Advances in Concrete Construction, *Vol. 4, No. 3 (2016) 207-220*
DOI: http://dx.doi.org/10.12989/acc.2016.4.3.207

Mechanical properties of concrete containing recycled materials

Pranshoo Solanki* and Bharat Dash[a]

Department of Technology, College of Applied Science and Technology, Illinois State University, Campus Box 5100, Normal, Illinois, 61790, USA

(Received July 12, 2016, Revised December 14, 2016, Accepted December 15, 2016)

Abstract. The objective of this study was to evaluate the influence of recycled materials, namely, shredded scrap tire (SST), reclaimed asphalt pavement (RAP) and class C fly ash (CFA) on compressive and tensile strength of concrete. Either SST or RAP was used as an aggregate replacement and class C fly ash (CFA) as Portland cement replacement for making concrete. A total of two types of SST and RAP, namely, chips and screenings were used for replacing coarse and fine aggregates, respectively. A total of 26 concrete mixes containing different replacement level of SST or RAP and CFA were designed. Using the mix designs, cylindrical specimens of concrete were prepared, cured in water tank, and tested for unconfined compressive strength (UCS) and indirect tensile strength (IDT) after 28 days. Experimental results showed aggregate substitution with SST decreased both UCS and IDT of concrete. On the contrary, replacement of aggregate with RAP improved UCS values. Specimens containing RAP chips resulted in concrete with higher IDT values as compared to corresponding specimens containing RAP screenings. Addition of 40% CFA was found to improve UCS values and degrade IDT values of SST containing specimens. Statistical analysis showed that IDT of SST and RAP can be estimated as approximately 13% and 12% of UCS, respectively.

Keywords: reclaimed asphalt pavement; shredded scrap tire; class C fly ash; Portland cement concrete; unconfined compressive strength; indirect tensile strength

1. Introduction

Concrete is one of the most widely used construction materials. Concrete being one of the oldest materials in the construction industry is a mixture of paste and aggregates (Gupta 2015). However, procuring aggregates and Portland cement for making concrete is becoming a severe problem due to reduction in natural resources and aggregate quarries.

Engineering properties of concrete such as strength and durability depends upon the properties of its ingredients, size and proportions of mix, method of compaction and curing. Concrete contains no less than 75% by volume of aggregate materials which may be locally available but in some places it may be economical to substitute those natural aggregates by more cheaply and

*Corresponding author, Assistant Professor, E-mail: psolanki@ilstu.edu
[a]Former Graduate Student, E-mail: bdash@ilstu.edu

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2234-0912 (Print), 2234-179X (Online)

abundantly available materials (Okafor 2010). Therefore, it is very essential to recycle or reuse the material.

The growing amount of waste rubber produced from scrap tires, reclaimed asphalt pavement (RAP) from road projects and fly ash from thermal power plants has resulted in an environmental problem. The adoption of aforementioned materials in concrete recycles waste which otherwise creates problem for disposal of waste. Consequently, the aim of the proposed study was to evaluate the influence of shredded scrap tire (SST) or RAP as an aggregate replacement and class C fly ash (CFA) as Portland cement replacement on compressive and tensile strength of concrete. In this research study, a total of 26 concrete mixtures containing different replacement level of SST or RAP and CFA were designed. A total of two types of SST and RAP namely, chips (particles ranging in size from 0.19 in. to less than 1 in.) and screenings (particles ranging in size from 0.19 in. to greater than 0.003 in.) were used for replacing coarse and fine aggregates, respectively. Cylindrical specimens of concrete were prepared and cured in water tank for 28 days. Then, specimens were tested for compressive and indirect tensile strength.

2. Review of literature

The two major applications of SST in the construction are utilization in asphalt paving and Portland cement concrete mixes. Several studies were conducted on utilization of waste tires in asphalt paving mixes (Epps 1994, Li *et al*. 2004). Khatib and Bayomy (1999) utilized SST to replace a portion of fine and coarse aggregates. They found that PCC containing SST showed systematic reduction in compressive strength and improvement in toughness. A regression equation for estimating compressive strength of SST containing concrete was also proposed. Hernandez-Olivares *et al*. (2002) summarized the experimental results of mechanical behavior of concrete specimens filled with small volumetric fractions of crushed scrap tire and polypropylene short fibers and cured for 7 and 28 days. The study evaluated both static and dynamic properties of concrete by conducting static compression, indirect tension, flexure and dynamic compression tests. This study reported that addition of scrap tire volume fractions of up to 5% in a cement matrix does not implied significant variations in the mechanical properties of concrete. Another benefit of using scrap tire in PCC is the light weight. Rubber of waste tire has much lower density than aggregates, so the replacement of aggregates with rubber consequently reduces the overall density of the PCC (Siddique and Naik 2004).

