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Coefficient of Thermal Expansion of Concrete Produced with Recycled Concrete Aggregates

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Abstract: This study presents a comparison between the coefficient of thermal expansion (CTE) of concrete produced with natural aggregate and that of concrete produced with recycled concrete aggregate. In order to achieve this, natural aggregate concrete (NAC) specimens were produced, tested, then crushed and sieved in the laboratory to obtain recycled concrete aggregates, which was then used in the production of recycled aggregate concrete (RAC) specimens. The RAC samples were then tested and compared to the NAC samples. The CTE testing was carried out using a AFTC2 CTE measurement system produced by Pine Instrument Company. In addition to CTE testing, the water absorption, specific gravity, and unit weight of the aggregates was determined. A vacuum impregnation procedure was used for the water absorption test. The recycled aggregate properties showed a significantly higher absorption capacity than that of the natural aggregates, while the unit weight and specific gravity of the recycled aggregate were lower than that of the natural aggregates. The average CTE results showed that both the NAC and the RAC samples expanded similarly. The results show that the CTE of RAC depends on the natural aggregate used in the NAC, which was recycled to produce the RAC. Also, there was no significant difference between the average CTE values of the RAC and that of NAC that could discredit the use of recycled aggregate in concrete.
Keywords: Coefficient of thermal expansion; Recycled concrete aggregate; Natural concrete aggregate.

1. Introduction

Concrete is a composite material, which comprises mainly of cement, fine and coarse aggregate, and water. Compared to other conventional building materials, concrete stands out as the most used material in construction. The high demand and application of concrete are due to its unique qualities such as: compressive and tensile strength, ability to be cast into various shapes and sizes, resistance to physical and chemical attack, etc., [1]. Concrete can be produced to possess a desired property or performance as long as the correct specifications are followed [2]. The properties of concrete (fresh or hardened), depends largely on its mixture design as well as the constituents used (i.e., aggregates, powders, additives, etc.). The various attributes and quantity of each constituent of concrete determines the final properties of concrete both at the fresh and hardened state. The properties of concrete varies as it transforms from a fresh and plastic state to a hardened state. Some of the properties of fresh concrete include, but not limited to: workability and rheological properties, bleeding, hydration and setting time. Hardened concrete properties also include: compressive strength, tensile strength, creep, shrinkage, elastic properties, transport properties, electrical, and thermal properties [3]. One of the thermal properties is the Coefficient of Thermal Expansion (CTE). The CTE is a value representing a material's response to a change in temperature. Some structures are exposed to differential heating and cooling while in service which can result in differential expansion and contraction. This volume stability could be detrimental and can result in premature failure if measures are not taking to allow for thermal expansion and stresses [1]. CTE values in concrete are largely dependent on the type of aggregate used to produce the concrete, since aggregate occupies approximately two-third the volume of concrete. The prevalent practice in construction involves the use of natural (virgin) coarse aggregate in producing concrete. However, there is a need to conserve the heavily used natural aggregate and instead adopt the use of recycled concrete aggregates, which has both economic and environmental benefits. This study aims at investigating how concrete produced with recycled concrete aggregates responds to changes in temperature compared to concrete produced with natural aggregates.

2. Research significance and goals

The significance of this study is additional insight and data into the use of recycled aggregate on the CTE properties of concrete. Up to this point there is minimal information and data on thermal properties of concrete as a whole, but in particularly the CTE of concrete produced with recycled concrete aggregates. Not only does this study aim to fill that void in the literature, but it is also an effort to produce a more sustainable construction building material. This is accomplished by demonstrating the capability of using recycled aggregates in concrete such that there is less strain on the industry to produce and use conventional natural aggregates. This study also demonstrated the CTE capability of structural pavement concrete mixtures, which could provide more informed data for concrete pavement produced with recycled concrete aggregate that will be exposed to large differential heating and cooling gradients, which could lead to more cracking and even premature failure and would require repair or a complete rebuild.

The specific objectives of this study are as follows:

1) To obtain the CTE of concrete samples produced using laboratory produced recycled concrete aggregates.

2) To compare the CTE values obtained from concrete produced using natural aggregates with that of recycled concrete aggregates and recommend possible application.

