75 mm–5 mm.

RA (recycled aggregate or recycled aggregates): aggregate composed of recycled materials

RAC (recycled aggregate concrete): it is the concrete that had recycled aggregates as a component in the mixing process.

recycled concrete aggregates or secondary aggregate: it is the fine and coarse aggregate that is produced from processing of the crushed original concrete.

ultimate compressive strength: the stress at which a material or structural component fails in compression or is crushed.

waste concrete: it is the concrete rubble of demolished structures, and/or the concrete that was rejected during construction of new structures.

¹ Definitions above were taken from the Dictionary of Architecture and Building Construction [1]

1 Introduction

Globally speaking, there is an evident need to recycle more and thus, reduce the amount of waste being disposed into landfills that are rapidly filling [2]. The construction industry in particular is notorious for the creation of vast amounts of waste [3]. It is only sensible that this industry should do more to develop new ways of bringing waste that can potentially be recycled back into the production line.

Because concrete is the most widely used construction material in the world today [4], this thesis focuses on a specific component that accounts for 80% of the volume of concrete [5], that is, aggregates. Aggregates are becoming increasingly scarce in urban areas. That means that aggregates have to be transported from longer distances into the urban areas, which is where most buildings are constructed. Stringent environmental laws and growing public awareness towards a more sustainable society have driven organisations and governments to search for a replacement to aggregates. [6.]

This thesis aims to provide an overview of recent studies that have been carried out to investigate the incorporation of recycled aggregates, hereafter referred to as RA, into the production of concrete. In particular, this thesis examines the results of those studies in regard to the compressive strength of concrete blocks made with RA, hereafter referred to as recycled aggregate concrete, or simply, RAC. The goal is to identify if RAC has achieved similar mechanical performances as normally expected from conventional concrete.

Considerable amount of research has been carried out with different types of materials. This thesis presents the most widely researched waste material used as RA, that is, concrete waste. In addition, other less commonly used waste materials are introduced. These are: general plastic, polyethylene terephthalate (PET) bottles, tyre rubber and coal bottom ash. It is important to note that each of these waste materials would require a book in their own right to explain their mechanical characteristics as RA.

Furthermore, the current Finnish situation of incorporating RA into concrete is discussed. Given that of all aggregates utilised in Finland in 2013, only 1% derived from a recycled source [7], this thesis aims to examine the reasons behind this almost non-existent application of RA in Finland.

Overall, the purpose of this thesis is to increase the awareness of the scarcity of aggregates in the metropolitan areas and to present alternatives that replace the use of aggregates. By diminishing the amount of aggregates extracted from nature, the use of RA creates an opportunity to preserve natural resources and offers and assists the pursuit of a greener planet for the present and future generations.

2 Aggregates

Aggregates are inert, granular materials such as sand, gravel, crushed rock and clinker used as a main solid constituent in concrete, plaster, tarmacadam and asphalt [1]. The European Aggregates Association (UEPG) states that the aggregate sector is by far the world's largest non-energy extractive industry today in terms of tonnes produced, companies operating and people employed [7]. Rather than only being an alternative to make the production of concrete more economically viable, aggregates play a pivotal role in the properties of concrete as cement alone is hardly suitable to most construction duties. Therefore, it can be said that without the use of aggregates, our buildings and infrastructures would simply collapse.

Aggregates are almost exclusively obtained by extraction from a wide range of natural resources. Sand and gravel are commonly dug up from lakes, rivers or the bottom of the ocean. Crushed stone can be collected by excavation and/or detonation of bedrocks. [5.] UEPG estimates that 400 tonnes of aggregates is needed for one single house to be built. This number skyrockets to a colossal 30000 tonnes for the construction of one single kilometre of highway. Due to the high costs of transportation, it is imperative that aggregates are obtained from local sources or otherwise the price for concrete production significantly increases, which in turn may delay the development of an area. UEPG emphasises that there is hardly any international trade between the 28 countries in the EU and the companies that extract aggregates are mostly comprised of small and medium-sized firms. [7.]

Domone and Illson explain that the use of aggregates has to correspond to the requirements of each individual project. These needs are mostly associated with durability, shape, frost and abrasion resistance, among other factors. [8.] Because aggregates make 80% of the volume of concrete [5], the option for the right aggregate has to be

carefully considered as the chosen application will exercise a significant influence on concrete's properties and performance as is seen in Chapter 4.

According to the annual review organised by UEPG, in the year 2013, EU consumed a staggering 2.5 billion tonnes of aggregates, with Germany as the top user (546 million tonnes). Although Finland only produced 83 million tonnes in 2013 (64% crushed rock; 35% sand and gravel; 1% RA), figure 1 shows that Finland leads the ranking of production per capita amongst EU countries with 16 tonnes per inhabitant. [7.]

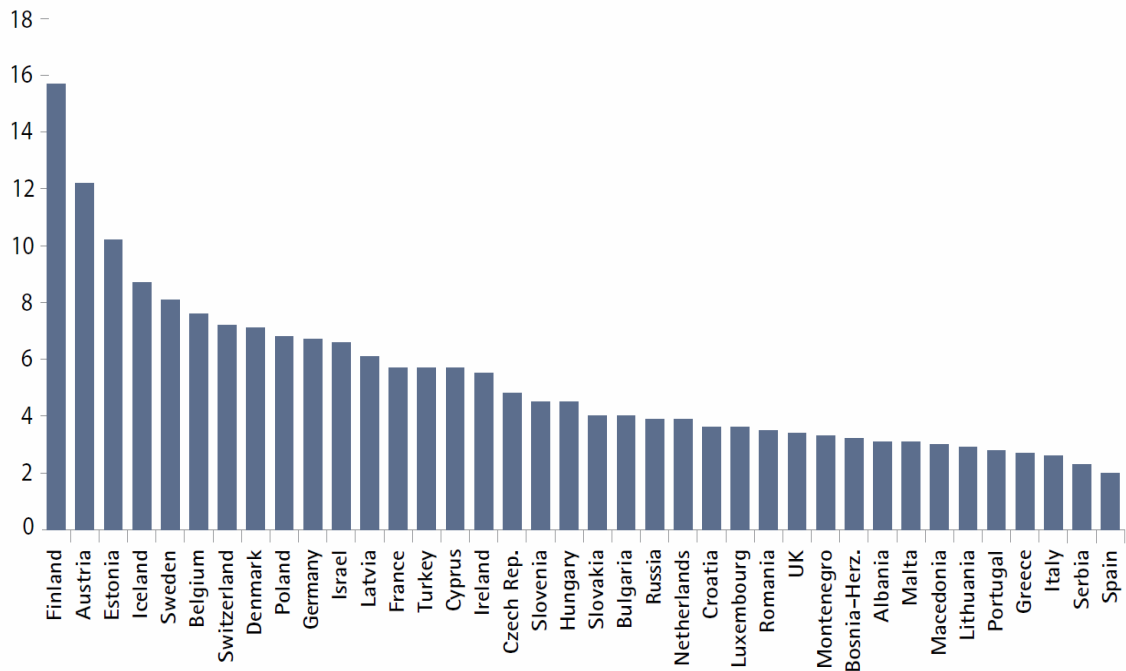


Figure 1. Tonnes of aggregate produced per capita by country [7]