Li *et al*. (2004) concluded that concrete containing SST in the form of fibers has higher strength compared with that made with larger size of tire shredding (or chips). By replacing fine aggregates with shredded tire screenings, Li *et al*. (2004) found reduction in concrete strength. Further, Li *et al*. (2004) reported that this decrease is even greater in the case when scrap tire chips were used to replace the coarse aggregates. This decrease in strength was attributed to the weak bonding between the rubber particles and the cement matrix. Siddique and Naik (2004) found that when water-washed rubber particles or rubber particles treated with carbon tetrachloride were added in concrete, it resulted in smaller reduction in compressive strength. Use of latex in concrete containing scrap tire improved strength of concrete by enhancing the adherence of the rubber particles to the cement mixture (Lee *et al*. 1998, Oikonomou *et al*. 2006).

Several investigators used class C fly ash for partially replacing Portland cement in concrete. They showed that concrete containing large volumes of class C fly ash can be proportioned to meet strength and workability requirements for construction applications (Cook 1981, Naik *et al*.

1994, Crouch *et al*. 2007). Naik and Chun (2003) studied the effects of incorporating high volumes of class C fly ash on the properties of concrete. In general, fly ash increases the setting time, improves long-term strength of concrete and reduces the water consumption, carbon dioxide (CO2) emission and heat of hydration of cement (Bilodeau and Malhotra 2000, Yilmaz and Degrimenci 2009).

A study by Naik and Ramme (1990) have substantiated that super plasticized CFA concrete with low water-to-cementititous material ratio can be proportioned to meet the very early-age strength as well as other requirements for precast and prestressed concrete products. The maximum cement replacement with the fly ash was reported to be 30% for such high-early strength concrete application. Another study by Naik *et al*. (1994) developed mixture proportions for paving roadway concrete using large amounts of fly ash. These mixtures were composed of 50% Class C fly ash and 40% Class F fly ash as a replacement of Portland cement. The results indicated that high volumes of class C and class F fly ashes could be used to produce high-quality concrete pavements with tremendous performance. Naik *et al*. (1994) also indicated that concrete containing large volumes of CFA can be proportioned to meet strength and workability requirements for construction applications.

Recent research studies examined the feasibility of incorporating RAP in Portland cement concrete (Huang *et al*. 2005, 2006). Huang *et al*. (2006) used two gradations of RAP (coarse and fine) materials to replace the fresh aggregate from a control concrete mixture. The study results indicated that concrete samples made with only coarse RAP resulted in strength reduction and improved toughness. Furthermore, Huang *et al*. (2006) attributed reductions in the strength to the fact that asphalt film around the aggregate particle were much softer than the concrete matrix and aggregates. Additionally, the slump test results of concrete showed that coarse or fine RAP containing concrete slump values were lower than that of control concrete. Huang *et al*. (2005, 2006), suggested that reduction in slump values could be attributed to the asphalt coating around both coarse and fine RAP so that the aggregates will absorb less percentage of water. Snelson *et al*. (2009) used scrap tires as coarse and fine aggregate replacement in concrete, combined with partial replacement of Portland cement with pulverized fuel ash.

Okafor (2010) study focused on the replacement of aggregates with RAP. The physical properties of RAP aggregates were compared with similar concretes made with natural aggregate. The results indicated that the strength of concrete made from RAP is dependent on the bond strength of the asphalt-mortar. His study also indicated that when natural aggregate was compared to RAP, it was found that RAP has lower specific gravity and lower water absorption.

A solution to a combined SST or RAP and CFA disposal problem would be to use SST or RAP as an aggregate replacement and CFA as Portland cement replacement in concrete, which has not received much attention. However, as noted in above paragraphs, there is a lack of literature on SST or RAP as an aggregate replacement and CFA as Portland cement replacement in concrete.

3. Methodology and experimental design

SST used in this study was collected from Treadstone Tire Recycling LLC located in Joliet, Illinois. A total of two size fractions of shredded tire were used: 0.003-0.19 in. (screenings) and 0.19-1 in. (chips). Fig. 1 shows two different size fractions of shredded scrap tire. RAP used in this study was collected from McLean County Asphalt Inc. located in Bloomington, Illinois. A total of two types of size fractions namely, RAP chips (particles ranging in size from 0.19 in. to

(a) (b)

Fig. 1 SST particles used in the experimental study

(a) (b)

Fig. 2 RAP particles used in the experimental study

less than 1 in.) and RAP screenings (particles ranging in size from 0.19 in. to greater than 0.003 in.) were used for replacing coarse and fine aggregates, respectively. Fig. 2 shows two different size fractions of RAP.

