Properties of Crumb Rubber Concrete

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ABSTRACT

Crumb rubber is a material produced by shredding and commutating used tires. There is no doubt that the increasing piles of tires create environmental concerns. The long term goal of this research is to find a means to dispose of the crumb rubber in Portland cement concrete and still provide a final product with good engineering properties. With this objective in mind the Arizona Department of Transportation (ADOT) and Arizona State University (ASU) initiated several crumb rubber concrete (CRC) test sections over the past few years. The test sections were built through out the state of Arizona and are being monitored for performance. Laboratory tests were conducted at ASU to support the knowledge learned in the field. The objective of this paper is to enhance the understanding of CRC material properties by presenting the laboratory test results from these test sections.

Concrete laboratory tests included compressive, flexural, and indirect tensile strength tests, thermal coefficient of expansion, and microscopic matrix analysis. The unit weight of the crumb rubber concrete decreased approximately 6 pcf for every 50 lbs of crumb rubber added. The compressive and flexural strength also decreased as the rubber content increased. Further investigative efforts determined that the entrapped air (causing excessive reductions in compressive strength) could be substantially reduced by adding a de-airing agent into the mixing truck just prior to the placement of the concrete. The laboratory test results also showed that as the rubber content increased, the tensile strength decreased, but the strain at failure increased. Higher tensile strain at failure is indicative of more ductile (energy absorbent) mixes. The coefficient of thermal expansion tests indicated that the CRC are more resistant to thermal changes.

In all of the mechanical tests, the CRC specimens remained intact after failure (did not shatter) compared to a conventional concrete mix. Such behavior may be beneficial for a structure that requires good impact resistance properties. If no special considerations are made to maintain a higher strength values, the use of CRC mixes are recommended in places where high strength concrete is not required.

INTRODUCTION

Since 1990, it has been the policy of the State of Arizona that the recycling and reuse of waste tires are the highest priority. The Arizona Department of Transportation (ADOT) has long supported the use of recycled waste tire rubber in asphalt rubber hot mix. In the past three years cooperative work between ADOT and Arizona State University (ASU) was conducted to extend the use of crumb rubber in Portland Cement Concrete (PCC) mixes. The intent was to use such mixes on urban development related projects. A list of feasible projects was identified. Examples are: roadways or road intersections, sidewalks, recreational courts and pathways, and wheel chair ramps for better skid resistance. This collaboration has also expanded to include members from industry associations, concrete suppliers and consultants.

There is no doubt that the increasing piles of tires create environmental concerns. Finding a way to dispose of the rubber in concrete would enhance the understanding on how to incorporate the crumb rubber in greater engineering usage. It is realized that partnership with states, industries and consultants is vital for the success of such initiative.

Several crumb rubber in concrete test sections were built throughout the state of Arizona and are being monitored for performance. Laboratory tests were conducted at ASU and industry associations to support the knowledge learned in the field. This paper summarizes findings to date and knowledge learned in the field.

PAST RESEARCH

Crumb rubber is a material produced by shredding and commutating used tires. The huge stockpile of used tires in the United States (US), which is estimated at about 2 to 3 billions, has been posing an environmental and health hazard to the public. How to reuse those stockpiled tires has been a driving force for new ideas, which has lead to a number of field experiments of using crumb rubber in Portland cement concrete. Here, the phrase “rubber concrete” is used as a generic name for a mixture of conventional Portland cement concrete with crumb rubber.

Early studies by Eldin and Fedroff explored the effect of rubber chips on the compressive and flexural strength of CRC mixes (1,2). Schimizze et al. suggested using tires in light-duty concrete pavements (3). Biel and Lee experimented with a special cement (Magnesium Oxychloride type) for the purpose of enhancing the bonding strength between rubber particles and cement (4). Goulias and Ali employed the resonant frequency method to measure the dynamics modulus of elasticity and Poisson’s ratio. They found that using rubber particles would improve the engineering characteristics of concrete. Toutanji’s study focused on replacing mineral coarse aggregate with rubber tire chips (5). Freeze-thaw durability of rubber concrete was investigated by Fedroff, Savas and Ahamd (6). Lee and Moon investigated adding crumb rubber into latex concrete (7). Khatib and Bayomy proposed a compressive strength reduction model of concrete mixes with added rubber content (8). Thong-On reported on the mechanical behavior of crumb rubber cement mortar (9).

