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Properties of concrete with thermal treated recycled concrete aggregates and cement

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Abstract

The cement and concrete industries are accountable for ~7% of global CO_2 emission and 25-30% of all waste generated; in the form of construction and demolition waste (C&DW). It is therefore imperative to find methods to reduce the impact from these industies. In This study both the cement and aggregate part of concrete are investigated. About 70 kg of concrete were recycled, where 3 kg was cement and the remaining part was aggregates. The concrete was crushed to appropriate size and then heat-treated for 4-7 hours in 650°C. After cooling the crushed material was grinded in a ball mill for 1 hour. The material was then sieved into the following fractions, 0-0.075 mm, 0.075-0.125 mm, 0.125-2 mm, 2-4 mm, 4-16 mm. Were 0-0.075 mm and 0.075-0.125 mm are considered as the cement fractions and 4-16 mm are the aggregates. The fractions 0.125-2 mm and 2-4 mm were not used in this study. The recycled material was mixed in different compositions with new cement and aggregates. For the recycled cement six different cement mixtures were made, including a reference. The ratio of recycled to new cement was 0/100 (reference), 10/90, 25/75 with 3 different cement fractions, and 50/50. The compressive strength was measured after 1, 7 and 28 days. After 28 days the reference showed a compressive strength at 61.7 MPa while the recycled material had results from 57,6 MPa for the 10/90 mix, down to 28.7 MPa for the 50/50. For the aggregates five mixtures were blended with the following ratios: 0/100 (reference) 25/75, 50/50 and 100/0 with heat-treated and non-heat-treated aggregates. The compressive strength for the concrete samples were determined after 1, 7 and 28 days. After 28 days the compressive strength for the reference sample was 61.7 MPa and the strength of the casted heat-treated mixtures were all around ~56 MPa after 28 days, whilst the non-heat-treated had a somewhat higher compressive strength at 61.5 MPa.

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Table of Contents

1. Introduction

When it comes to global carbon emission, there is a disproportionate amount produced by three industries. The industries are the oil, steel and cement industry, were the cement industry is responsible for roughly 7% of global CO_2 emissions. Hence there are large future challenges, both with regards to recycling and energy optimization [5]. The steel industry has recently been making progress towards using green energy in the production process; the material is also easy to recycle, minimizing its waste impact. The oil industry has environmental improvements in its production mainly as an increase in efficiency in the engines that use oil. Few improvements have been done in the past in the cement industry, which can be attributed to lack of financial incentive. The raw material needed to produce concrete is rather cheap as well as the energy required to make cement. The production of cement is a well-known and reliable process. Thus, there has been less interest in improvement when the economic gain is low [1]. However, the interest to produce cement with less CO_2 footprint has drastically increased during the last decade and lots of effort is now put into developing more environmentally friendly cement and concrete.

1.1 Aim

The aim of this study is to examine the feasibility of using recycled concrete aggregates in new concrete compared to juvenile aggregates as well as compared to crushed concrete as aggregates. The study will also look briefly at using recycled cement and how it compares with non-recycled cement.

2. Fundamentals of concrete

2.1 Cement chemistry

Concrete is a mixture of three primary materials, water, cement and aggregates. Commonly some type of shear-thinning agent is also used to reduce the amount of cement used [1]. The purpose of the concrete construction, e.g. buildings or bridges, determines the ratio of the materials used as well as the type of aggregates used. It is important that the aggregates have desirable properties, such as size, strength and smoothness, which is also taken into consideration when mixing concrete.
Portland cement is the most common used cement around the world and used as standard cement. To create Portland cement three ingredients are needed; calcite, high temperatures

and clay mineral containing Si, O, Al, Fe and Ca. The first step is to thermally breakdown calcite at a temperature above 600℃, forming quicklime and CO_2, reaction (1), as well as decomposing the clay minerals [2].

$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

In the second step, where the clinker formation occurs, quicklime and quartz in addition with the decomposed clay minerals react to form alite, belite, aluminate and ferrite, according to reaction (2). This reaction starts at a temperature above 1300℃.

$$CaO + quartz + clay\ minerals \rightarrow alite + belite + aliminate + ferrite \quad (2)$$

The last process is the sintering of the clinker which requires temperatures of up to 1500℃ but commonly 1450℃ is used. This stage partially liquefies the clinker and increases the amount of alite, reaction (3), and various calcium silicates and calcium aluminoferriets.

$$belite + quicklime \rightarrow alite \quad (3)$$

The sintering stage also nodulizes the particles and increases their size. The final clinker is then grounded into a powder and mixed with a small amount gypsum. The gypsum is used to control the setting time of cement, so it would not instantly harden when mixed with water.

