Engineering Materials

ENGR 220

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Abstract

With environmentalism on the rise, the options to use greener materials in the construction industry can seem more appealing in modern times. Concrete is a mundane material that is used in almost every construction project ever done. Bridges, roads, and buildings all have some variation of concrete put into them. With the push to use produce less waste, materials such as recycled concrete using recycled aggregate (RCA) must be examined and considered as a viable replacement for concrete that uses freshly quarried natural aggregate (NA). This paper analyzed if recycled concrete can be a suitable replacement for NA based concrete. The physical and mechanical properties of recycled concrete were examined and compared to those of NA concrete, along with a cost analysis and the manufacturing process. The results indicated that RCAs have a lower density, thermal conductivity, tensile strength, and Young's modulus than NA. However, NAs were found to be more brittle than RCAs as seen in the stress-strain curves having their fracture point appear earlier in the curve. Through testing multiple concrete mixes and designs with varying percentages that when a mix has closer to 0% recycled aggregate, its properties will be closer to that of concrete made with pure natural aggregate.

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Introduction

Natural aggregate (NA) is what laymen to the concrete industry call the building block of "standard concrete". Natural meaning it is straight from quarry to mixer and aggregate referring to the fragments of rock that make up concrete [1]. NA is extracted from quarries and riverbeds. Recycled concreted aggregates (RCA) are the product of recycling what was concrete into aggregate [2]. RCAs can be the base of recycled concrete. The differences in NA and RCAs are a focal point in the debate of recycled concrete versus regular concrete. Aggregate being one of the main ingredients in concrete is very crucial in reflecting what properties a certain design mix of concrete will have. An underlying goal of using RCA is to form a closed loop of concrete. The term "closed loop" is merely a phrase to describe the cycle of concrete. A closed loop is where the materials for the concrete keep getting put back into concrete production causing a lesser need for quarries to add more material into each mix [2].

Motivation

In a modern society where the ultimate goal is to make a cleaner, greener and more efficient future, it only makes sense to start from the ground up. In the case of recycled concrete, that ground is quite literal. Concrete is the foundation to not only buildings, but to almost everything we see around us from sidewalks to towering skyscrapers. Concrete is what keeps progress moving. With all the hustle and bustle of a society charging towards the future, does it ever stop and look around to see the minute details that can be changed to help create this utopian idea of a green future? The waste of normal concrete is dumped into landfills sitting in the earth decomposing slowly over time along with the rest of the trash the world discards. The possibility of using the remnants and scraps from demolished concrete or spare concrete must be considered and researched more.

Applications

Concrete is one of the most common materials used in the construction industry. Its counterpart, recycled concrete, can be used for many of the same projects such as, curbs, sidewalks, foundations and sub-foundations (Figure 1. [4]) [4]. Sidewalks after a five-year period saw minimal effects or maintenance needed and withstood a freeze-thaw cycle up to -24.8 degrees Celsius (Figure 2. [4]) [4].

However, recycled concrete is limited in its use for road pavement construction [5]. The limited use of recycled concrete used in highway work can be attributed to the precise mix design needed for recycled concrete to be at its strongest and to minimize adverse effects [1]. There is a smaller window of error in using RCAs rather than using NAs. Due to the nature of highway heavy wear-and-tear that every road must deal with, more testing and edits to the mix design of recycled concrete must be done for it to pass the standards of being a common material for roads.

Figure 1(below): projects that use recycled concrete:(a) a casting of a foundation for a house (b) casting of a sidewalk (c) coring of a block (d) sidewalk with RCA content [4]

Figure 2 (above): A sidewalk after five years of use [4]

1. Definition

RCAs have various origins such as reclaimed wasted concrete and previously demolished concrete [5]. In general, RCAs are more porous and as a result have deeper penetration depth [6]. The exact properties of RCAs depend on the quality of the originally concrete [6].

1.1 The Class of Materials

The class of material is not changed when comparing NAs and RCAs. This is due to the only difference between the two is where the aggregate comes from, not a change in general contents. While concrete is a composed of an aggregate, it may be misleading to label it as a composite material. Concrete is considered a ceramic. Ceramics are non-organic nor metallic.

2.Physical Properties

2.1 Density

The density of RCA ranged from 2,217 kg/m^3 to 2,368 kg/m^3 depending on the percentage of recycled aggregate used in the mix [8]. The mixes contained 5% to 20% recycled aggregate, where the percentages closer to 5% had the higher densities [8]. The reference aggregate using no recycled materials had a density of 2,399 kg/m^3 [8]. As seen through the Table 1 [8], the NAs are denser than RCAs and the RCAs become less dense the more recycled material is added.