Similar work on mechanical evaluation of rubber concrete has also been reported outside of the US. This included studies by Li et al. in Hong Kong (10); Hernandez-Olivares et al in Spain provided Scanning Electro Microscope (SEM) photos of rubber/cement interface, as well as the evaluation of complex modulus (11). Proceedings of the International Conference on Concrete in Dundee, United Kingdom (UK) also contained a number of studies on this subject matter.

Most of the studies previously mentioned were analytical and/or laboratory based experimental work. The major findings were that rubber concrete would suffer a reduction in compressive strength while it may increase ductility. Whether rubber concrete is suitable for any practical application has remained to be explored.

Since 1999, a wave of pioneering effort to build rubber concrete test sites in Arizona was undertaken by ASU, ADOT, and the Arizona Department of Environmental Quality (ADEQ), and local concrete and tire recycling industries (12). In February 1999, a section of rubber concrete sidewalk was poured on the campus of ASU with a content of 40 lbs of crumb rubber per cubic yard of concrete. In May 2001, the ADOT Materials Group built a section of parking lot in its Phoenix Division site with a design of 50 lbs of crumb rubber per cubic yard. A routine amount of sampling and testing was performed. Compressive strength on cored samples were as high as 3,260 psi. In June 2001, a wheel chair ramp near a building on ASU campus was also poured with a design of 20 lbs of crumb rubber per cubic yard. In March 2002, a resident in Mesa AZ, had the contractor pour his patio foundation with rubber concrete (20 lbs. of crumb rubber for per cubic yard of concrete). In March 2003, the author experimented with the use of rubber concrete (25 lbs of crumb rubber per cubic yard) for a sidewalk at his home in Scottsdale, Arizona.

In April 2002, four concrete mixes were placed by the author's supervision on the campus of Northern Arizona University in Flagstaff, Arizona (cold climate with 7 months of freeze-thaw cycles). Three mixes had up to 60 lbs of crumb rubber per cubic yard, with no air-entraining agent (AEA). The major purpose of this experiment was to evaluate the use of crumb rubber concrete as reducing the need for air entraining agents in cold climate. Again, an extensive sampling and testing program was conducted.

Perhaps the single largest project that utilized higher contents of crumb rubber in concrete was an experimental outdoor tennis court in Phoenix. Leading to the final construction of this tennis court, a series of experimental test slabs (2 x 4 ft in size, with a thickness of 2 to 3 inches) were built in January 2003 with rubber content varying between 50 to 300 lbs. of crumb rubber per cubic yard. The experimental testing program included: compressive strength, flexural strength, indirect tensile strength, and thermal coefficient of expansion. The preliminary results were very encouraging.

It is hypothesized that rubber crumbs may function as a distribution of mini expansion / control joints inside the concrete. Thus, the crumb rubber concrete may exhibit good characteristics in controlling crack initiation and propagation. To further evaluate this hypothesis, in January 2003, the first of several test slabs, 5 x 25 feet and 2 inches thick, was built. The slab contained 400 lbs of crumb rubber per cubic yard (representing 25% of the concrete mix by volume), and it was placed without any joints, at Hanson's Aggregates in Phoenix, AZ. No shrinkage cracks have been observed to date. It should be noted that the slab serves as a truck parking facility. Encouraged by the performance of this first slab, additional slabs have been built and are being evaluated.

The building of these test slabs have provided very useful experience and the means to evaluate firsthand knowledge about mixing, hauling, pumping, placing, finishing, and curing of crumb rubber concrete.