To create a satisfying concrete blend around 25-40% cement is mixed with 60-75% aggregates. Then 85% of the dry blend is mixed with 15% water to form concrete. The water starts the hydration reactions, causing the calcium silicates, alite and belite to reaction with water forming calcium silicate hydrate gel (C-S-H) and portlandite according to reaction (4).

$$\text{alite, belite} + H_2O \rightarrow C\text{-}S\text{-}H + Ca(OH)_2 \quad (4)$$

It is the C-S-H gel that binds the aggregates together and forms concrete [1, 2].

2.2 Properties of recycled concrete aggregates (RCA)

One of the major differences between juvenile aggregates and RCA is the increased water absorption. This is mainly caused by the cement residue still stuck on the aggregates. Even with cutting edge treatment not 100% of the cement can be removed. The increased water absorption will affect the rheological properties of the concrete if high amount of RCA is used. This will also make the blend stiffer and more difficult to work with and lower its general quality. Making slight alterations in the ratio of water or adding water-reducing admixtures are ways to circumvent the issue. Much research has been done on the properties of RCA and how it compares to juvenile aggregates are well understood. As noted in the book "Sustainability improvements in the concrete industry" using less than 20% RCA does not even affect the performance of the concrete [1].

To recycle concrete the construction waste usually needs to be transported to a recycling plant to be crushed. It is important that the concrete waste does not contain any other types of material such as the reinforcement bars. The aggregates are thereafter sorted by size to facilitate later use. There is also the possibility to use a portable recycling plant at the construction or demolition site. Although they can't process the same amount as a stationary one, they can provide an advantage. Recycling at the spot eliminates transportation cost for the material, also recycling fresh concrete is a lot easier than even slightly aged concrete.

The main problem in increasing the usage of RCA is question of economics rather than chemistry. The RCA needs to have close to the same performance as juvenile material whilst being economically favorable. Both advancements in the technology used and changes in the legislation are pushing RCA forward, with the Waste Framework Directive (2008/98/EC) from the EU being one of the more pressing one. The EU directive states that by 2020 a minimum of 70% by weight of non-hazardous C&DW should be recycled or undergo other material recovery [10].

2.3 Previous research on RCA

Previous research on compressive strength of recycled concrete has shown very similar results for mixes with 25-75% for crushed concrete. Generally, there was a strength reduction of 15-30% compared to the reference in mixes with crushed concrete [8]. In another study the strength development of concrete with RCA is observed to be higher than that of juvenile aggregates, especially at later ages [9]. This is proposed to be due to residual non-hydrated cement left on the aggregates which then react with water. This study also reported that the compressive strength for concrete 100% RCA can be reduced by up to 30% or increase by 20% depending on moisture level in the aggregates. The cause for weaker compressive strength firstly due to the interfacial transition zones taking place between the original aggregate and old mortar for RCA, whilst for new aggregates it takes place between the aggregate and mortar. Secondly, higher amount of water is generally used for concrete with RCA to achieve desirable workability, which lower the compressive strength.

2.4 Current uses of RCA

Recycled concrete aggregates are most commonly used in highly urban areas. This is due to the scarcity of minerals in the near surrounding. This causes juvenile aggregates to be transported from farther away and thus making it economically more favorable to use RCA. However, most of the RCA is not used for new concrete but is instead used as a secondary resource. This is both due to the sheer cost, in both energy and equipment, to sufficiently cleansing the aggregates from cement, and the tax benefit gained due to it being a secondary resource. Therefore RCA is used primarily for earthworks such as roadbeds, pavements and land raising [1].

3. Environmental impact

The cement and concrete industry pose both a problem for global warming and destruction of land. Starting with the impact on global warming, the main factors are energy consumption and production itself. The manufacturing of cement requires temperatures up to 1500℃ which tends to come from carbon-based fuels. In addition to the energy needed, during the process large amounts calcium carbonate ($CaCO_3$) are calcinated, releasing carbon dioxide. In addition to heating and calcination, the transportation also consumes lots of energy due to the large volumes of the material. This adds up to 900 kg carbon dioxide emitted per 1000 kg of Portland cement produced [2,3]. A novel method that is currently developed is the carbon dioxide capture technique []. This technique will capture the carbon dioxide, released from the calcination step, and the gas will then be collected and stored deep in the bedrock.