Concrete Type	Mix proportions (kg/m^3 of finished concrete)						w/c ratio	Slump (mm)	Density kg/m^3
	Water	Cement	C.A*	F.A*	RCA*	RA*			
0% RCA	252	446	961.00	585	0.0	0.0	0.56	75.3	2399
5% RCA	252	446	912.95	585	48.1	0.0	0.56	65.0	2368
10% RCA	252	446	864.9	585	96.1	0.0	0.56	52.0	2345
15% RCA	252	446	816.85	585	144.2	0.0	0.56	45.0	2322
20% RCA	252	446	961.00	585	192.2	0.0	0.56	41.0	2298
10% RA	252	446	961.00	526.5	0.0	58.5	0.56	62.5	2292
20% RA	252	446	961.00	468.0	0.0	67.5	0.56	61.0	2217

Table 1(above): The relation between density and percentage of RCA [8]

2.2 Thermal conductivity

The thermal conductivity of RCA ranged from 0.91 (W/m K) to 1.20 (W/ m K) depending on the percentage of RCA used [8]. The mixes contained 5% to 20% recycled aggregate, where the percentages closer to 5% had the higher thermal conductivity. The reference aggregate using no recycled materials had a thermal conductivity of 1.25 (W/m K) [8]. As seen in Table 2 [8], concrete with more recycled aggregate in the mix design will a lower thermal conductivity than concrete mixes containing little to no recycled aggregate.

RCA mixes

Mix	RCA (%)	Compressive Strength (MPa)	Water Absorption (%)	Thermal conductivity (W/m K)
Reference mix	0	27.33	12.0	1.25
5% RCA	5	25.5	12.2	1.20
10% RCA	10	24.0	12.5	1.10
15% RCA	15	23.0	13.0	0.95
20% RCA	20	22.3	13.3	0.91

Table 2(above): The relation between thermal conductivity and percentage of RCA [8]

2.3 Electrical conductivity

The electrical conductivity of concrete does not depend on how much recycled material is incorporated into the mix design [14]. The electrical resistance of concrete is dependent on the slump of the concrete when it is still fresh and not yet hardened [14]. When there is a larger slump in the mix, it is more conductive due to the increase of water used in the design to give the concrete a greater slump [14].

2.4 Thermal expansion

When a NA and RCA were preloaded to 70% of their strength at an ambient temperature, the effects of brief thermal strains cancel out the effects of free thermal expansion [13]. The thermal strains of NA were much greater than that of RCA, causing the NA to spall at a higher temperature than RCA [13].

2.4.1 Thermal Behavior

Concrete made with 30% recycled aggregate had almost an equivalent performance level to natural aggregate concrete under stress and strain while under elevated temperatures [13].

2.5 Magnetic properties

Due to recycled concrete falling in the ceramic class of materials, it is not magnetic. Even with the steel rebar inside the concrete having magnetic properties, they are not strong enough or noticeable enough to be noted. This is evident while using a magnet on any sidewalk or structure that contains concrete, the rebar's magnetic pull is too miniscule to attract the magnet to the surface of the concrete.

2.6 Optical properties

Recycled concrete will have the same optical properties as NAs. RCAs are opaque and absorb light.

2.7 Corrosion resistance

The differences between NA concrete and RACs does not span over the type of rebar used to support it. As a result, the corrosion of the rebar will be the same for NAs and RCAs. Unless the concrete is damaged and the rebar is exposed to the elements, the rebar will be protected inside the concrete. The concrete itself is corrosion resistant.

3. Mechanical Properties

3.1 Yield strength

The yield strength of any mix or RCA will always be lower than any pure NA mix (Figure 3 [10]). This can be attributed to the loose porosity and microcracks found in RCAs [10]. Figure 3 depicts the stress-strain curves of RCAs of 50% and 100% as well as a NA labeled RCA 0%. When an increase of applied compression is done on the RCAs and NA, the stress-strain curves are altered. In the graphs, compression of 0.4, 0.6, and 0.8 are applied. According to Figure 4, the yield strength of NA (RCA 0%) is approximately 28MPa to 30MPa depending on the compression applied. RCA 50% is the next highest ranging from 19MPa to 25MPa depending on the compression applied. The lowest yield strength is RCA 100% ranging from 17MPa to 21MPa depending on the compression applied.