The production of aggregate in a particular region is highly dependent on the construction development in that specific area. That means to say, if there is a new shopping centre and hospital being built in Turku (southwest Finland), the production of aggregate will significantly increase around the Turku region only. The construction of this hospital and shopping centre in Turku will not increase the amount of aggregate being produced in areas distant from this city, such as Rovaniemi (north Finland), for example.

In a global scale, if the construction industry is booming in a certain country, the production of aggregates will simply skyrocket in that specific country. In the other way, an economic downturn will push aggregate companies out of business. As prove of this, UEPG records show that countries members of the European Free Trade Association (EFTA) produced 3,65 billion tonnes of aggregates in 2007. The economic recession of

2008 has brought the production of aggregates within EFTA countries to 2.60 billion tonnes in 2013, a decrease of 29% from 2007.

The worldwide consumption of aggregates can be difficult to estimate as big producers such as India and China hold poor or dubious records. Different sources demonstrate a striking discrepancy; values for the annual worldwide production of aggregates ranged from 16,5 to 30,0 billion tonnes in 2005 [9-10]. Regardless of what the real number is, it seems clear that there will be severe implications if predatory use of our natural resources continues.

Habert and Roussel suggest that the biggest threat to the concrete industry is the depletion of aggregates surrounding the developed areas, whereas worldwide depletion is not a concern. Their studies estimate that the price of RA doubles for every 30km of distance that the product has to be transported. [11.] Since aggregates are of very bulk size and weight, CO₂ emissions from transportation leave an immense carbon footprint behind.



Figure 2. Extraction of aggregates in Finland [12]

Environmental impacts associated with extraction of aggregates are easily distinguishable as seen in figure 2. The operation of heavy machinery, coupled with detonations and drillings, generate an unceasing noise and create a huge amount of dust. In addition to that, the process of extracting aggregates brings about a devastating visual burden to

the local landscape as thousands of trees have to be cut down and cleared in order for the aggregates to be extracted. Cutting down the trees not only cause a visual pollution, but it also dislocates or completely annihilates local fauna.

As for marine aggregates, that is, aggregates that are dredged from lakes, rivers or the bottom of the ocean, a study conducted by Messieh et al. [13] investigated the overwhelming destruction of sea life by the marine aggregate industry in eastern Canada. Their studies presented and explained the physical damages and the adverse biological effects of dredging aggregates.

Governments around the world are increasingly more aware of the disastrous consequences caused by irresponsible extraction of aggregates. Therefore, environmental regulations are becoming more restrict. In Finland, the Ministry of the Environment has amended the Environmental Protection Act (86/2000) in several occasions in order to discourage the extraction of natural resources and to stimulate the recycling of waste materials [14].

3 Recycled aggregate concrete (RAC)

There are many reasons why concrete has been the most widely used material in the world for many decades now [4]. The most advantageous characteristics of concrete can be listed as: relatively low cost, grand scale availability of its raw components, durability, workability, how adaptable concrete is to be shaped into any form and its fire resistance. But there is a price to pay for all these benefits, namely, the colossal energy consumption and devastating pollution that results from the manufacturing of cement [15].

To reduce this impact and achieve a more sustainable product, waste materials can be incorporated into concrete in the form of RA. The most extensively researched material used in the production of RA is waste concrete, that is, fine and coarse debris from demolition sites. Also, less common components such as glass, coal fly ash, plastic, tyres, volcanic ash and foundry sand have been investigated by several researchers [16-20]. Concrete with RA as a component in the mixing process is referred to as recycled aggregate concrete.

Considering the shortage of aggregates around developed areas and most importantly, the environmental impact caused by the extraction of these materials, it is only natural to imagine that the use of RA is at full speed. The truth is far from this. According to UEPG, only 1% of the total amount of aggregates produced in Finland in 2013 originated from a recycled source (crushed old concrete, scum and ash) [7].

Russia and Turkey produced 550 and 431 million tonnes of aggregates, respectively, without using any recycled material. Some EU countries have the same RA input as Russia and Turkey, that is, none. On the other hand, UEPG shows that 25% of all aggregates produced in the Netherlands came from a recycled source. Other EU countries are also using RA in a greater scale than in Finland. In the UK, 21% of all aggregates produced derive from recycled materials, whereas in Belgium and Germany, this number reaches 18% and 12%, respectively. As for the 28 members of the EU put together, the average percentage of RA being used in the EU is 7%. [7.]

A study carried out by Tam [21] drew an economical comparison between the use of conventional concrete and RAC with old concrete debris as RA. Her final results demonstrated remarkable cost savings when RAC was utilised as replacement for conventional aggregates. In addition to being a more environmentally friendly option, RAC can also be used as a way of cost reduction in an increasingly competitive construction market [21].

Since aggregates are a vital part of concrete, and concrete is widely used in the world today, this thesis presents a brief literature review on the use of RA in the production of concrete, the end product is referred to as recycled aggregate concrete (RAC). The aim of this review is to establish the mechanical properties of RAC and to compare results with the mechanical performance of conventional concrete, that is, concrete made of aggregates that did not incorporate recycled materials as aggregate.

4 Literature review

Concrete has a variety of characteristics such as splitting tensile strength, modulus of elasticity, absorption, bending, sorptivity, and water penetration under pressure, among others. Although these properties play a part in defining the strength of concrete, the most important parameter of concrete is its compressive strength values and all other values are related to it [22]. With respect to carrying loads, by analysing the compressive

strength of concrete, one is able to judge if the structure will fulfil the duties it is expected to satisfy. For this reason, this thesis does not present figures related to other properties of concrete mentioned above, focusing mostly into the compressive strength of concrete.