The destruction of land comes in two ways, first the harvesting of aggregates and second one is the construction and demolition waste (C&DW) generated. The aggregates need for concrete is gravel and sand, however not any type of sand and gravel will create good concrete. Due to the amount needed this causes vast areas to be destroyed which will then affect the local ecosystem. Also, with the surface layer of rock removed it renders the area unusable for anything else. However, it is not easy to measure these types of environmental damage, which it is often undervalued in studies. The impact done by C&DW is caused by the sheer amount generated. About 25-30% of all waste generated by weight comes from concrete C&DW. There is also a substantial amount of waste generated from the production of prefab concrete parts, such as hollow concrete decks. This prefab waste also needs to either be recycled or deposited in a landfill. With that amount of waste generated that currently cannot easily be recycled, it is therefore put in landfills. With more buildings starting to reach their age limit more area will be used for concrete deposition. Using vast areas of land to store concrete will displace the ecosystem in a similar way as aggregate extraction does. Due to regulations companies that deposit concrete in this way will have to pay a few in order to incentivize a long-term solution. In the EU, new regulations will take place that will force non-toxic C&DW to be recycled by 70% minimum, further creating incentive to find a better solution [3,4,5].

4. Experimental design

4.1 Material preparations

The used concrete was a few months and was provided by Strängbetong AB. The concrete had been trimmed of from the final product at the production site and have thus never been used. Around 100kg of the concrete were worked and prepared for testing and the reinforcement bars have been removed beforehand. The material was first crushed using a steel sledge and chisel, breaking the concrete into smaller chunks (about fist sized or smaller) as seen in figure 1.

Figure 1. The supplied concrete the rough size it was broken down to in the first step.

The crushed concrete was then heated in 650℃ for 4-7 hours and cooled down to room temperature before being further crushed to smaller sizes. The heating for the smaller chunks was 4 hours and for the larger chunks it was set to 7 hours as shown in figure 2.

Figure 2. The smaller fragments (left hand side) required 4 hours to achieve satisfactory dehydration of the calcium silicate hydrate. Whilst the larger chunks (right hand side) needing 7 hours for it.

The heat-treated concrete was put into two steel containers and was grinded in a ball mill (figure 3 left-hand side) for 1 hour to remove the remaining cement from the aggregates. After the grinding the samples were sieved into different size fractions. (figure 3 right-hand side).

Figure 3. The ball mill with the steel containers that was used on the left-hand side. On the right-hand side, the sieve with the varying sizes of filters stacked to the side of it.

The sieved material below 75μm was considered as the fraction with highest cement content and was saved for testing. The fraction 0-125 μm was also considered as a “cement” fraction. Both these two fractions were used in the compressive strength tests. Aggregates from 125 μm-2 mm as well as 2-4 mm were sorted out and not used in this study. The aggregates from 4-16 mm the gravel part, was the one of interest. After sorted by size the aggregates were washed with water and dried displayed in figure 4.

Figure 4. The final RCA, fraction size 4-16 mm, after washing with water.

About 20 kg of the aggregates were obtained from non-heat-treated concrete. In this case the concrete was crushed with a steel hammer separating the hydrated cement from the aggregates, followed by washing the aggregates with water. Around 1 kg of pulverized recycled aggregates, in the range 0-125 μm (figure 5), was produced to be used as an inert reference material in the cement compressive strength tests.

Figure 5. The process of creating pulverized recycled aggregates. The larger particles were crushed with a steel hammer until reaching a certain size and were then sieved. This process was repeat several times.

4.2 Experimental execution

4.2.1 Concrete

With the following recipe, as listed in table 1, five batches of concrete were prepared as shown in figure 6. The same amount of water and shear-reducing agent were used in each batch. The first batch is a reference in order to compare to the other batches with varying amount of recycled aggregates. The second and third batches are with 25% and 50% RCA, respectively. The fourth is with 100% RCA and the fifth is with 100 % non-heat-treated RCA.

Figure 6. The process of making one of the concrete batches.

Table 1. Materials and amount used in each of the concrete batches.