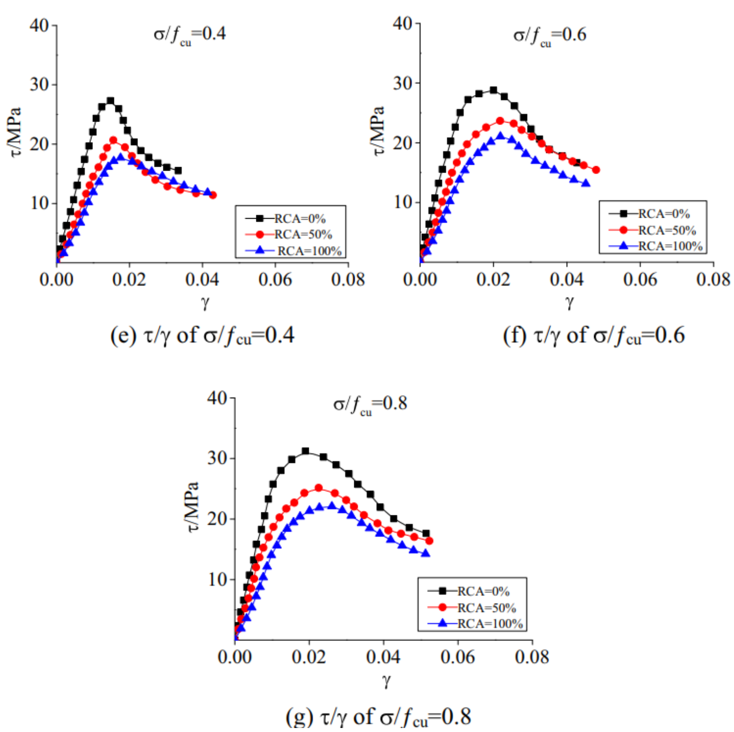

Figure 3(Left): The stress-strain curves of different percentages of RCA with different compression applied.[10]

3.2 Tensile strength

The ultimate tensile strength, or tensile strength for short can be found at the peak of a stress-strain graph. Observing Figure 3, it can be concluded that tensile strength decreases when a higher percentage of RCA is incorporated into the mix design. NA (RCA 0%) is shown to have a tensile strength of approximately 29 MPa to 33MPa depending on the amount of compression applied. RCA 50% has the next highest tensile strength with it being approximately 21MPa to 25MPa depending on the amount of compression applied. RCA 100% has the lowest tensile strength with it being approximately being 19MPa to 21 MPa depending on the amount of compression applied.

3.2.1 Elastic Deformation

When analyzing Figure 3, the conclusion can be made that under any amount of compression, NA (RCA 0%) will have a shorter elastic deformation phase than any percentage of RCA due to the more brittle nature of standard NA. This is seen by the steeper slope NA has on the stress-strain curve.

3.2.2 Plastic Deformation

When analyzing Figure 3, the conclusion can be made that the higher percentage of RCAs will have a larger plastic deformation phase. This can be seen by the line of NA (RCA 0%) always being shorter than the lines of RCA 50% and RCA100% thus making its fracture point sooner, thus giving it less of a plastic deformation phase.

3.3 Shear strength

There is no evidence of reduction of shear strength when increasing the percentage of recycled aggregate in the mix [16]. This can be attributed to the same rebar being used when placing slabs of both RCA and NA [16]. The rebar strengthens the concrete against shear forces.

3.4 Young's modulus

The modulus of elasticity for RCAs ranges from 47.8 MPa to 44.4 MPa, depending on the percentage of RCA used. The specimens contained 10% to 100% recycled aggregate, where the percentages closer to 10% had the higher Young's modulus. NA had a higher Young's modulus of 55.5 MPa [9]. As seen in Table 3 [9], specimens containing more recycled aggregate had a lower Young modulus. In Table 3, PR (%) represents percentage of RCA while E_{cyl} (MPa) represents the Young's modulus of each specimen.

Table 3(Below): The relationship between percent of RCA and Young's modulus [9]

Specimen	*PR*(%)	E_{cyl}(MPa)
50-A-0-0r*	0	30.1
50-A-0-10	10	28.3
50-A-0-20	20	25.6
50-A-0-35	35	23.9
50-A-0-50	50	25.3
50-A-0-75	75	24.2
50-A-0-100	100	24.6

*Control specimen.

3.5 Modulus of rigidity

When 50% of the natural aggregate is replaced with recycled aggregate the modulus of rigidity of concrete is at its peak [15]. However, the modulus of rigidity can be affected by any internal defects of the RCA [15].

3.6 Ductility

When analyzing Figure 3, the conclusion can be drawn that the more recycled aggregate incorporated into a concrete mix design the more ductile it will be. This can be seen while comparing RCA-0% and RCA-100%. RCA-0% has a much steeper slope making it more brittle than its recycled aggregate counter-part RCA-100% which has a more gradual slope making it the more ductile material.