3. Literature review

3.1 Recycled concrete aggregate

Recycled concrete aggregates are artificial aggregates derived from the mechanical processing of hardened concrete recovered from concrete demolition [4]. The processing of concrete demolition and further material separating and processing leads to recycled concrete aggregates of different sizes. Some of these aggregates are largely retained on the 4.75mm (No. 4) sieve and can be termed coarse aggregates, while the rest that pass through the 4.75mm (No. 4) sieve and retained on the 75µm (No. 200) sieve are termed fine aggregates [5]. It is recommended to screen and discard recycled concrete aggregates that are less than 2mm (0.08 in.) due to the substantial reduction in the strength of concrete attributed to its usage [4]. Although there have been numerous evaluations and demonstrations on the use of RCA in several nations, precautions need to be taken while it is being used. Some of the reasons why precaution should be taken are as follows: recycled aggregate might have contaminants that could make concrete susceptible to chemical attack, such as chloride penetration; the recycled aggregates could have been obtained from deteriorated concrete which could lead to a reduction in freeze-thaw resistance, due to an inferior air void system within the adhered mortar, and degrading of concrete during the process of production and placing; and, there might be a need to increase water requirement due to a potential high absorption capacity of the recycled concrete aggregates [6]. The mechanical and physical properties of natural aggregates differ from that of recycled aggregates. Natural aggregates exhibit the characteristics of the parent rock from which they were obtained. Whereas, the characteristics of recycled concrete aggregate are determined by both the parent rock and other constituents of the original concrete [7]. Recycled concrete aggregate contain mortar from the original concrete, which makes them more porous with high water absorption capacity compared to natural aggregates [8-9]. This is due to the aggregates being a solid material and the adhered mortar being a mixture of cement, water, and sand in which small pores are highly likely to form simply due to the mixing action, combination of materials, particle size distribution, and the nucleation/growth kinetics of the cement hydration process as the material solidifies. In order to compensate for the high absorption capacity of recycled concrete coarse aggregate, an additional quantity of water is required by the concrete mixture [10]. Concrete produced using recycled concrete aggregate tend to have more interfacial transition zones compared to that of concrete produced with natural aggregates and as a result the mechanical properties of recycled aggregate concrete (RAC) are undermined by such weak zones [8]. According to Kou and Poon (2013), durability and mechanical properties of recycled aggregate concrete such as resistance to chloride ingression, dry shrinkage, tensile splitting and compressive strength, modules of elasticity can be improved by adding fly ash or reducing effective water-cement ratio [11]. Certain properties of aggregate like bulk unit weight, moisture content, specific gravity, size and texture, and gradation are required for a suitable concrete mix proportion with good workability [1]. In a study carried out by Wagih et al., (2013) the specific gravity and bulk density test results showed lower values for recycled concrete aggregate compared to natural aggregates [12]. Other researchers have indicated that recycled concrete coarse aggregates are less resistance to abrasion compared to natural coarse aggregate and tend to break down during mixing, thus, affecting the workability of concrete due to increased fines [1, 12]. Many researchers have also investigated the possibility of using RCA in place of natural aggregates in concrete. Wagih et al. (2013) investigated the possibility of using coarse aggregates generated from crushing and sieving demolished concrete waste obtained from fifteen different locations in Cairo, Egypt to replace natural coarse aggregates in concrete production [12]. A total of fifty mixtures involving eight different mixture proportions were prepared for testing. Seven out of the eight mixture proportions involved 0%, 25%, 50%, 75% and 100% replacements of natural aggregate with recycled concrete aggregate while one of the groups (control) had fifteen mixtures involving the recycled aggregates only. The seven groups were designed to ascertain the effect of different recycled coarse aggregate replacements, cement amount, use of superplasticizer and silica fume. The superplasticizer content used were 0% and 1.3% while cement content was 350, 400 and 450 kg/m^3 (590, 674, and 759 lb/yd^3). Concrete samples were tested for bulk density, compressive strength, splitting tensile strength and modulus of elasticity. The results showed that the 100% recycled aggregate concrete samples exhibited a significant reduction in concrete properties compared to the natural coarse aggregate concrete. However, no significant change in concrete properties was observed in the samples involving 75% natural aggregate and 25% recycled aggregate. It was concluded that demolished concrete waste can be converted to recycled coarse aggregate, which possess characteristics that qualifies their use in Egypt for erecting concrete structures [12]. To determine the mechanical properties of RCA concrete that has been exposed to high temperature, Vieira et al. (2011) produced concrete cylinders comprising of 100% natural coarse aggregate as well as cylinders that had their natural coarse aggregate content replaced by 20%, 50% and 100% recycled coarse aggregate. Specimens from the various aggregate combinations were subjected to a reference temperature of 200ºC and higher temperatures of 400ºC, 600ºC and 800ºC for one hour in accordance to ISO 834 standard. The results of the compressive strength, elastic modulus and tensile splitting strength test carried out on samples after cooling to ambient temperature were compared with the reference values obtained before heating. They concluded that no significant difference exists in the mechanical properties of concrete made with the recycled aggregate compared to natural aggregates [10].