This literature review investigates commonly used types of RA followed by a presentation of experiments conducted around the world concerning the compressive strength of concrete when aggregate is partially or fully substituted by RA. All these studies have been conducted in appropriate laboratories and results were extracted after a period of 28 days for curing. It was observed in all these experiments that the compressive strength of concrete increased with age; therefore, the reader must not assume that the results given are final values. All these researches have met the requirements on concrete manufacturing of the country where the samples were analysed in and no modification on the amount of cement applied was made when using recycled and conventional aggregate.

Hundreds of researchers have conducted experiments that evaluate the mechanical properties of concrete when old crushed concrete is utilised as RA. Waste concrete used by researchers has been predominantly collected from demolition sites. This thesis presents four studies that have incorporated waste concrete as RA. In addition, this thesis displays studies that have utilised one of these materials as RA: plastic, polyethylene terephthalate (PET) bottles, rubber tyres and lastly, coal bottom ash. It is important to note that incorporating rubber, plastic, asphalt and wood as RA has to be carefully considered beforehand as these materials may hold hazardous substances that may spread to the concrete that is prepared using these materials [23].

4.1 RA: Recycled Concrete

The construction industry is notorious for the waste it produces. Demolition sites generate an immense amount of mixed waste that most of the time ends up in a landfills when the potential reuse of this materials is simply ignored [24]. Apart from concrete, other components also create significant volumes of waste such as gypsum board, shingles, metals, glass, insulation component, earth, paper, etc [25].

Statistics indicate that Finland alone produced over 16 million tonnes of construction and demolition waste (CDW) in the year 2013, of which 26% was recycled; although this value is rather respectable when compared to developing countries, it falls behind the EU average of CDW recycling of 47%. [26.]

The production of RA using CDW offers an opportunity to utilise material that would otherwise go to landfills. Recycling protects the environment by preserving natural resources, reduces energy and transportation costs, and eliminates the need to dispose of old concrete in landfills that are being filled at a fast pace, especially in bigger cities (including Helsinki). Furthermore, recycling CDW creates new job opportunities in a field that is not yet extensively exploited thereby turning demolition sites from a problem to a solution.

The EU countries alone produced a staggering 821 millions tonnes of construction waste in 2013 [26]; therefore, it does not come as a surprise that there are numerous studies advocating the use of old concrete or mixed construction waste as RA [27-32]. Although the results of the varied sources for the compressive strength of RCA can be scattered and inconsistent, the outcome in terms of the quality of the end material always seems to match to the quality of the concrete waste being utilised. For example, the better the condition of the waste, such as age, cleanliness and purity of concrete waste, the better the results for compressive strength.

4.1.1 Coarse concrete debris

Lee et al. analysed the compressive strength of concrete made of coarse RA (old concrete debris). For this experiment, 12 cubic samples with a diameter of 800mm x 800mm x 200mm and 240 cylinder units with a diameter of 100mm and height of 200mm were used. [33.]

A summary of the results for ultimate compressive strength is presented in table 1 according to the percentage of RA content.

Table 1. Compressive strength of concrete made of coarse concrete debris as aggregate [33].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	38.49

30%	70%	37.87
50%	50%	38.01
100%	0%	38.76

These results demonstrate that the deterioration of the compressive strength of concrete has not occurred. In this particular experiment conducted by Lee et al. [33], it could not be confirmed that utilising coarse concrete debris as a replacement for aggregates affects the compressive strength property of concrete.

4.1.2 Fine concrete debris

Zega and Di Maio conducted experiments on cylindrical blocks of concrete with a diameter of 100mm and height of 200mm. The RA utilised was finely crushed old concrete obtained from a demolition site. Zega and Di Maio explained that the use of fine RA in the composition of concrete are still very limited, but the application of fine aggregates has significantly increased in the last decade. To this date, it is more common to find studies conducted with coarse RA. [34.]

A summary of the results for ultimate compressive strength is presented in table 2 according to the percentage of RA content.

Table 2. Compressive strength of concrete made of fine concrete debris as aggregate [34].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	43.6
20%	80%	42.7
30%	70%	41.4

The compressive strength of concrete cylinders was slightly decreased by 5% as the percentage of RA was increased to 30% [34]. Although results indicate a marginal deterioration with the addition of RA, the utilisation of fine concrete debris as RA may not be ruled out as a more sustainable option for concrete production.

4.1.3 Concrete debris (manually crushed)

Suryawanshi et al. performed compressive strength tests on concrete cylinder specimens with a diameter of 150mm and height of 200mm. RA applied was old concrete debris manually crushed by hammer in the laboratory where the experiment took place. [35.]

A summary of the results for ultimate compressive strength is presented in table 3 according to the percentage of RA content.

Table 3. Compressive strength of concrete made of waste concrete debris manually crushed [35].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	38.19
20%	80%	36.65
40%	60%	35.82
60%	40%	35.36
80%	20%	34.69
100%	0%	34.10

In contrast with the experiment referred to in section 4.1.1, where Lee et al. applied similar RA as used in this experiment, the results presented in Table 3 demonstrate a gradual loss of compressive strength as the amount of RA increases. Nevertheless, even with 100% RA, the compressive strength of concrete only declined by 11%. [35.]

4.1.4 Fine ceramic waste and mixed coarse debris

Etxeberria and Gonzalez-Corominas conducted two types of experiments on high performance cubic concrete blocks measuring 150mm x 150mm x 150mm and 100mm x 100mm x 400mm. RA utilised for the first test was fine tile waste from Barcelona's ceramic industry. As for the second experiment, coarse mixed waste from a demolition site was utilised as RA. [36.]

A summary of the results for ultimate compressive strength is presented in table 4 according to the percentage of RA content.

Table 4. Compressive strength of concrete made of fine ceramic waste as aggregate [36].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	102..09
15%	85%	109.70
30%	70%	109.06

A summary of the results of for ultimate compressive strength using coarse mixed aggregate is presented in table 5.

Table 5. Compressive strength of concrete made of coarse mixed debris as aggregate [36].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	102.09
20%	80%	97.39
50%	50%	84.23

100%	0%	72.28
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Comparing the results in table 4 and 5, there is a distinctive difference between the compressive strength of concrete when utilising fine ceramic waste (table 4) and coarse mixed debris (table 5) as RA.