3.7 Impact strength

Impact strength decreased when replacing NA with RCA [17]. This was due to the imperfections in the blend of RCA added into the concrete mix [17]. When a specimen with 100% RCA had a 10% decrease in impact strength [17].

3.8 Fatigue resistance

In order to test if a material can be used for any realistic and practical applications, the material must withstand two million load repetitions at a definite stress level without failure [11]. The fatigue resistance of RCA of 100% is approximately 3%-7% lower than that of concrete made of pure NA [11]. The lower fatigue resistance can be attributed to micro-deformities in the recycled pieces of aggregate [11]. Currently, more tests and mix designs are being created to boost the fatigue resistance of RCAs [11].

3.9 Failure Analysis and Prevention

Failure of concrete can be a subjective topic. When making a sidewalk, cracking over a period can be acceptable. However, when constructing a building, cracks over any time period in the concrete can be catastrophic to the building's foundation and end up destroying it. Due to the plethora of uses concrete has, failure will be considered when the concrete has a fracture. This is also assuming the mix design was followed correctly and there is no human error involved. Analyzing Figure 3, it is seen that the NA (RCA 0%) fractures the soonest out of the three mix designs. RCA 100% fractures the second quickest, leaving RCA 50% to fracture last. A conclusion can be made that there is a mix design that incorporates both NA and RCA will have the least likely chance to fail.

4. Manufacturing Process

Recycled concrete is made from either the waste of excess concrete mix from a project, or the demolished concrete used in past projects. Wasted concrete can be acquired if a project uses less concrete than was ordered. An example would be a company only using three yards of the four total yards they ordered for a project. That spare yard of concrete can be used in newer recycled concrete mix. Using previously scrapped and demolished concrete is more of a process (Figure 4. [1]).

The first step for creating recycled concrete is to gather demolished concrete from structures [1]. Next the recycled concrete must go to a plant for processing [1]. At the plants, the recently demolished concrete goes through a crushing and washing process to make the aggregate more uniform and clean any unwanted debris [1]. The concrete must also go through a sieving process to remove any unwanted material and to ensure that aggregate of the appropriate sizes is kept [2]. After crushing, washing and sieving, the aggregate is then manufactured the same was natural aggregate is turned into concrete [2]. Any type of concrete is made with the three main ingredients of aggregate, water, and cement. However, the size of aggregate, the specific type of cement and the amount of water is all dependent on the called for mix design.

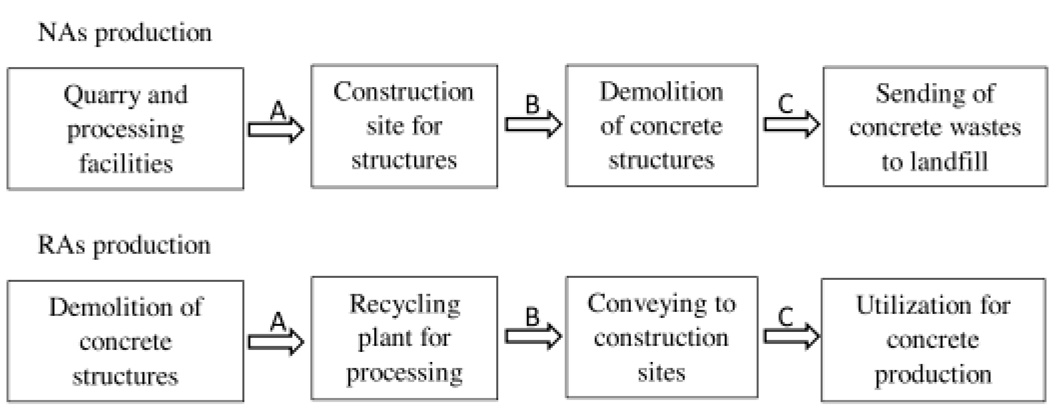

Figure 4 (Above): The production cycle of NA and RCA [1]

5. Materials and Environment

The materials required to make RCAs, are essentially the same as any other basic concrete: aggregate, bonding agent (cement), and water. The key difference between RCAs and NA, is the aggregate used, hence the terms RCA and NA. The aggregate for RCAs is harvested from demolition sites or the leftovers from mixing trucks and plants [1]. This differs from NA based concrete which is mined from quarries [1]. Just from harvesting the aggregate, RCA is already more environmentally friendly than NA. Instead of having to acquire the materials from a quarry and did up more earth, the materials are already on the surface waiting to be recycled and reused. In addition to the harvesting the materials being more environmentally friendly, the disposing of RCAs is more environmentally friendly too. Once a structure containing concrete is demolished or taken down, usually the rubble including the old concrete is thrown into a landfill [1]. If that concrete is taken from the demolition site to plant for refurbishing and recycling, that would immediately cut the amount of waste dumped in landfills. If a cycle were created where each time concrete is destroyed its recycled, the number of materials that could be used for construction would increase tremendously while simultaneously lower waste in landfills.