Last year, ADOT experimented with the use of crumb rubber concrete on two thin whitetopping PCC pavements. Laboratory evaluation tests included compressive strength, thermal coefficient of expansion, fracture, shrinkage cracking and microscopic matrix analysis.

OBJECTIVES

The objectives of this paper are to:

- Enhance the understanding on crumb rubber concrete material properties through laboratory testing and field evaluation.
- Develop test information that may aid in the eventual goal of drafting a practical rubber in concrete specification for non-structural / low loading usage.
- Evaluate possible advantages of using crumb rubber in concrete including: resistance against cracking, reduction of thermal expansion and contraction, and lightweight concrete.

Through a series of the above-mentioned test sections, these possible advantages were evaluated and results are discussed in the following sections.

MIX CHARACTERISTICS AND TEST RESULTS

Mix Information

The crumb rubber concrete samples in this study were obtained from different field experiments and produced by local concrete suppliers. The mix information / identification for the various samples are shown in the Table 1. The first six were trial mixes of various amount of crumb rubber (0, 50, 100, 150, 200, and 300) per cubic yard of concrete. The mix having 60 lbs of Crumb rubber per Cyd was for a test slab in Northern Arizona University in Flagstaff, Arizona. It was a standard 4000 psi concrete with no air-entraining agent. The mixes with crumb rubber content of 300 and 400 lbs per Cyd were obtained from test slabs prepared for the tennis court experiment in Phoenix. These mixes were a standard 6000 psi concrete and with no air-entraining agent. Figure 1 also shows the development of compressive strength, slump and air content of the trial mixes as a function or rubber content. Figures 2 and 3 show a cross sectional view of crumb rubber content variation in the trial mixes, and a microscopic view of crumb rubber distribution in the 400 lbs/Cyd mix, respectively. The crumb rubber particles size were about 1 mm.

Tests

Mechanical tests were conducted at room temperature using two replicates for each test / mixture combination. Compression tests were conducted on cylindrical specimens 3 x 6 in under closed-loop control with measurements of axial and radial strains. Three point bending flexural tests were performed on 18 x 4 x 4 in beam specimens with an initial notch of 0.5 in. A test span of 16 in was used. Specimen displacement and crack opening were measured using Linear Variable Differential Transformers (LVDT's). Crack Mouth Opening Deformation (CMOD) of the three point bending specimens was measured across the face of notch using an extensometer with a range of +1.3 mm. The deflection of the beam was also measured using a spring-loaded LVDT with a 0.1 inch range. The test was performed with the loading controlled by CMOD feedback. Development of these testing procedures has been discussed in an earlier work (14).

The coefficient of thermal expansion test was conducted according to American Association of State Highway and Transportation Officials AASHTO TP60-00 Provisional Standards. The indirect tensile strength was conducted on disc specimens approximately 1 inch thick and 4 inches in diameter. The load was applied at a constant rate of deformation of 0.5 in/min. The test was stopped at total failure of the specimen. The horizontal tensile stress at the center of the test specimen was calculated. The indirect tensile strength is the maximum stress developed at the center of the specimen in the radial direction during loading for a fixed geometry. The time until failure and strains at failure were also recorded.

Test Results

Compr*essive Strength – Trials and Tennis Court Mixes*

Figure 1 showed the compressive strength, unit weight, slump and air content as a function of the rubber content. The figure shows that, on the average, 60% of the 28-day strength was achieved at 3 days, and 80% was achieved at 7 days. The compressive strength decreased as the rubber content increased. A polynomial model representing this relationship is given by:

$$f_c = 0.0366(RC)^2 - 24.726(RC) + 4557.7 \qquad (1)$$

Where f_c is the compressive strength at 28 days and RC is the rubber content per cubic yard of concrete. The model coefficient of determination is 0.9721.

The unit weight decreased approximately 6.2 pcf for every 50 lbs of crumb rubber added. On the other hand, the percent air increased about 5% for every 50 lbs increase of crumb rubber, suggesting that entrapped air need to be better controlled with crumb rubber addition. The slope was also notably decreased, and at crumb rubber content of 300lbs, the mix was so dry that additional water needed to be added to improve workability.