Both ordinary Portland cement and class C fly ash (CFA) were collected in cooperation with Lafarge Cement North America office located in Chicago, Illinois. The CFA was produced in a coal-fired electric utility plant and the source was Pleasant Prairie. The properties of CFA and cement are presented in Table 1. The differences between the chemical composition and physical properties among CFA and cement are clearly evident from Table 1.

Virgin aggregates were collected from Prairie Material, a local ready-mix concrete plant located in Normal, Illinois. All mixtures were prepared by adding required amount of dry ingredients in a Hobart mixer. After preparation of mixtures, the workability of mixtures was evaluated by conducting slump test in accordance with ASTM C 143. Then, cylindrical specimens of concrete were prepared in accordance with ASTM C 192. Cylindrical specimens were cured in a water tank with the water being renewed on a monthly basis. After 28 days of curing, these cylinders were tested for compressive strength and indirect tensile strength in accordance with ASTM C 39 and ASTM C 496 test methods, respectively. Both compressive strength and indirect tensile strength tests were conducted in a universal testing machine.

Table 1 Chemical properties of ordinary Portland cement and CFA used in this study

Chemical compound/Property	Percentage by weight (%)	
	OPC	CFA
Silicon dioxide (SiO_2)[a]	22	38.8
Aluminum oxide (Al_2O_3)[a]	5	20.0
Ferric oxide (Fe_2O_3)[a]	3	5.4
Calcium oxide (CaO)[a]	64	22.6
Magnesium oxide (MgO)[a]	1	4.3
Sulfur trioxide (SO_3)[a]	3	1.2
Alkali content (Na_2O+K_2O)[a]	0.9	2.0
Free lime[b]	1.94	0.2
Loss on ignition (LOI)[c]	1	0.7

CKD: cement kiln dust; OPC: ordinary Portland cement; [a]X-ray fluorescence analysis; [b]ASTM C 114 alternative method B; [c]ASTM C 114

Table 2 Design of concrete mix proportions

Mixture#		Cementitious Material		Coarse Aggregates		Fine Aggregates	
		Portland Cement (%)	Fly Ash (%)	Virgin Aggregates (%)	SST or RAP Chips (%)	Virgin Aggregates (%)	SST or RAP Screenings (%)
1		100	0	100	0	100	0
2		60	40	100	0	100	0
With SST	With RAP	*Mixes prepared by replacing coarse aggregate with SST or RAP*					
3	15	100	0	90	10	100	0
4	16	100	0	80	20	100	0
5	17	100	0	60	40	100	0
6	18	60	40	90	10	100	0
7	19	60	40	80	20	100	0
8	20	60	40	60	40	100	0
9	21	100	0	100	0	90	10
10	22	100	0	100	0	80	20
11	23	100	0	100	0	60	40
12	24	60	40	100	0	90	10
13	25	60	40	100	0	80	20
14	26	60	40	100	0	60	40

A total of 26 concrete mixtures containing different replacement level of SST and CFA were designed in this study. All mixtures were prepared by mixing cementitious material, fine aggregates and coarse aggregates in the ratios of 1:2:2. Table 2 shows proportions of all concrete mixtures which were considered in the proposed study. Mix #3 through #14 were prepared by replacing coarse and fine aggregates with SST chips and screenings, respectively, with replacement level of 0%, 10%, 20% and 40% by weight. Mix #15 through #26 were prepared by replacing coarse and fine aggregates with RAP chips and screenings, respectively, with replacement level of 0%, 10%, 20% and 40% by weight. On the other hand, Portland cement concrete was replaced with 0% and 40% CFA by weight as shown in Table 2. The water-to-

Table 3 Summary of UCS and IDT values of mixes containing SST

% CFA	0%		10%		20%		40%	
	UCS	IDT	UCS	IDT	UCS	IDT	UCS	IDT
SST Chips								
0%	2409	459	531	294	293	199	282	289
40%	6958	831	1229	216	1115	196	1066	164
SST Screenings								
0%	2409	459	2332	337	1480	145	1450	146
40%	6958	831	1901	464	1039	139	168	22

Table 4 Summary of UCS and IDT values of mixes containing RAP

% CFA	0%		10%		20%		40%	
	UCS	IDT	UCS	IDT	UCS	IDT	UCS	IDT
RAP Chips								
0%	2409	459	2703	514	4010	495	2822	463
40%	6958	831	4160	335	3682	518	3021	464
RAP Screenings								
0%	2409	459	4560	435	3079	336	3089	257
40%	6958	831	4278	415	1874	376	2044	292

cementitious material (Portland cement and fly ash) ratio was fixed for all the mixtures at 0.5 and slump values for all mixes was found within 3 in. ± 0.5 in.