Mix	**Reference**	**25/75**	**50/50**	**100/0**	**100/0 Untreated**
Water (kg)	2.80	2.80	2.80	2.80	2.80
Cement (kg) SH Skövde	7.60	7.60	7.60	7.60	7.60
Shear-reducing agent (kg)	0.114	0.114	0.114	0.114	0.114
Riksten NK 0-8 mm (kg)	20.48	20.48	20.48	20.48	20.48
Enhörna 8-16 mm (kg)	16.35	12.26	8.17	0	0
RCA 4-16 mm (kg)	0	3.95	7.91	16.4	16.4

A slump flow test was performed on each batch to determine the workability of the concrete, as shown in figure 7. Having good rheology is important for when casting the concrete. The test shows the rheology of the concrete and is an indirect indicator of properties such as water absorption of the aggregates in the concrete mixture. The height difference from the top of the cylinder to the top of the concrete showed low deviation, and the values were not significant. Instead each batch was assessed by the lab technician to judge the workability of each batch.

Figure 7. The slump flow test measures the height difference from the top of the cylinder to the top of the concrete after a predetermined time interval.

Figure 8. The concrete test cubes before they have been smoothed out using the shake board.

Nine cubes were casted from each batch and used for testing the compressive strength of the concrete (triple tests for 1 day, 7 days and 28 days). The cubes were made with standardized molds and by using a laboratory shaker the sides of the cubes were smoothed out due to concretes the thixotropic nature of concrete, which can be seen in image 8. Tests were carried out after 1, 7 and 28 days to determine the compressive strength (figure 9).

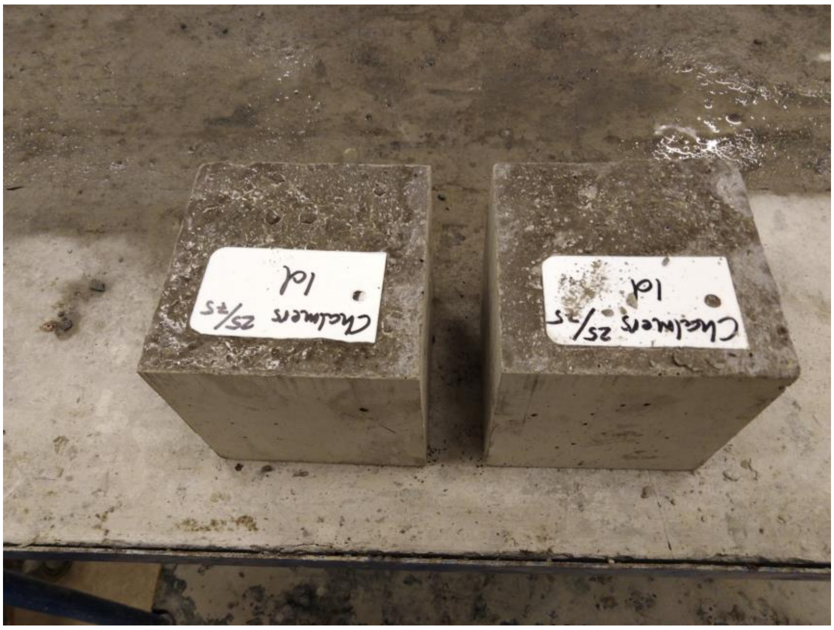

Figure 9. Two of the cubes for the 25% RCA batch once they have hardened for 1 day.

4.2.2 Cement

A blend containing different ratios of recycled cement and juvenile material were prepared for testing along with one reference. In total 3 batches with the fraction <0.125 mm were made with the following ratios, 10/90, 25/75 and 50/50 recycled to unhydrated ordinary cement. Two other batches were made with 25/75 ratio, but one used the fraction <0.075 mm and the other used <0.125mm but with pulverized recycled aggregates. The juvenile cement in all batches were SH Cement Skövde. Norm prisms, as shown in figure 10, were casted followed by testing the materials tensile strength after 1, 7 and 28 days. The standard used for the cement tests were EN 196-1:2016 for compressive strength, and EN 196-3:2016 were used for binding time.

Figure 10. Norm prisms made with 25% recycled cement before they have hardened.

5. Results

5.1 Concrete results

The results from the concrete compressive tests are shown in table 2. Both the 25/75 and 50/50 mixes performed close to the reference batch. The 25/75 had almost the same compressive strength as the reference on day 1 and 7 but deviated a bit more on day 28. The 50/50 batch showed similar trends as the 25/75 one but performing slightly worse on day 7. Both the 100/0 mixes also performed very close to the reference for day 1 and 7, despite a bad result from the slump flow tests.