When fine ceramic waste was incorporated as RA, this material yielded surprising results for the compressive strength of the concrete block produced. As the amount of fine ceramic waste increased in percentage of the volume, the compressive strength of concrete blocks also increased. In short, the more the fine ceramic waste was used, the better were the results for the compressive strength of the concrete blocks. Table 4 shows that using 15% of fine ceramic as aggregate raised the compressive strength by 7%. [36.]

In the other experiment conducted by Etxeberria and Gonzalez-Corominas, table 5 shows that the compressive strength of concrete decreased by 5% when the amount of recycled coarse mixed aggregates was 20%. An experiment utilising only this kind of RA (100% RA) in the production of concrete blocks shows that the compressive strength of the blocks is weakened by 29% [36.]

4.2 RA: Plastic waste

Plastic is considered one of the most innovative materials developed in the 20th century and is now an integral part of our lives [37]. Firstly contrived in the 1860s, plastic only became widely used by industries in the 1920s. From 1940 to today, the production of plastic skyrocketed from 1,7 million tonnes in 1950 to the astronomical figure of 299 million tonnes in 2013, a 4% increase from 2012 and this rise does not seem to be slowing any time soon. [38.] Such a phenomenal growth can relate to the low cost and weight, and adaptability of plastic. This relatively new material can turn into almost anything from packages, bags, bottles, toys and even car parts.

Recycling of this material, though, is still insufficient. The amount of plastic related waste being deposited in landfills or ending up in the oceans continues to increase each year, turning plastic into an ecological villain in this civilization.. In Finland, Keep the Archipel-

ago Tidy Association carried out a two-year research to establish how clean the waterfront around the Baltic Sea is. The results revealed that the most prevalent waste material found in Finland's coastal area is plastic, at around 75% of all found debris [39].

The United Nations Environmental Program estimates that between 22% to 43% of all the plastic used worldwide is disposed of into landfills [40]. The environmental threat societies are now facing is evident when statistics suggest that in most developed countries, the consumption of plastic per person hovers at around 100 kilograms per year [38]. In Asia this number is only 20 kilograms per person but this value is expected to rise as the economical situation in the continent is improving [41].

Plastic components include a variety of toxic chemicals (cadmium and lead as the most hazardous) that pollutes soil, water and air. Plastic waste that is not properly disposed of may block the drainage systems of municipalities, proliferating the breed of rodents and mosquitoes; curbs the development of tree roots in the soil and hinders the passage of ground water [42.] Perhaps the most disturbing effect of plastic waste is the contamination of oceans and destruction of marine life. Plastic breaks down into very small grains that are then ingested by sea-life creatures and birds, contaminating and killing them. Also, bigger animals are trapped in plastic waste, causing a slow, nasty death. [43.]

Nabajyoti and Brito explain that although plastic is easily combustible, incinerating it releases toxic chemicals such as poisonous dioxins back to the atmosphere. The other option, to deposit it into landfills, is an equally grim alternative since plastic is not a biodegradable material and, therefore, harmful substances stay in the soil for generations. [42.] Since the demand for concrete is ever increasing, a possible choice examined by researchers is to incorporate plastic as a RA for concrete production. This appears to be one of the best possible environmental solutions to get rid of this unwanted waste. [44-48.]

Ismail and Al-Hashmi conducted a compressive strength experiment on 70 cubes of concrete measuring 150mm x 150mm x150mm. The shredded plastic utilised for these tests was collected from plastic manufacturing companies in Iraq. The material is composed of 80% polyethylene and 20% polystyrene. [44.]

A summary of the results for ultimate compressive strength is presented in table 6 according to the percentage of RA content.

Table 6. Compressive strength of concrete made of plastic waste as aggregate [44].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	45
10%	90%	32
15%	85%	27
20%	80%	27

Results seen in table 6 display a rapid decrease of 40% in the compressive strength of concrete when the volume of shredded plastic incorporated into concrete is only 20% of the total aggregate. Ismail and Al-Hashmi explain that the poor results derives from low adherence levels between concrete paste and plastic, but they emphasise that the minimum requirement for the compressive strength of concrete as a structural component is 17,24MPa in Iraq. Therefore, plastic waste can potentially be employed as RA. [44.]

A number of studies have experimented with the possibility of applying different types of recycled plastic waste as RA in concrete and their results are somewhat similar [42;45-48].

4.3 RA: Waste polyethylene terephthalate (PET) bottles

Polyethylene terephthalate (PET) is the most common thermoplastic polymer resin of the polyester family, and vastly used in the production of plastic bottles [49]. Although PET is only one of thousands of types of plastic, PET corresponds to 7% of all plastics consumed in the EU, and it is also extensively used around the world [50]. PET bottles have replaced glass bottles most probably due to the ease of transportation, storage, low cost, durability and lightweight. One of the various problems about plastic is that it almost exclusively becomes waste in a very short period after purchase.

Finns consumed 378 million PET bottles in 2015, but due to its return system, where the buyer is given a chance to recover costs by returning empty bottles, the recycling rates

in Finland are extremely high (93.5% in 2012) [51]. Another interesting aspect of getting back money for returning containers is that one sees hardly any PET bottles on the streets of Finland as it is profitable to pick them up in exchange for money. In the central area of Helsinki, it is common to see people collecting tins and bottles from the floor or even trash cans.

The environmental threat behind the mass consumption of PET materials is directly related to plastic waste in general as it was previously discussed in chapter 4.2. The benefits of incorporating PET waste into the construction industry are also equal to those of all other forms of plastic

There are several recent studies that investigated the incorporation of shredded PET bottles as RA to concrete production [52-56]. Frigione conducted experiments on six cubes of concrete measuring 150mm x150mm x 150mm. The method applied was to replace 5% of fine aggregate with the same weight of shredded PET bottles sized 1mm - 1,5mm. Frigione utilised different concrete mixtures for the experiment, that is, the amounts of cement and coarse aggregate were modified. [49.] The results for the ultimate compressive strength of concrete types A,B,C and D are presented in table 7.

Table 7. Compressive strength of concrete made of waste polyethylene terephthalate (PET) bottles as aggregate [49].