Investigative efforts by Thornton Kelly of Hansen Aggregates, Phoenix, Arizona, determined that the entrapped air could be substantially reduced by adding a de-airing agent into the mixing truck just prior to the placement of the concrete. By doing so, trial mixes performed by Kelly resulted in re-capturing a large portion of the compressive strength lost by adding the rubber; thus creating a more durable finished product. Regrettably, much of Thornton Kelly work on mixing and placement of crumb rubber concrete did not continue as he passed away in early 2004.

Compressive Strength – Pavement Sections

Table 2 present additional closed loop compression tests conducted at 14 and 28 days for the tennis court mixes (as constructed 300 lbs CR per Cyd, and a trial mix of 400 lbs CR per Cyd), in addition to the thin whitetopping PCC pavement sections (a control and a 50 lbs CR per Cyd mixes). First it is noted that the high rubber contents greatly reduces the compressive strength of the mixes; note that the closed loop compressive strength (controlled by stress developed in the specimen) yields lower compressive strength results compared to a conventional compressive strength test, however, for tennis court (non-structural use) the compressive strength are considered adequate. The peak axial strain is 6 to 10 times higher than a control mix or a mix with low rubber content. The modulus of elasticity decreased slightly for the low crumb content mix, and was also drastically reduced for the high crumb rubber mixes (almost equivalent to an asphalt concrete modulus). The Poisson's ratios calculated were in the expected range. The pavement section with 50 lbs CR per Cyd had about 75% less compressive strength at 28 days than the control mix.

Flexural Strength

The flexure response in this test is dominated by the cracking that initiates at the notch and grows along the depth of the specimen. The controlled variable in the flexural test is the crack mouth opening (CMOD), similar to a displacement. Once the entire load deformation response of the specimen under load is measured, the energy absorbed throughout the loading cycle can be used to calculate the toughness of the material. The test results are then compared as an indicator for mixtures' potential performance. Table 3 presents a summary of the flexural tests conducted at 14 and 28 days for the Tennis Court mix and thin whitetopping PCC pavement sections.

The control mix exhibited the highest flexural capacity when compared to other mixes. The 50 lbs CR per Cyd pavement mix showed a flexural capacity 22% less than that of the control mix. The tennis court control mix flexural strength was almost 50% less than the control mix. However, the rubber mixes had higher CMOD values and comparable toughness (energy absorption) compared to the control mix.

Indirect Tensile Strength

Indirect tensile strength tests were conducted on discs sawn from cylindrical specimens. The tests were conducted on the trial mixes with varying rubber content (0 to 400). The tensile strength and strain at failure results are shown in Table 4. The results show that as the rubber content increased, the tensile strength decreased, but the strain at failure increased. Higher tensile strain at failure is indicative of more ductile mixes and more energy absorbent mixes. In fact, the product of the tensile strength and strain at failure is indicative of the energy absorbed by each mix until failure. These values are 95, 107, 55, and 47 psi – in/in for 0, 200, 300, and 400 CR mixes, respectively. Therefore, the mix containing 200 lbs CR per Cyd had the highest energy value. Doubling the crumb rubber content reduced the energy value by almost half.

Figure 4 presents a view of a CR mix and a conventional one before and after the indirect test was conducted. As seen in this figure, the sample containing 400 pounds of CR per cubic yard did not shatter compared to the conventional concrete sample without crumb rubber. Similar breaking mechanism was also noted during the compressive strength tests. Notably, the CRC specimens appeared to stay intact (did not shatter) and failed in the upper half of the specimen, indicating that the rubber particles were absorbing the compressive force and not distributing it to the lower half below. Such behavior may be beneficial for a desired material / structure that requires good impact resistance properties.