Table 2. Gives the compressive strength for 1,7 and 28 days for each of the different concrete batches that was made.

Mix	**Reference**	**25/75**	**50/50**	**100/0**	**100/0 untreated**
1 day (MPa)	34.4	33.6	33.6	31.2	30.3
7 days (MPa)	53.9	52.2	50.	50.8	53.2
28 days (MPa)	61.7	56.3	56.6	54.7	61.5

5.2 Cement results

The results from the compressive strength of the norm prisms test are shown in table 3. The 10/90 mix performed like the reference. Both mixes with 25/75 had ~67% of the reference's compressive strength after 1 day. The mix with <0.075mm had slightly higher compressive strength by day 7 compared to the 0.125mm sample. However, by day 28 they evened out and had ~80% the compressive strength of the reference. The mix with 50/50 <0.125mm had a very low compressive strength after 1 day, with only ~33% of the reference. In addition, that mixture was in general difficult to work with. Despite the low workability it reaches ~50% the strength of the reference by day 28. The pulverized recycled thermal treated aggregates showed lower compressive strength than the other mixtures with 25/75 ratio, both on day 1 and 7.

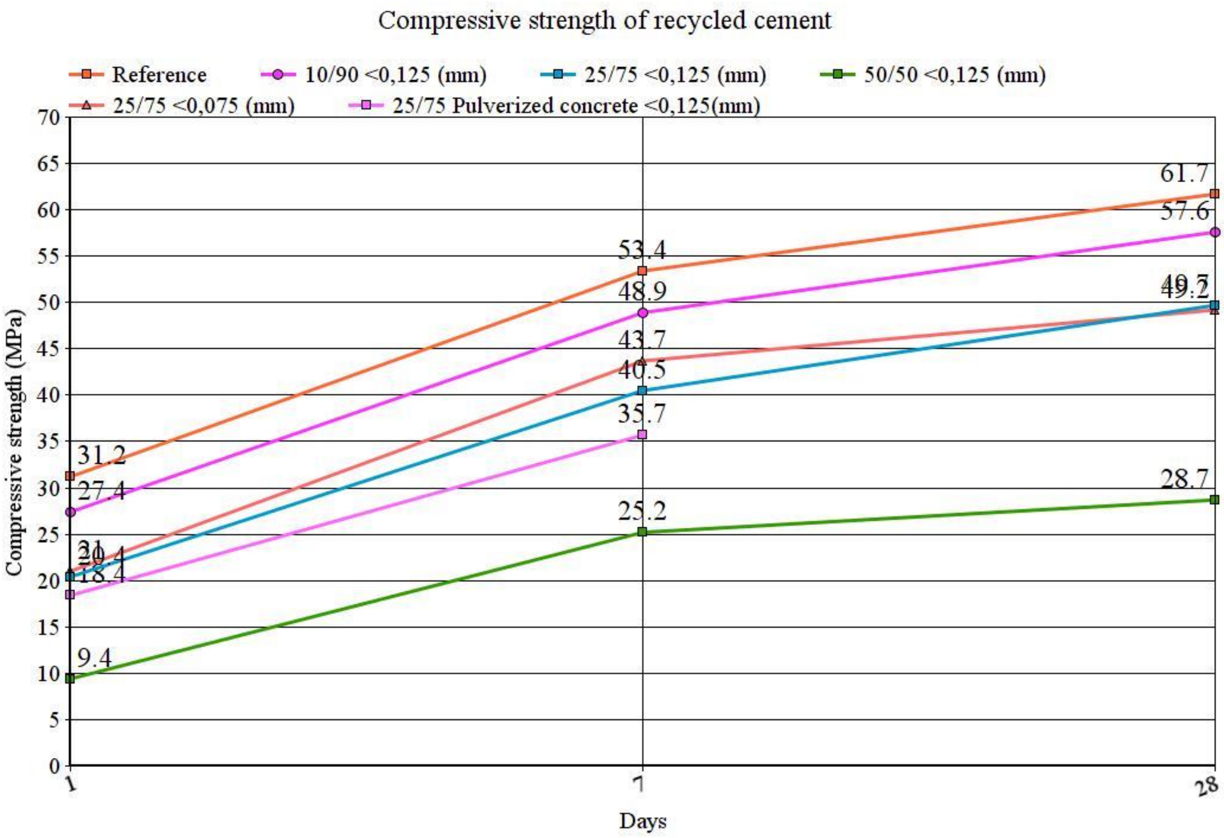

Figure 11: The results from table 3 in graphical form.