Concrete type	Shredded PET bottles as in % of aggregate weight	Aggregate as in % of weight	Compressive Strength in MPa
A	0%	100%	68.0
A	5%	95%	67.5
B	0%	100%	41.5
B	5%	95%	40.7
C	0%	100%	70.0
C	5%	95%	69.7
D	0%	100%	44.0

D	5%	95%	43.2
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Although the results in table 7 demonstrate a tendency of lower compressive strengths for all samples composed of RA, differences are almost irrelevant. A mixture of 5% of shredded PET bottles of the total weight of aggregate only declined the compressive strength of concrete by less than 2% in all cases. Considering the amount of PET bottles disposed of into landfills without use, the results provide an alternative to channel PET waste into a better end.

4.4 RA: Waste rubber tyre

The ever-increasing number of cars in the world can only lead to a rise in the number of tyres being disposed of into landfills. According to the European Tyre Recycling Association (ETRA), EU member states and Norway have permanently removed 300 million tyres from passenger cars, utility vehicles and trucks, and defined them as waste in the year 2013 alone [57]. That is a staggering figure of 822,000 tyres being disposed of every single day.

The issues associated with rubber are similar to those of plastic that were already mentioned in section 4.2 and 4.3. For example, rubber waste is extremely resistant to most natural environments such as heat, light, atmospheric gases, microorganisms; therefore, rubber tyres are hardly decomposable, having disastrous consequences to the nature [58]. Beyond the environmental threat, abandoned tyres provide a habitat for numerous pests and insects that present a public health hazard. In Brazil, the spread of diseases such as yellow fever and dengue are commonly blamed on open water containers such as tyres that provide an ideal breeding place for mosquitos [59]. Moreover, fire hazards are another serious problem. The burning of tyres releases toxic gases to the atmosphere that harm the environment, not only the air, but also water and soil.

The environmental and aesthetic problems related to tyre waste are more evident in developing countries where the state lacks resources to reinforce legislation on the disposal of tyres. As an example to be followed, Finland, Sweden and Norway have laws obliging manufacturers to be fully responsible for the collection and disposal of tyres and therefore these countries have high recycling rates [57].

EU legislation on waste has banned the landfilling of shredded or whole tyre, prompting other means of disposal for this product to be elaborated [60]. Incorporating tyre waste into concrete can provide an efficient way to mitigate the issue of tyre disposal and, in turn, preserve natural resources by reducing the extraction of raw aggregates.

Various studies have been carried out to assess the mechanical properties and possibility of using waste tyres as aggregate for concrete [61-65]. Abas et al. performed compressive strength tests utilising shredded car waste tyres as fine aggregate. Half of the rubber aggregate was of size 13mm - 100mm and the other half 0,14mm - 13mm. For this experiment, 68 cubes of concrete measuring 10mm x 10mm x 10mm were used to measure the compressive strength of the blocks. [66]

A summary of the results for ultimate compressive strength is presented in table 8 according to the percentage of RA content.

Table 8. Compressive strength of concrete made of shredded rubber tyres as aggregate [66].

Shredded waste rubber tyres as in % of aggregate weight	Aggregate as in % of weight	Compressive Strength in MPa
0%	100%	40
10%	90%	35
15%	85%	32
20%	80%	25

The results show that the compressive strength of the concrete block has decreased from 40MPa to 25MPa when 20% of the total aggregate weight was composed by shredded rubber. This result represents a significant decrease of 38% in the compressive strength of the concrete block. Therefore, a limit on the amount of shredded rubber incorporated into concrete has to be considered. Nevertheless, the production of concrete utilising old shredded tyres as RA could be implemented as for example, flexible pavement in school playgrounds or other sporting facilities. Regardless how little rubber tyres

can be utilised as RA, incorporating tyre into concrete production provides a better option than dumping waste tyres into landfills.

4.5 RA: Coal bottom ash (CBA)

Coal bottom ash, hereafter referred to as CBA, is the non-combustible residues that settle at the bottom of an incinerator or furnace. CBA must not be mistaken for fly ash, which in turn is the portion of ash that escapes up the flue or ducts. [1.] According to International Energy Agency, after oil, coal is the second largest fuel source for the production of electricity worldwide, at around 29%. Most predominantly, electricity is generated by incinerating coal at power plant stations. [67.] The European Coal Combustion Products Association (ECOBA) estimates that five million tonnes of CBA was produced in the EU in the year of 2008 [68]. According to Hjelma et al., around 60,000 tonnes of bottom ash is produced in Finland each year, but this number includes all other types of bottom ash such as coal, peat and wood. [69].

At the beginning of energy production by coal combustion, the ashes that remained at bottom of furnaces was considered as waste material. Little was known about the properties of this material and most of this ash was disposed into landfills. In the course of time, a variety of serious studies have been carried out to evaluate the viability of recycling CBA. The construction industry has been very receptive to new ideas to apply this by-product into more sustainable applications. [70.]

Compared to coal fly ash, CBA has not been widely used in the manufacturing of cement due to its higher unburned carbon volume, but CBA can be utilised as an alternative for aggregates in the production of concrete [71]. The mechanical and chemical characteristics of CBA vary according to the source of the coal but depend also upon the conditions of the power plant where the ash was formed [72].

The availability of studies that incorporate CBA as a substitute for aggregates can help to mitigate the environmental harm of discharging CBA in a more sustainable and economical way at the same time diminishing the need of extracting natural resources.

A fair number of researchers have assessed the mechanical properties of concrete using CBA as a replacement for aggregates [72-76]. Andrade et al. performed compressive

strength tests utilising CBA collected from a thermoelectric power station as fine aggregate measuring between 0,1mm to 10mm. Prismatic concrete samples measuring 70mm x 70mm x500mm were used for this experiment. [77.]

A summary of the results for ultimate compressive strength is presented in table 9 according to the percentage of RA content.

Table 9. Compressive strength of concrete made of coal bottom ash (CBA) as aggregate [77].

RA content in % of volume	Aggregate in % of volume	Compressive Strength in MPa
0%	100%	32.6
25%	85%	26.1
50%	50%	28.5
75%	25%	27.2

Although the results summarised in table 9 show a trend to compressive strength loss in line with the addition of CBA as fine aggregate, it must be noted that 75% of this kind of RA only decreases the compressive strength of concrete by 17% [77]. The results demonstrate that CBA can be used as a sustainable alternative in the production of concrete, particularly in concrete works that do not require a high compressive strength. The Finnish Building Code (see Appendix 1), presents six classes of concrete that allow for the compressive strength of concrete to be less than 28MPa. This means that CBA can be used as 75% of the total volume of aggregates in the production of lower strength concrete. These results represent a compelling opportunity to reuse CBA instead of disposing of it into landfills.