3.2 Coefficient of thermal expansion

A CTE of a material is an increase in length per unit length per rise in degree of temperature [13]. The failure of concrete structures exposed to differential heating and cooling is inevitable if the CTE of concrete used is not known and considered during construction [1]. CTE helps to ascertain the potential for failures such as: blow ups, spalling, cracking and joint opening in pavements [3]. Concrete responds to variations in temperature. An increase or decrease in temperature will cause concrete to either expand or contract respectively [14-15]. The extent to which concrete expands or contracts due to changes in temperature depends on the aggregate used and the mixture design [1]. Although the CTE of concrete is attributed to the collective CTE of the cement paste and aggregate constituents of concrete, the aggregate still stands out as the major determinant of CTE for concrete because it constitutes the bulk of the entire concrete structure [1]. The CTE also differs from one aggregate type to the other. For instance, the CTE of limestone is smaller than that of flint and when they are used in concrete, they also affect the CTE of the concrete in the same manner [8]. When concrete is exposed to high temperatures, their performance is influenced by the type of aggregate, thickness of concrete mass and the water-cement ratio [7]. Some research has been carried out to find out how various factors affect the CTE of concrete including the use of recycled concrete coarse aggregate instead of natural coarse aggregate. According to an experiment conducted by Yang et al., (2003) to evaluate the factors influencing the CTE of concrete using AASHTO TP60-00 standard test method, the following parameters were considered: six types of coarse aggregates including a recycled aggregate, cycles of warming and cooling, cylindrical and prismatic specimen, dilatometer and strain gauge types of measurement. The result of their experiment are as follows: specimen shape was found to influence CTE greatly as the CTE for the cylindrical specimen was lower than prismatic specimen, CTE was dependent on coarse aggregate type, the cycles of warming seem not to have much influence as the values were almost the same for the prismatic specimen, the CTE values from both the dilatometer device and PML 60 (strain guage) were similar [14-15]. Smith and Tighe (2009) investigated the effect of partial replacement of virgin coarse aggregate with recycled coarse aggregate on the CTE of concrete as well as the impact on the performance of concrete pavement when the same replacements are applied. CTE testing was carried out on four sets of four core samples of 152mm (6 in.) diameter extracted from four different sections of a test track. These sections were designed to have 0% recycled aggregate within the first 30 meters, 15% recycled aggregate replacement for the next 50 meters, 30% replacement for another 50 meters and 50% replacement for the last 50 meters. A Mechanistic Empirical Pavement Design Guide (MEPDG) was also carried out using computer simulation to evaluate the impact of the recycled aggregate replacements on the performance of concrete pavement. The CTE result showed that CTE values decrease as the recycled aggregate content increases. Also, the MEPDG simulations showed an improvement in the performance of concrete as CTE values decreases due to an increase in recycled aggregate content [14-15].

This study was focused on comparing the CTE of concrete cylinders produced with natural aggregates with that of recycled aggregate produced by crushing the natural aggregate concrete cylinders into required coarse aggregate sizes. The natural coarse aggregate concrete cylinders were produced with six different natural coarse aggregates from Texas Department of Transportation (TXDOT) and tested for CTE prior to this study. Aside CTE, aggregate property testing like absorption, specific gravity and unit weight were carried out on the six RCA and compared with that of the natural aggregate obtained prior to this study. It was expected that the CTE values of the RCA cylinders will be lower than that of the natural aggregate concrete cylinders that was crushed to produce them. Also, there was expectation of some significant difference in the aggregate property results for both the recycled concrete aggregate and the natural aggregate.