6. Cost Analysis

When analyzing the cost to manufacture RCA versus NA, the long-term cost of producing a single tonne of RCA is 49% lower than that of NA [12]. Also, the environmental cost for RCA is significantly lower than that of NA [12]. When breaking down the cost of using NA, about 35% of the money goes towards environmental costs (Figure 5 [12]). The disposal fee for the landfill at Johannesburg is US$ 15.52 per tonne for NA concrete [12]. The total cost of NA seen by

Figure 5 is approximately US$ 68.05 tonnes, while Figure 6 shows that the cost to produce RCA is approximately US$ 34.39 tonnes. From an environmental and a general standpoint, RCA is the cheaper material.

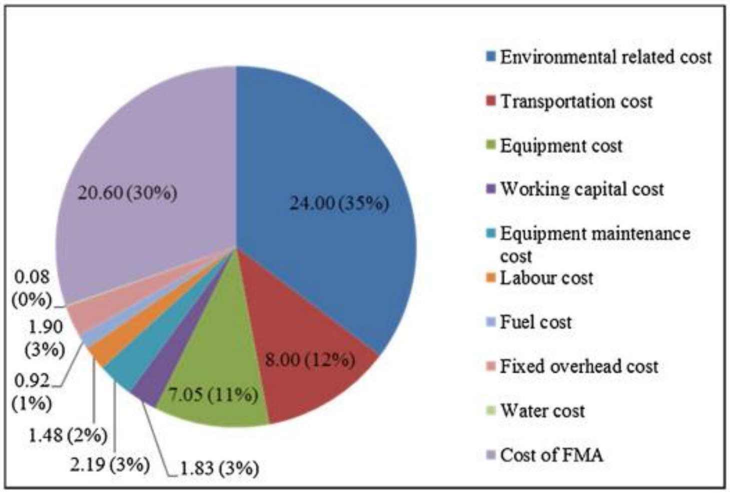

Figure 5(Above): the cost components of producing NA, given in US$ per tonne [12]

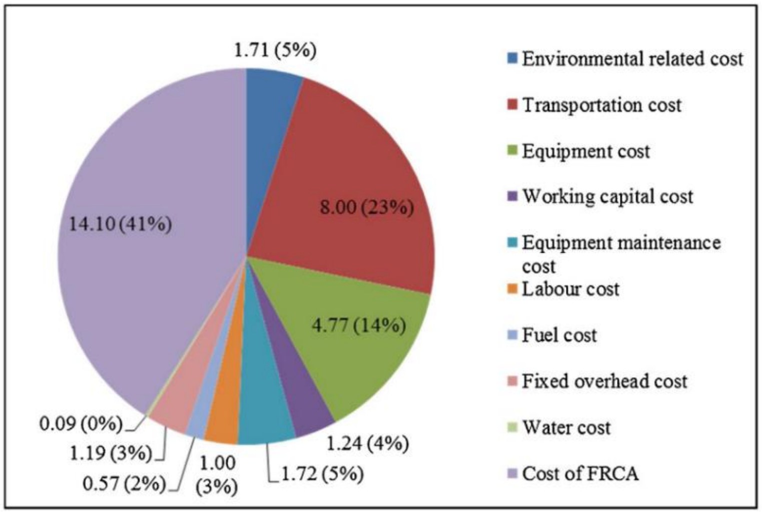

Figure 6(Above): the cost components of producing RCA, given in US$ per tonne [12]

Summary

In conclusion, RCA can be a substitute for NA in some structures and projects. Due to the current tools and research devoted to RCAs, RCA in its current state would be best suited for smaller projects such as sidewalks and buildings that require smaller foundations. RCA would need to iron out some of the errors cause by imperfections in the mixture. The possible use of an inspector to inspect the aggregate being poured into the mixture for any impurities or any problems that a specific aggregate could cause later. While most of the properties of RCA are very comparable to NA, it would be wise to conduct more large-scale tests on the material to see if it can withstand the force of larger structures such as residential housing, skyscrapers and airports.

Financially, using RCA would be a huge positive for the construction industry. The general cost of producing and disposing RCA is significantly lower than that of NA. If the occasional minor imperfections of the aggregate used in RCA can eliminated from every mix, then the money saved can be used for more projects or however the commissioning company sees fit.

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