Coefficient of Thermal Expansion

Figures 5 and 6 compare the coefficient of thermal expansion test results obtained for mixes with varying rubber content and also compared to other PCC mixes. Figure 5 shows that the CTE values decrease as the rubber content is varied from 60 to 300 or 400 lbs per Cyd. Similar results were obtained from expansion (heating) and contraction (cooling) cycles. Figure 6 compare the 300 lbs CR mix with other commonly used mixtures in Arizona. Comparing the average CTE results for all the four mixes in Figure 6, CRC mix had the lowest value. It was 50% less than the value of the standard / control mix. The mix with high content of flyash exhibited the highest value of CTE among all the mixes. Compared with CTE values in Figure 5, the addition of crumb rubber (60 lbs per Cyd) reduced the CTE values by about 29% when compared to the control mix. These results indicate that the crumb mixes are more resistant to thermal changes; however these lower values are also associated with a drop in compressive strength. If no special considerations are made to maintain a higher strength values (as discussed earlier), the use of such mixes are recommended in places where the strength of concrete is not as important (e.g. sidewalks).

CONCLUSIONS

There is no doubt that the increasing piles of tires create environmental concerns. Finding a way to dispose of the rubber in concrete would enhance the understanding on how to incorporate the crumb rubber in greater engineering usage. It is realized that partnership with states, industries and consultants is vital for the success of such initiative.

Several Crumb Rubber Concrete (CRC) test sections were built in Arizona and are being monitored for performance. Laboratory tests were conducted at ASU and industry associations to support the knowledge learned in the field. This paper summarized findings to date and some knowledge learned in the field. Preliminary conclusions of this study are:

- The unit weight of the CRC mix decreased approximately 6 pcf for every 50 lbs of crumb rubber added.

- The compressive strength decreased as the rubber content increased. Part of the strength reduction was contributed to the entrapped air, which increased as the rubber content increased. Investigative efforts showed that the strength reduction could be substantially reduced by adding a de-airing agent into the mixing truck just prior to the placement of the concrete.
- The high CRC rubber content mix (tennis court) had a flexural strength almost 50% less than the control mix. However, the CRC mix had more ductility and comparable toughness values to the control mix.
- As the rubber content increased, the tensile strength decreased, but the strain at failure also increased. Higher tensile strain at failure is indicative of more energy absorbent mixes.
- The coefficient of thermal expansion test results indicated that the CRC mixes are more resistant to thermal changes.
- In all failure tests, the CRC specimens stayed intact (did not shatter) indicating that the rubber particles may be absorbing forces acting upon it. Such behavior may be beneficial for a structure that requires good impact resistance properties.
- Because of the long term performance of these mixes are not known in the field, especially for pavement sections, the use of such mixes are recommended in places where high strength of concrete is not as important (e.g. sidewalks).

Future follow up work will strengthen the conclusions arrived at in this work and will add to the state of knowledge in this area. One specific area is the freeze-thaw durability of CRC mixes in northern or high altitude climates, where the crumb rubber would aid in reducing the need for air entraining agents.

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Table 1 Mix Ingredients for the Crumb Rubber Concrete Mixes.

Project / Mix ID #	*Unit Weight lbs/cu ft*	*W/C ratio*	*Dry weight of materials, (lbs/Cyd)*		
			Cement	*FA*	*CA*
0 lbs per Cyd *(Trial)*	147.8	0.42	525	1417	1731
50 lbs per Cyd *(Trial)*	140.1	0.44	525	1367	1731
100 lbs per Cyd *(Trial)*	135.7	0.45	525	1317	1731
150 lbs per Cyd *(Trial)*	125.7	0.46	525	1267	1731
200 lbs per Cyd *(Trial)*	126.5	0.47	525	1217	1731
300 lbs per Cyd *(Trial)*	109.2	0.48	525	1117	1731
60 lbs per Cyd *(NAU)*	137.8	0.44	317	855	1044
300 lbs per Cyd *(Const.)*	112.1	0.48	525	467	1371
400 lbs per Cyd	98.8	0.50	525	117	1251
Thin Whitetopping PCC, Control	147.5	0.37	752	1195	1800
Thin Whitetopping PCC, 50 lbs per Cyd	139.5	0.39	752	1145	1800

All mixes had an additional 125 lbs of fly ash

Table 2 Compressive Strength Test Results.