4. Methodology

Six different natural coarse aggregates were procured from Texas quarries to evaluate and test their CTE performance in concrete. Each of these natural aggregates were used to produce NAC cylinders with 100mm (4 in.) diameter and height of 200mm (8 in.). After the cylinders were cast and cured for 28-days the NAC cylinders were tested for their CTE in accordance to TEX-428-A [16]. Following testing of the NAC cylinders, they were crushed and processed to produce recycled concrete aggregate. A compression machine was used to crush each concrete cylinders to a manageable size, followed by using a steel mallet weighing 8.10kg (17.86lb) to crush the concrete further into smaller aggregate sizes (<25mm [1 in.]). Following crushing the recycled concrete aggregate was then graded in accordance to TEX-428-A. The newly obtained recycled concrete aggregate was then used to produce new RAC cylinders with the same mixture proportion aside from a 100% replacement of the natural coarse aggregate with the newly created recycled coarse aggregate. The new cylinders were the same dimensions as the NAC cylinders and were cast and cured in the same manner. The newly produced RAC cylinders were then tested for their CTE, also in accordance to TEX-428-A. In addition to the CTE of the concrete cylinders, the natural and recycled aggregates were tested for water absorption, unit weight, and specific gravity.

4.1 Materials

A low-alkali Type I/II portland cement obtained from a local cement producer in Texas with alkali content <0.60 Na_2Oeq was used for producing both the NAC and the RAC cylinders. The fine aggregate used for both the NAC and RAC cylinders was a natural river (concrete) sand also procured locally in Texas. Six different natural coarse aggregates were procured from various queries in Texas and Oklahoma. The different aggregates were selected as they are typical aggregates used in concrete, however their specific location and mineralogy may have an influence on the concrete's thermal properties. In order to distinguish between the six aggregates a Unique Identification Number (UIN) was used, which includes the year extracted and a unique quarry location code. These UIN will be carried over and used in this study to distinguish between all of the NAC. Table 1 lists the six different natural aggregates, their respective UIN, and their specific location to which they were acquired. Visually, all of the natural aggregates were mostly angular in shape, and a tan/gray color.

Table 1. Natural coarse aggregates and their query location.

Unique Identification Number (UIN)	Type	Location
15-0382	Crushed Limestone	San Antonio, TX
16-1002	Partly Crushed Siliceous and Limestone Gravel	La Grulla, TX
17-0299	Crushed Limestone	Elgin, OK
17-0303	Crushed Limestone	Ardmore, OK
17-0337	Partly Crushed Siliceous Gravel	Garwood, TX
17-0355	Partly Crushed Siliceous Gravel	Victoria, TX

All of the aggregates received in Table 1 and the recycled concrete aggregate produced in this study were graded in accordance to TEX-428-A, which is a Texas Department of Transportation (TxDOT) standard for performing CTE testing. The gradation of the aggregates from the standard corresponds to the gradation listed in Table 2.

Table 2. Coarse aggregate gradation requirement for CTE testing (TEX-428-A).

Sieve Size		**Mass, kg (pounds)**
Passing, mm (in.)	**Retained, mm (in./No.)**	
25.4 (1”)	19 (¾”)	8.5 (18.7)
19 (¾”)	13 (½”)	17.8 (39.2)
13 (½”)	6.4 (#4)	12.4 (27.3)

Each aggregate from Table 1 was separated out in the graded manner shown in Table 2, then recombined to form approximately 38.4 kg (85.2 lbs) of batched coarse aggregate. Each individually separated aggregate (including the recycled coarse aggregate) was then included in a $0.021m^3$ ($0.75 ft^3$) concrete batch according to TEX-428-A. The remaining concrete batch quantities can be seen in Table 3.

Table 3. Concrete batch quantities according to TEX-428-A for CTE testing.

Material	Batch Weight, kg (lbs)
Type I/II Cement	10.63 (23.45)
Municipal Water	5.22 (11.49)
Fine Aggregate	23.3 (51.44)
Coarse Aggregate (total from Table 2)	38.4 (85.2)

4.2 Water absorption and specific gravity

Prior to concrete testing the water absorption and the specific gravity of each coarse aggregate system was determined, including the prepared recycled concrete aggregate. For the natural coarse aggregate listed in Table 1, the water absorption and specific gravity were determined in accordance to ASTM C127-15 [17]. While this procedure is applicable for natural (virgin) coarse aggregate and recycled concrete aggregate, a vacuum impregnation test was used on the recycled concrete aggregate. Vacuum impregnation is required for the recycled concrete aggregates primarily due to the high absorption capacity commonly noted from recycled concrete aggregates. The test set up for this test can be seen in Figure 1.