5 Evaluation of results of the literature review

This thesis only presented five different types of RA, but there are numerous other materials that have or are currently being researched in order to establish if they can be used as an alternative for aggregates. For example, foundry sand, glass, coal fly ash, rice husk ash, wood ash, volcanic ash and cement kiln dust are some of the substances or materials that are currently being experimented as recycle aggregate.

According to the studies analysed in this literature review, the most significant aspects that influence the compressive strength of concrete are the type of cement used, the conditions where the samples are cured, the water/cement ratio and the quality and type of aggregate. Therefore, even if the exact same ratios are applied for a specific type of RA, it is quite possible that the results vary widely or even head towards opposite directions.

This thesis showed that if only considering the compressive strength of RAC, RA can be used as a replacement for aggregates in the composition of concrete. However, according to Jeffery et al., for the application of RAC to be successfully implemented, there are certain requirements that most constructors are unfamiliar with, such as the higher absorption and lower specific gravity of recycled concrete. Therefore, adjustments must be made during the stages of making concrete. Jeffery et al. continue to explain that concrete made with RA can demonstrate higher shrinkage, creeps and permeability compared to conventional concrete. [78.]

Plastic and rubber presented the least impressive results for the compressive strength of concrete when these materials are utilised as RA. Ismail and Al-Hashmi explained that concrete paste has a low adherence to plastic or rubber, therefore the results for compressive strength were not completely satisfactory [44]. On the other hand, these results do not exclude plastic nor rubber from the goal of turning waste into RA. Less robust concrete can be applied for other purposes rather than load-bearing structures such as public pavements or school playgrounds that do not require a high compressive strength.

Figure 3 shows the test results for the compressive strength of concrete when different types of waste materials were incorporated into concrete as RA. As a general conclusion of this literature review, it is possible to indicate that there are appropriate RA that can be used as a complement to aggregates without undermining the mechanical properties

of concrete. For example, the Finnish Building Code has imposed requirements for the compressive strength of various types of concrete. These values range from 8MPa to 100MPa (see Appendix 1). In the Finnish Building Code, there are six classes of concrete that allow for the compressive strength of concrete to be less than 28MPa and eight classes that permit less than 32MPa.

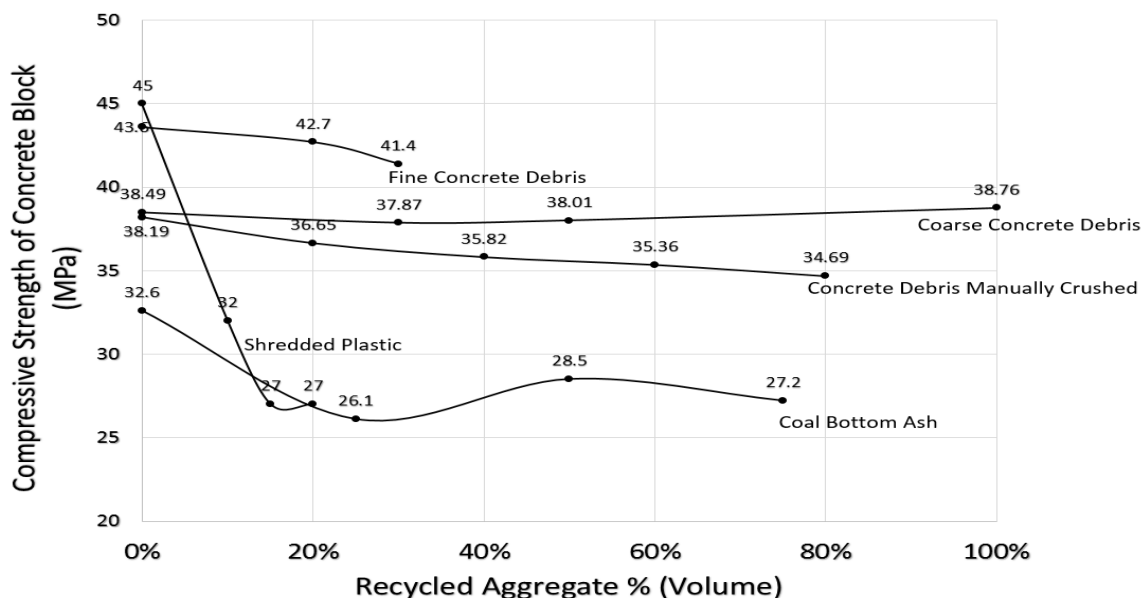


Figure 3. Results for compressive strength of concrete when waste material is utilised as RA [33-36;44;49;66;77]

Of all aggregates produced in Finland in the year of 2013, only 1% derived from a recycled source. This number falls well behind Netherlands, where 25% of aggregates come from a recycled origin. [7.] Considering the possible applicability of RA in Finland, what are the reasons for the country to only consume an almost negligible amount of RA? The answer to this question can be found in the next chapter.

6 Barriers on the application of recycled aggregates in Finland

It is clearly noticeable that the EU is placing a great amount of effort and commitment into developing a more sustainable society. For example, the EU has set promising environmental targets for the year 2020 [79]. Finland, a member of EU, is expected to vigorously assist the EU to reach those targets. In May 2012, the Finnish Waste Act (646/2011) (see appendix 2) was once again amended in order to encourage a more recycling society [80]. Finland is committed to develop methods that aim to use materials

in a more efficient way, and as a result, decrease waste disposal into landfills. The Finnish Waste Act encourages a more responsible approach to the use of natural resources and promotes an enhancement of current waste management practises.

However, when looking into the mechanical properties of RCA and its presumably potential application, it seems Finland is rather reluctant to adopt a more sustainable way of producing concrete that incorporates recycled material. Overall, the 1% use of RA in Finland is far from desired levels [7]. There has been thorough research into the current environmental protection legislation in Finland. The studies have reached the same conclusion: Implementing environmentally friendly options is not always easy.