MIX. ID	Age Days	Average Compressive Strength psi	Peak Axial Strain in/in (10^{-3})	Axial Modulus of Elasticity psi (10^{6})	Poisson's Ratio
300 lbs per Cyd *(Const.)*	7	822	9.65	0.15	NA
300 lbs per Cyd *(Const.)*	28	1080	10.32	0.16	NA
400 lbs per Cyd	14	546	6.50	0.11	NA
TW_CTR	14	5363	1.05	5.30	0.25
TW_CTR	28	5975	0.52	6.10	0.26
TW_CR	14	3704	1.29	3.14	0.25
TW_CR	28	4430	0.73	5.63	0.22

CTR = Control Mix, CR = Thin Whitetopping PCC, 50 lb Crumb Rubber / Cyd.,
NA = Not Available (was not measured)

Table 3 Flexural Strength Test Results.

MIX. ID	Age Days	Flexural Load lbs	CMOD in (10^{-3})	Flexural Strength (psi)	Toughness psi x in
300 lbs per Cyd *(Const.)*	28	481	1.85	157	9.4
TW_CTR	14	1049	0.97	341	8.4
TW_CTR	28	1188	1.30	387	10.3
TW_CR	14	807	1.67	263	7.6
TW_CR	28	932	1.39	303	9.5

CTR = Control Mix, CR = Thin Whitetopping PCC, 50 lb Crumb Rubber / Cyd.

Table 4 Indirect Tensile Strength Test Results.

Rubber Content lbs per Cyd	Thickness (in)	Diameter (in)	Load (lbs)	Tensile Strength (psi)	Strain at Failure, %
0	0.85	4	410	307	0.31
200	0.77	4	192	159	0.67
300	0.96	4	193	128	0.43
400	1.03	4	139	86	0.54