Figure 1. Vacuum impregnation of rest set-up for recycled concrete aggregate

The test set up consists of three plastic cylindrical chambers (to allow testing of three samples simultaneously), in which the aggregate sample is placed. The chambers are affixed with an air pressure meter and a vacuum to pump air out of the system and to create the vacuum. The chambers are also affixed with an inlet to allow deionized water to flow in. This process allows the sample to be vacuum impregnated with the deionized water to ensure all voids are saturated in order to take a saturated surface dry weight. The testing process consists of first placing an oven-dried recycled concrete aggregate sample under each chamber. After the chambers are sealed the vacuum pump is switched on to introduce vacuum in the chambers. This is continued until the vacuum gauge dial reading was 28 inches of mercury for a minimum of 4 hours. While still under vacuum, deionized water is then introduced from the water tanks by turning the valves on the tank and at the bottom of the chamber to allow the flow of deionized water into the chamber. The water continues flowing until the entire aggregate sample is fully submerged with 50-75mm (2 – 3 in.) of deionized water. The valves at the water tank and bottom of chambers are then turned off and the vacuum pump is allowed to increase the vacuum pressure in the chamber back to 28 inches of mercury. At this vacuum pressure the vacuum pump and the top valves connecting the vacuum pump to the cylindrical chambers are turned off. The entire set up is then left for additional 20 hours, after which the set up is dismantled and the aggregate samples removed. Then the surface of the samples is dried to saturated surface dry condition immediately after removal from the vacuum chambers using dry rags, then their weight was recorded. Afterwards, each of the recycled concrete aggregate samples were placed one after the other in a basket and weighed in completely submerged in a water bath. The basket was also weighed empty both in air and complete submersion in the same water bath. Each of the recycled concrete aggregate samples were transferred to containers and placed in an oven at 110 ± 5°C (230 ± 9°F) for 24 hours. The weight of samples and containers as well as the empty containers were obtained after drying. The absorption and unit weight were then obtained using the same equations from ASTM C127-15 [17].

4.3 CTE testing

The CTE for all samples produced in this study was determined in accordance to TEX-428-A using the AFTC2 CTE measurement system produced by Pine Instrument Company. This equipment was designed to follow AASHTO T336 measurement procedure with minimal operator attention. The equipment comprises of a water bath, CTE frame with displacement transducers (also known as fixtures), temperature measurement arrangement, interface electronics, computer and refrigerated heating/cooling circulating chiller. The AFTC2 CTE measurement system was rated to test specimen over a temperature range of 10ºC to 50ºC (50ºF to 122ºF). The equipment runs automatically when started and stops when the CTE measurement of two consecutive test segments for each specimen falls within 0.3 x 10^{-6} mm/mm/ºC of each other. A photograph of the AFTC2 CTE system can be seen in Figure 2.

Figure 2. AFTC2 CTE Measurement System

5. Results and discussion

5.1 Aggregate property results

The results for the natural and recycled aggregate testing are presented in Table 4. The results can also be seen graphically in Figures 3 - 5 for an easier comparison. Visually, all of the recycled aggregates listed in Table 4 were angular and mostly grey in color, due to the adhered mortar.

Table 4 and Figure 3 – 5 shows that the specific gravity of the recycled concrete aggregates was from approximately 2.42 to 2.51 while that of the natural aggregates was from 2.50 to 2.60. The specific gravity of the natural aggregates conforms with that of most aggregates, which is in the range of 2.5 to 2.8 as stated by [1]. This low specific gravity result exhibited by the recycled concrete aggregates is likely due to high porosity from the adhered mortar on the natural aggregates due to the crushing process. The specific gravity results of natural aggregates and recycled concrete aggregate obtained in this study also aligns with that obtained by [12].