Kuosa observes that the production of concrete in Finland follows the European standards for concrete EN 206-1, and the use of aggregates accords with to Betonin kiviainekset 2008 BY 43 [81;82]. The Confederation of Finnish Construction Industries publishes *Betoni kiviaineket 2008 BY 43* as a guideline book for the use of concrete aggregates. Although the use of RA is permitted in Finland, the very high standards of code BY 43 can hinder a broader utilisation of RA in the country. Kuosa explains that the use of RA has to be assessed for each particular case. This consists of proving that the application of RA is suitable for a specific project and the concrete produced with waste materials will fulfil the standards demanded by BY 43. There is a vast amount of criteria that has to be fulfilled in each case before the use of RA in Finland. As an example, Kuosa mentions the minimum compressive strength reviewed in this thesis and additional factors that must be taken into account such as carbonation, freeze/thaw taking into consideration de-icing agents in use and when not applied, corrosion caused by chlorides and other chemical factors must be identified. [81.]

Pajunen et al. have examined several environmental laws, such as the above mentioned Waste Act (646/2011), but also Waste Tax Act (2010/1126), Chemical Act (744/1989) and the Environmental Protection Act (86/2000). They observed that the current legislation adds a heavy bureaucratic burden when it comes to turning waste into a product. A company producing concrete from RA is required to have an environmental permit for each project and has to prove that they have sufficient expertise regarding the waste product used. This permission is far from being available to any kind of waste. Sometimes a license can only be obtained for a certain waste originating from a particular area. That is to say, if a firm wishes to collect old concrete from a demolition site and then use

the debris as RA, the company needs to apply for a permit to use that specific waste only, from that specific demolition site. [83.]

Heiskanen et al. explain that environmental permits are not simple to secure. The process of obtaining a license presents several stages where authorities and even the general public evaluate the possible risks and implications of turning waste into a product. A company will only be granted authorisation to use a specific waste if no objections are filed against it by the public. In cases where members of the public resist an application, the firm has to recur to an administrative court. If further objections are sustained, this process can then continue to the Supreme Administrative Court (SAC) and finally, if the SAC is not able to reach a conclusive verdict, the case is transferred to the Court of Justice of the European Communities (ECJ) which will then decide if a specific waste material can be used as a component in concrete aggregate. Furthermore, the researchers add that Finnish legislation regarding waste can be even more detailed than the European regulations are. Finland has a variety of restrictive regulations on waste that are not applied in its European counterparts. These rules deal mainly with the collection, treatment and storage of waste. [84.]

As indicated by the researchers above, the whole process of utilising waste as a component in concrete aggregates can be rather time-consuming and expensive. One can only guess how many environmental permits a company has to apply for and how many times a firm has to go through legal procedures in order to produce sustainable concrete in Finland.

A more recent study conducted by Levänen suggests that the biggest barrier hindering the wider application of RA in Finland is the legal distinction between classification of waste and product. The definition given to a material, be it waste or a product, is paramount for a company that wishes to utilise this material. In other words, a firm is free to operate with a material defined as product, whereas if the material is described as waste, there is a great amount of bureaucracy involved in the use of this material as described above. [85.]

To turn a material defined as waste into a product is a time-consuming process that requires a great deal of expertise and resources. To receive approval for the use of RA that are not homogeneous, such as concrete waste, can be very challenging and may not necessarily turn into a cost-effective investment. In addition to legislation barriers,

human's intrinsic resistance to change is also an obstacle to a desired large-scale use of RA. The simple fear of the unknown can hinder even the most extraordinary ideas. It is worth remembering that the erection of high-rise steel structures encountered fierce resistance in its inception and much the same can be said regarding the current situation of multi-storey wooden buildings in Finland [86]. Because RCA is almost unheard of in Finland, it can be difficult for concrete producers to sell the idea to a construction industry that is not familiar with the concept, especially when the decrease, no matter how modest, in the compressive strength of RAC is prevalent.

7 Discussion

Developed areas such as Helsinki anticipate or already face a shortage of aggregates [87]. The price of the material has risen substantially due to the costs associated with transportation and the increasingly restrictive environmental laws. It is becoming more difficult to obtain extraction permits close to urban areas. Therefore, aggregates have to be transported from longer distances to the end-use location. [6.] Transportation of such a bulk material, and vast quantities that are needed leaves behind a remarkable carbon footprint. In addition, the extraction of aggregates presents other serious environmental concerns and should be handled in a sensible way. A more sustainable option as a substitute for aggregates has to be found.

Several studies have been carried out to evaluate the use of waste materials such as plastic, rubber, foundry sand and coal bottom ash as a component in aggregates. The most notorious element investigated is waste concrete that can be crushed and applied as coarse or fine RA; this method would dramatically increase the life cycle of concrete and preserve natural resources. Studies have found that the mechanical properties of RAC do not deteriorate significantly in comparison with conventional methods [33-36;77]. Therefore, RAC can offer a more sustainable alternative to concrete production.

Of all aggregates produced in the European Union, only 7% originate from a recycled source, with Netherlands being the role model with 25% of aggregates produced there derived from a recycled material. Finland's 1% ratio is far from adequate. [4.] The reason for this unsatisfactory mark may be rooted in the strict legislation in Finland that discourages companies and investors to choose a more sustainable approach to RCA production. Perhaps the biggest issue is that Finland lacks a legal system that changes the

definition of a material from waste to product in a rapid and efficient process. According to a study conducted by Sorvari, Finland is in an urgent need of an authority that focuses only on assessing the properties of materials against environmental requirements and quickly reach a conclusion if the material is no longer waste, but a product that can be reused. [88.]

The current intricate and bureaucratic system is not suitable for a country that wishes to reach the environmental targets set by the EU by 2020. Political representatives must elaborate more straightforward means to funnel good-quality waste back into the market as a product instead of letting it to be deposited into landfills or even worse, as in the case where waste ends up in oceans, river and lakes.

Entrepreneurs and investors are discouraged by legislation that most of the time is difficult to predict. If they cannot be certain about how authorities will react to a new product, financing research and production of RA can be a dangerous gamble. This is one of the main reasons why authorities must work together with companies trying to achieve a more sustainable option for concrete. Levänen proposes that officials should be engaged from the very initial stages with companies investigating the incorporation of waste into aggregates [85]. As it is at the moment, the authorities only appear on the final phase when it is to give a decision whether certain waste can be defined as a product or not.

It must be noted that regulations are there to protect the environment and the consumer. No one wishes to live in a home where there is a risk of contamination due to hazardous products used to build its walls. Worse still, if a house is built with concrete that has not met the minimum requirements for compressive strength, there is a risk of the structure simply collapsing. Legislation makes sure that appropriate standards are kept and the quality of concrete reaching the end consumer is as high as intended.