Table 3. Showing compressive strength of the different mixes at 1,7 and 28 days. As well as binding time and water requirement.

Mix	**Reference**	**10/90 <0.125 (mm)**	**25/75 <0.125 (mm)**	**50/50 <0.125 (mm)**	**25/75 <0.075 (mm)**	**25/75 Pulverized recycled aggregates <0,125(mm)**
Compressive strength 1 day (MPa)	31.2	27.4	20.4	9.4	21.0	18.4
Compressive strength 7 day (MPa)	53.4	48.9	40.5	25.2	43.7	35.7
Compressive strength 28 day (MPa)	61.7	57.6	49.7	28.7	49.2	41.4
Compressive strength 91 day (MPa)	-	-	56.5	-	-	46.1
Binding time (minutes)	N/a	190	200	210	-	-
H_2O requirement	32.0%	32.4%	33.6%	36.6%	-	-

6. Discussion

The results from the recycled cement followed expectations with some deviations. The 25/75 <0.075mm mix performed very similar to the sample with larger particle size (25/75 <0.125mm). This suggests that there are still large amounts of active material in the coarse particle samples, which would make the separation process of the material much easier. Both 25/75 mixes also showed a higher compressive strength compared to pulverized recycled aggregates, a mostly inert material, which would mean that the method used to produce recycled cement works; and that it is not pulverized concrete. This is further reinforced by the results from the 91day tests. where the compressive strength of the pulverized recycled aggregate increase a lot slower compared to the sample with recycled cement with the same ratio used.

The results from the concrete testing strayed a bit from expectations. The 25/75 and the 50/50 mixtures performed very close to the reference for day 1 and 7 but lost a bit more on day 28. These mixtures also had very similar slump flow results as the reference, so they would be workable if produced for industrial use. This was expected and is in accordance with previous reported results in the literature [8,9]. The results from the 100/0 batches also were not entirely unexpected. Both the heat-treated and the untreated aggregates showed similar compressive strength compared to the 25/75 and 50/50 mixtures for day 1 and 7. As stated previously, it is possible for concrete with RCA to exhibit and increase in compressive strength depending on the higher water absorption of the recycled aggregates. Since all batches used the same amount of water, this most likely benefited the 100% RCA batches giving them a higher compressive strength.

The 100/0 batches however did not perform very well in the slump flow test, where both mixtures crumbled down and did not stay as neat pile (figure 7). So even though they have slightly higher compressive strength as the batches with lower RCA these will not be as workable when used. So, it will be better to use lower amounts of RCA in the concrete in order to make it more like the reference product. One possibility for the bad slump flow tests are the size distribution of the particles. Since the interval of RCA was 4-16 mm, it is possible there was a disproportionate number of particles on the lower end. With fewer larger particles it would affect how well the material binds together during casting. An area of further research would be to do the same test but use more well-defined size intervals.

Scaling up this process for industrial purpose will be difficult due to the energy required and minimal financial incentive, since aggregates are so cheap throughout most of the world. What could push it to become viable is a higher price for putting concrete in deposits, thus eliminating that cost if it is recycled. There will also be more incentive for it with rapid depletion of aggregates, both for sand and gravel. This technique could also find use where aggregates are naturally scarce and would require long transport. Making the energy needed similarly priced to the transportation cost. The use of recycled cement needs more research for it to become viable. It is difficult to produce and costly in terms of energy and time. This laboratory method was only able to produce small amounts. Also, the compressive strength declines with larger amounts of recycled cement. A way to enhance the recycled cement and make it more active again would be a possible route ahead. As the material stands now it cannot compete with other mineral additives coal fly ash.

7. Conclusions

- The method used to separate the cement from aggregates works
- The recycled cement is not inert and has positive effect on the compressive strength as compared to the pulverized recycled aggregates
- There is no apparent difference in using <0.125 mm or <0.075 mm recycled cement
- The use of recycled concrete aggregates did not affect the compressive strength significantly
- The batches with thermally treated aggregates showed a better workability then the non-heat-treated samples

8. Further research

- Testing recycled concrete with specifically aged concrete
- Making concrete with a well-defined size distribution of the recycled aggregates to examine the impact on the compressive strength and workability
- Investigate if it is possible to further refine or enhance the recycled cement fraction <0.125mm to improve its compressive strength.

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