Table 4. Aggregate property testing results for RCA and NA

Specimen UID	Specific Gravity		Water Absorption (%)		Unit Weight (lb/ft^3)	
	Recycled	Natural	Recycled	Natural	Recycled	Natural
15-0382	2.44	2.57	5.98	2.00	83.44	98.30
16-1002	2.42	2.60	5.73	2.04	91.97	101.10
17-0299	2.46	2.75	5.48	0.95	87.34	96.80
17-0303	2.51	2.50	4.60	0.80	87.93	96.60
17-0337	2.42	2.56	5.28	1.26	85.30	94.30
17-0355	2.47	2.57	4.29	0.64	91.00	106.80

The results of the water absorption test shown in Table 4 and graphically in Figure 4 shows that the recycled concrete aggregates had higher water absorption capacity compared to the natural aggregates. Figure 4 shows that the percentage absorption for the natural aggregates was from 1 to 2%, which is the absorption capacity range of most normal weight aggregates as stated by Mindess et al., (2003) [1]. The recycled concrete aggregates absorption capacity was from 4.29 to 5.98%, which is an abnormal high absorption capacity for aggregates. However, this is the norm for water absorption for recycled concrete aggregate and the results obtained in this study conforms with the results of water absorption carried out on recycled concrete aggregate by Wagih et al., (2013) [12]. This high water absorption capacity of the recycled concrete aggregates is likely due to the high porosity from the adhered mortar on the natural aggregates.

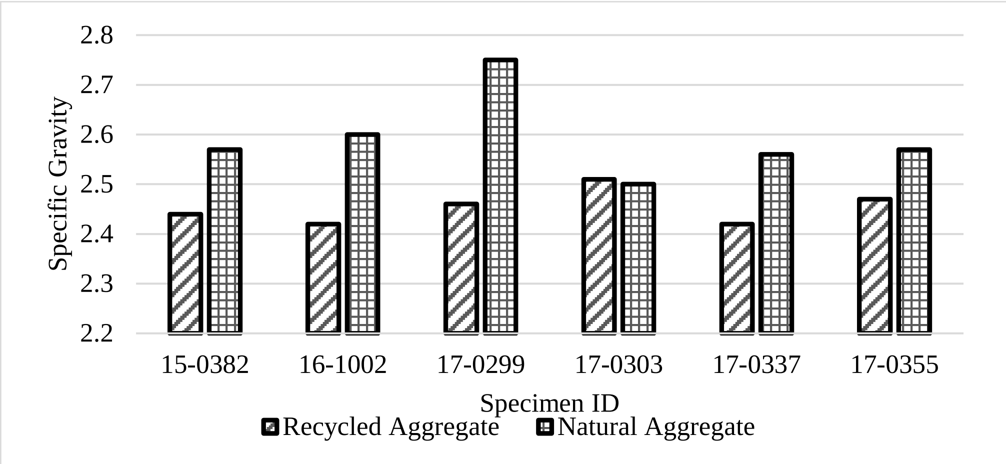

Figure 3. Specific Gravity of the recycled and natural aggregates.

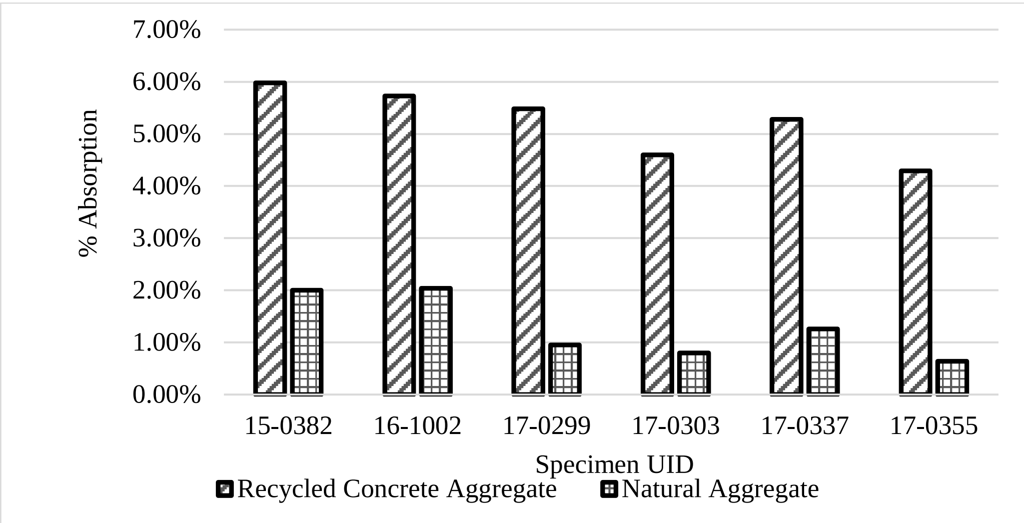

Figure 4. Water Absorption Capacity for RCA and NA.