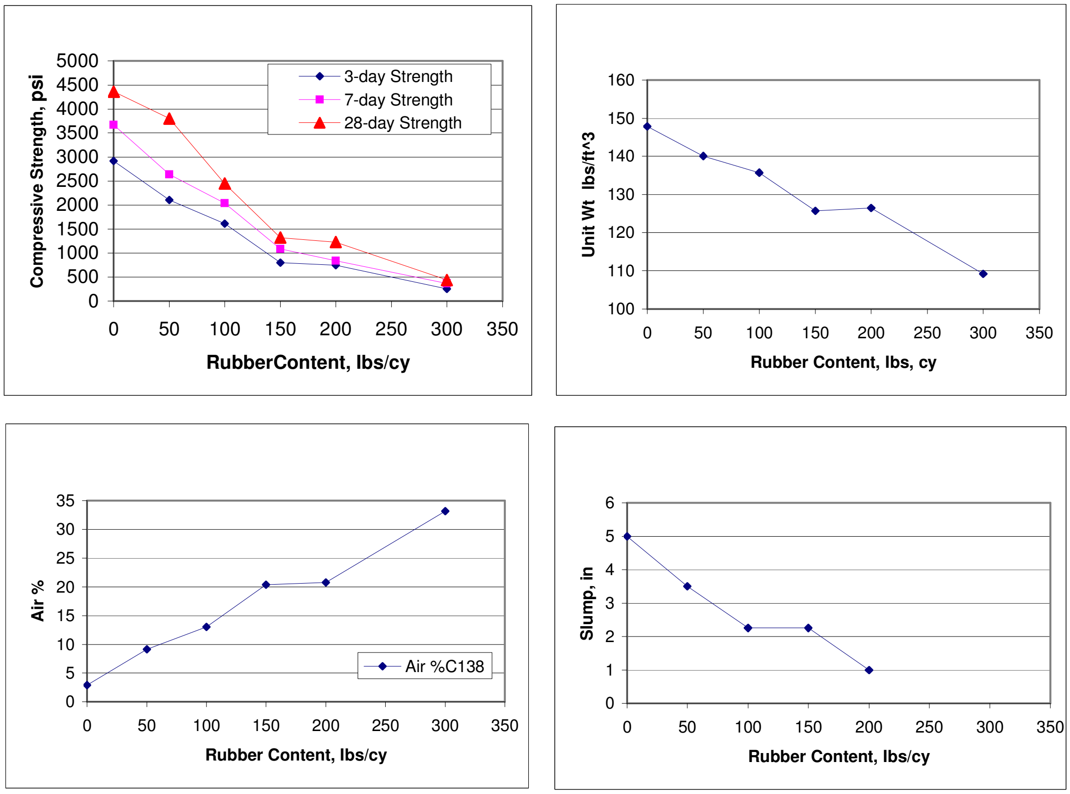

Figure 1 Compressive Strength, Unit Weight, Air Content and Slump Variations with Rubber Content.

Figure 2 Cross Sectional View of Crumb Rubber Content Variation in Trial Mixes.

Figure 3 Microscopic View of Crumb Rubber Distribution in a 400 lbs CR / Cyd Mix.

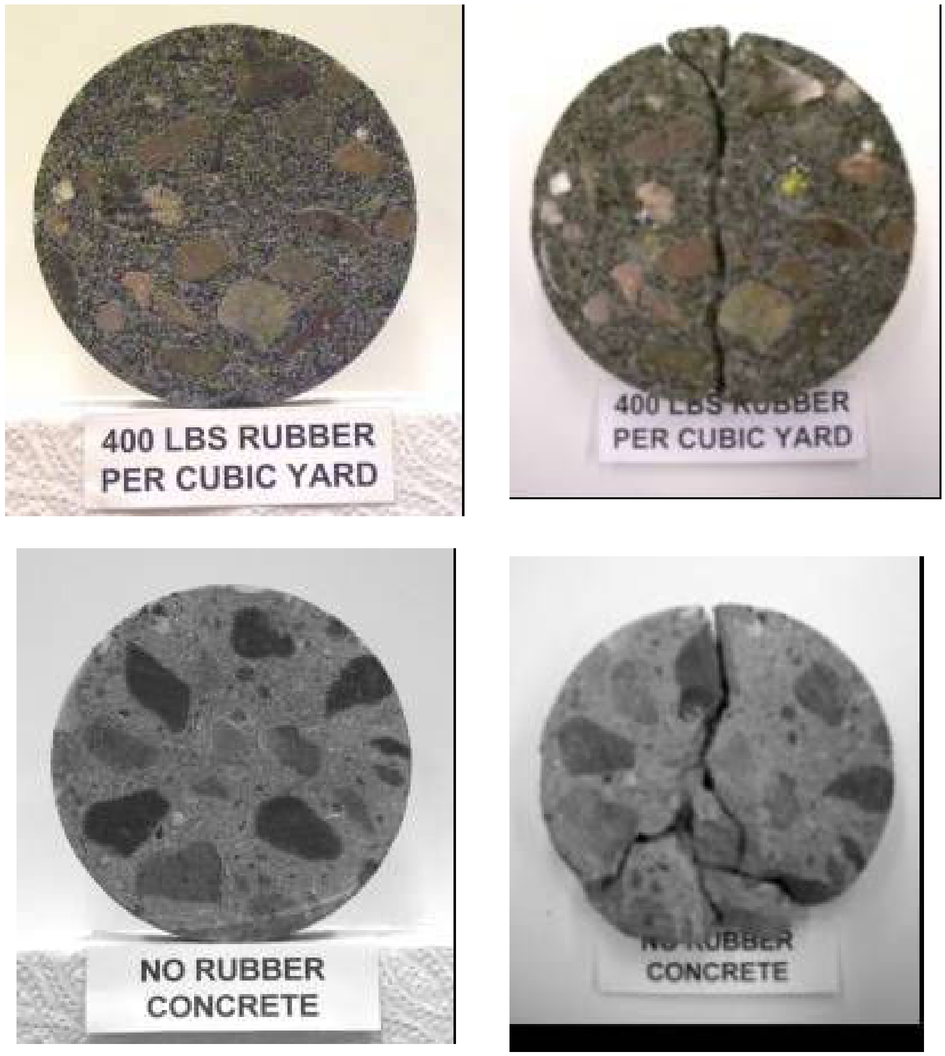

Figure 4 Tensile Strength Failure Mechanism.