For RA to establish itself in the Finnish market, the product has to offer competitive prices and grant similar mechanical properties as those of conventional aggregates. Cooperation between the Finnish private and public sector can stimulate the research of innovative systems to produce sustainable and economical concrete, at the same time reducing waste disposal. As further information on the production of RA and RAC is gathered, it will become less complicated for authorities in Finland to draw specifications regarding the use of controlled waste into concrete.

8 Conclusion

The main emphasis of this thesis was to investigate the possibility of incorporating waste into the construction industry, more specifically, into concrete manufacturing. The aim was to establish if RA can serve as a more sustainable option to concrete production. Having found indications that RA can be used as concrete component, this thesis attempted to explain why the usage of RA in Finland remains embarrassingly low.

Because compressive strength is the absolutely most important parameter of concrete, this thesis has focused mostly on experiments that have investigated the compressive strength of RCA. The tests that were presented in this thesis have partially and/or fully replaced conventional aggregate by recycled aggregate. Results indicated that the mechanical properties of recycled concrete are highly dependent on the quality of the waste material that was utilised to make the sustainable concrete. The more inhomogeneous the RA, the more challenging its application to concrete production becomes.

Perhaps not surprisingly, plastics and rubber yielded less satisfactory results. Nevertheless, their results for compressive strength were above the national requirements in the country where the tests were carried out. Also, the Finnish Building Code includes several types of concrete that require values for compressive strength that are inferior to the results introduced in this thesis, as appendix 1 demonstrates.

Even the worst performers, concrete with plastic or rubber as RA, demonstrated sufficient mechanical properties that are in line with the Finnish Building Code. Overall, the results demonstrated the feasibility of incorporating waste materials into concrete preparation. If more RA are used as a component in concrete, less conventional aggregates need to be extracted from nature. Therefore, the environmental impact of extracting aggregates is reduced. Furthermore, reusing waste materials in the composition of concrete presents a partial solution to the ever-growing problem of waste disposal. The challenge is how to put this into practise.

EUPG argues that national legislations in some European countries hinder the implementation of RCA [7]. As discussed in chapter 6, the actual circumstances in Finland reinforce EUPG's concern. There is an urgent need to create means to overcome unnecessary obstacles such as the complexity of achieving an end-of-waste status for a

material. A more cooperative relation between local authorities and the private sector is required to facilitate the development of sustainable ideas.

A possible measure to promote the use of RA in Finland is to create a straightforward route where companies can prove they are utilising waste materials safely and according to the legislation from the very beginning of a process. In this way, organisations would not have to go through time-consuming procedures not knowing if the authorities will give a permission to a product at the end stage. In addition, the concrete industry may consider forming a network system where members can share their experience of incorporating waste into concrete production and, from the results gathered, justify to the authorities that the current regulation can be modified to promote recycled concrete more efficiently.

To embark onto an innovative idea can be costly, sluggish and carry a high risk. Therefore, new environmental legislation could also be devised to support companies which are investing in recycled concrete. As seen above, EU policies already strongly encourage the reuse of waste materials to reduce environmental impacts. What is needed now is to find practical ways of turning this idea into reality. To achieve that, there is a need to continuously adapt regulations into facilitating the processes of turning waste material back into an applicable product.

In the future, it would be worthwhile to perform Life Cycle Assessments on RA with a view to establish if the use of RA provides a more sustainable approach to concrete production. Recycling per se cannot be taken as the ultimate solution. There must be enough legitimate evidence that prove and ensure that incorporating waste into concrete actually contributes to environmental protection and is economically viable. For example, it may not be sustainable to collect, treat and transport RA from long distances to the end use site if there are aggregates available nearby. Carbon emissions, energy consumption and other aspects such as overall costs must be taken into consideration.

From the chemical point of view, one may choose to investigate the migration of hazardous compounds from waste materials into the interior of the building. Or else, how to safely and efficiently treat waste with the interest of verifying that it can be reused as a material.

On the Finnish regulations aspect, there is a need to conceive methods that simplify the legal processes of defining a material deemed waste into a product again. This may involve bringing concrete industry representatives and local authorities to the same table to analyse possible ideas that align sustainability with high health and safety standards that are there to protect the consumer. One suggestion is to fully examine how Netherlands successfully achieved the mark of 25% RA usage [7].

The author hopes that conclusions drawn from this research can encourage further studies into the development, production and implementation of RCA wherever the reader may be.

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Finnish Building Code Requirements for Compressive Strength of Concrete

Specimen: Cylinder: diameter of 150mm and height of 300mm

Concrete strength class	Characteristic value of compressive strength in MPa
K10	8
K15	12
K20	16
K25	20
K30	25
K35	28
K37	30
K40	32
K45	35
K50	40
K55	45
K60	50
K67	55
K70	57
K75	60

K80	65
K85	70
K90	75
K95	80
K100	85
K105	90
K115	100

Waste Act 646/2011 [72]

(Amendments up to 528/2014 included)

Definition of waste

(1) For the purposes of this Act, waste means any substance or object which the holder discards, intends to discard or is required to discard.

(2) A substance or object is not waste but a by-product, if it results from a production process whose primary aim is not the production of that substance or object, and:

- 1) further use of the substance or object is certain;
- 2) the substance or object can be used directly as is, or without any further processing other than normal industrial practice;
- 3) the substance or object is produced as an integral part of a production process; and
- 4) the substance or object fulfils all relevant product requirements and requirements for the protection of the environment and human health for the specific use thereof and, when assessed overall, its use would pose no hazard or harm to human health or the environment.

(3) Further provisions on the criteria referred to in subsection 2 for classification as a by-product, specified per by-product, may be given by government decree.

(4) Further provisions by types of waste, on when a substance or object no longer constitutes waste, may be given by government decree, if:

- 1) the substance or object has undergone a recovery operation;
- 2) the substance or object is commonly used for a specific purpose;
- 3) a market or demand exists for the substance or object;
- 4) the substance or object fulfils technical requirements for specific purposes and meets the existing regulations applicable to similar products; and
- 5) the use thereof will not, assessed overall, pose any hazard or harm to human health or the environment.

(5) Further provisions may also be issued by government decree on concentrations of contaminants and their permitted solubility for a substance or object referred to in subsection 4, the technical requirements applicable to the use of the substance or object, and other corresponding aspects.