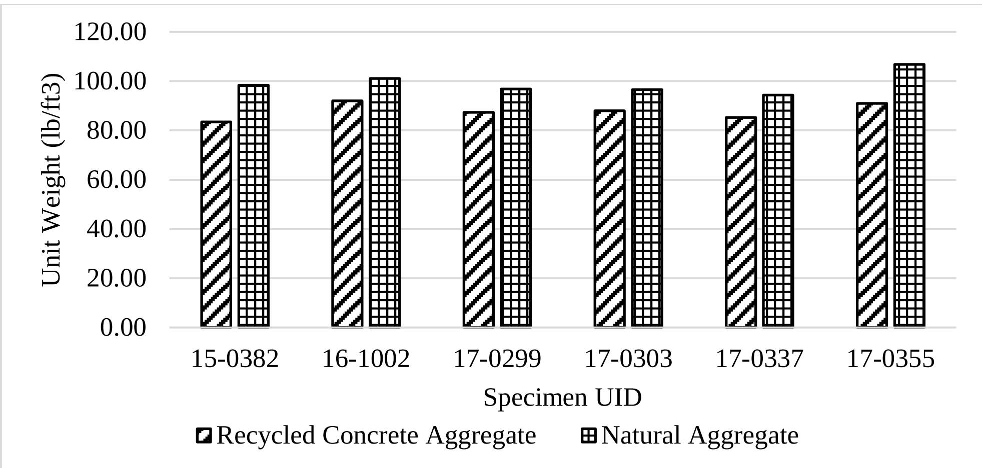

Figure 5. Unit weight of recycled and natural aggregates.

The results of the unit weight test for the recycled concrete aggregates and natural aggregates shows that the unit weights of the natural aggregates were more than that of the recycled aggregates. The lower unit weights of the recycled aggregates are likely attributed to the porosity on the adhered mortar on the natural aggregates, similar to the rationale for the higher absorption.

5.2 CTE results

Table 5 and Figure 6 shows the average CTE for each specimen as well as the CTE average and standard deviation of the three specimens (RAC cylinders) representing each UID. It also shows the average CTE values of the NAC cylinders.

Table 5. CTE results for RAC and NAC samples.

Specimen UID	CTE_{AVG} (in/in/^{0}F) for Recycled Aggregate Concrete Cylinders (RACC)			CTE_{AVG} (in/in/^{0}F) RACC	CTE_{AVG} (in/in/^{0}F) NACC	Standard Deviation RACC
	Specimen 1	Specimen 2	Specimen 3			
15-0382	4.49E-06	4.23E-06	4.41E-06	4.38E-06	3.76E-06	1.34E-07
16-1002	5.38E-06	5.30E-06	5.34E-06	5.34E-06	5.61E-06	4.45E-08
17-0299	4.67E-06	4.56E-06	4.40E-06	4.54E-06	4.03E-06	1.38E-07
17-0303	4.62E-06	4.54E-06	4.40E-06	4.52E-06	3.92E-06	1.07E-07
17-0337	5.98E-06	5.73E-06	5.83E-06	5.85E-06	6.26E-06	1.23E-07
17-0355	6.02E-06	5.95E-06	5.90E-06	5.95E-06	6.21E-06	6.04E-08