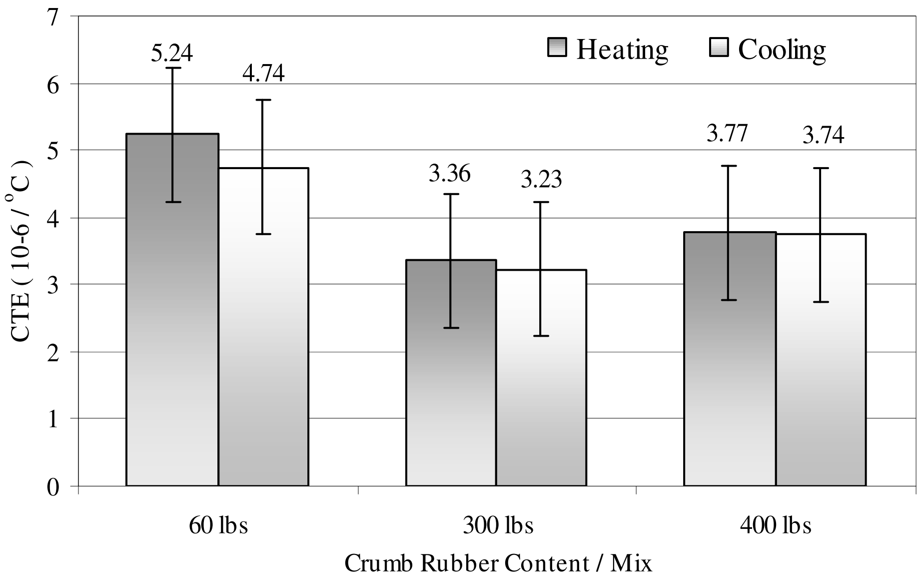

Figure 5 Comparison of CTE as a Function of Crumb Rubber Content.

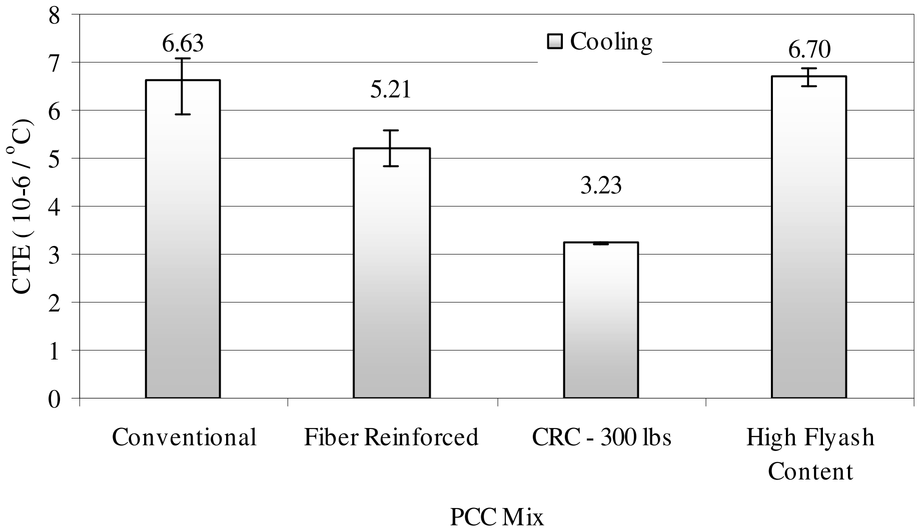

Figure 6 Comparison of CTE for a Variety of PCC Mixes.