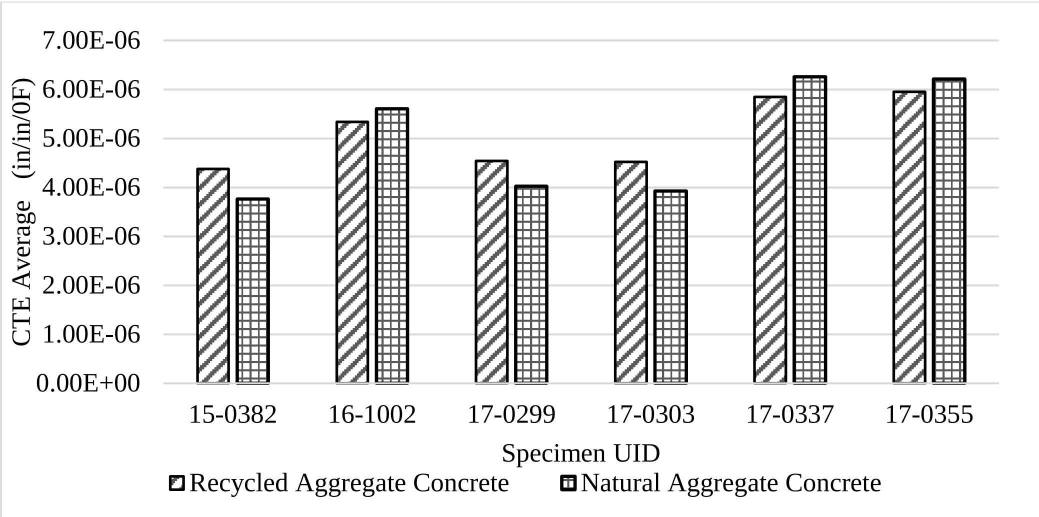

Figure 6. Average CTE results for the RAC and NAC cylinders.

Figure 6 shows the plotted average CTE values of the RAC cylinders and the NAC cylinders. Figure 6 also shows that the average CTE values for the NAC cylinders with UID numbers: 17-0335, 17-0337, and 16-1002 were more than that of recycled aggregate concrete cylinders with the same UID numbers. Whereas the average CTE values for RAC cylinders with UID numbers: 15-0382, 17-0299, and 17-0303 were more than that of the NAC cylinders with the same UID numbers. However, comparing the average CTE values of RAC cylinders with UID: 15-0382, 17-0299, and 17-0303 to that of RAC cylinders with UID: 17-0335, 17-0337, and 16-1002, it was observed that the average CTE values for 15-0382, 17-0299, and 17-0303 were lower than that for 17-0335, 17-0337, and 16-1002. The low expansion exhibited by these RAC cylinders can be attributed to the low expansion of the natural aggregates in the natural NAC cylinders that was recycled to produce them. This was supported with the fact that average CTE values of the NAC cylinders followed the same trend as the RAC cylinders (CTE values for UID: 15-0382, 17-0299, and 17-0303 are lower than that of 17-0335, 17-0337, and 16-1002). These results are as expected and also conform to similar studies [1-3].

It is interesting to note that the RAC cylinders produced using aggregates comprised of crushed limestone (UID: 15-0382, 17-0299, and 17-0303) were the only ones that showed a higher average CTE value compared to their counterpart NAC cylinders. On the other hand, RAC cylinders produced using partly crushed siliceous and limestone gravel (UID: 17-0335, 17-0337, and 16-1002) consistently showed a lower average CTE value compared to their NAC cylinders. Previous research has shown that the CTE of RCA is affected by not only the type of the original virgin aggregate but also by the residual mortar (RM) fraction attached to the RCA. Generally, the CTE value of the RM is higher than that of concrete. Hence, the higher expansion exhibited by the RAC cylinders recombined with crushed limestone can be attributed to the crushing process that likely involved removing more softer limestone particles and exposing more of the RM fraction. On the contrary, the CTE for RCA samples in which partly crushed siliceous and limestone gravel was used as the original virgin aggregate showed that the RM did not have a significant impact on the measured CTE in NCA samples.

In order to ascertain if there is any significance between the RCA and NAC cylinders a statistical analysis was completed. A student t-test was completed on the data with a 95% confidence level and the results show that there is, in fact, no statistical significance between all data points, confirming that there is no significant difference between each RCA and NAC cylinder with each aggregate system.

6. Conclusions

Based on the results from this study the following conclusions can be made.

1) The CTE of recycled aggregate concrete depends on the natural aggregate used in the original concrete that was recycled to produce them.

2) No significant difference was seen between the average CTE values of the recycled aggregate concrete and that of natural aggregate concrete that could discredit the use of recycled aggregate in concrete. Therefore, this would reduce the amount of demolished concrete sent to landfill, while also reducing the burden of having to use virgin natural aggregates.

3) Higher average CTE values are observed in recycled aggregate concrete comprised of softer, crushed limestone particles due to the higher residual mortar fraction contained in the RCA samples.

4) The water absorption of recycled concrete aggregates was higher than that of natural aggregates. Hence, the water absorbing capacity of recycled concrete aggregates should be considered when designing a mix that involves such aggregates

5) The specific gravity and unit weight of the recycled concrete aggregates were lower than that of the natural aggregates.

6) Further research on CTE for recycled concrete aggregate from different sources is recommended.

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