4. Analysis of data

A summary of results is presented in Tables 3 and 4 for mixes containing SST and RAP, respectively. Further, results are analysed and discussed in sections below.

4.1 Effect of replacement of coarse aggregate with SST or RAP chips

4.1.1 Unconfined Compressive Strength (UCS)

The individual results of the 28-day UCS values of concrete specimens containing different percentages of coarse aggregate and SST or RAP chips are graphically presented in Fig. 3. As noted in Fig. 3, specimens containing SST chips showed reduction in the UCS values with an increase in the amount of SST. For example, UCS values of cylindrical specimens containing 10%, 20% and 40% SST with 0% CFA decreased respectively by 78%, 87% and 88%, as compared to a control specimen containing no SST. Other researchers also reported similar trend of decrease in compressive strength values of specimens containing SST (Eldin and Senouci, 1993; Topcu, 1995). The reduction in the UCS values could be attributed to the physical properties of the rubber particles, since they are less stiff than the cement paste. Also, decrease in the compressive strength values might be due to a poor bonding between the cement paste and the rubber particles.

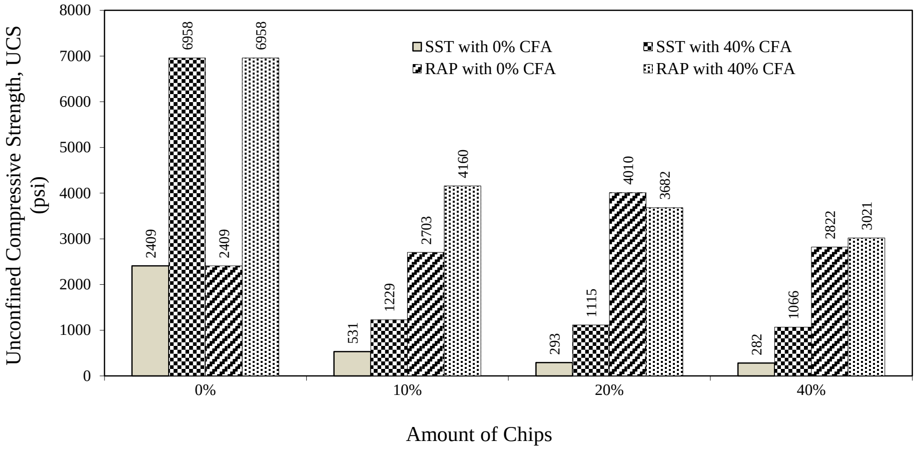


Fig. 3 UCS values of concrete containing different percentage of RAP or SST chips and CFA

(a) (b) (c) (d) (e) (f)

Fig. 4 Photographic view of cylindrical specimens containing (a) 10% SST, (b) 20% SST, (c) 40% SST, (d) 10% RAP, (e) 20% RAP, and (f) 40% RAP after UCS testing

On the contrary, specimens containing RAP chips showed increase in the UCS values with maximum improvement at a RAP content of 20%. For example, UCS values of cylindrical specimens containing 10%, 20% and 40% RAP with 0% CFA increased respectively by 12%, 67% and 17%, as compared to a control specimen containing no RAP. The coarse aggregate particles of RAP were smooth and rounded compared to virgin aggregates which might have increased the workability of the mix.

It is also evident from Fig. 3 that addition of 40% CFA significantly improved the UCS values of all the mixes containing SST chips. For example, UCS values of mixes containing 10%, 20% and 40% SST and 40% CFA increased by approximately 131%, 281% and 278%, respectively, compared to corresponding mixes containing 0% CFA. On the other hand, CFA was found to be slightly effective in improving the UCS values of mixes containing 10% (approximately 54% increase) and 40% RAP (approximately 7% increase) compared to corresponding mixes containing 0% CFA. Mix containing 20% RAP showed slight decrease (approximately 8%) in the UCS value with 40% CFA. A photographic view of broken cylindrical specimens containing different percentage of SST and RAP is presented in Fig. 4. As indicated in Figs. 4(a) through (c) for SST and Figs. 4(d) through (f) for RAP, decrease in percentage of SST or RAP in concrete showed failure pattern with wider cracks.

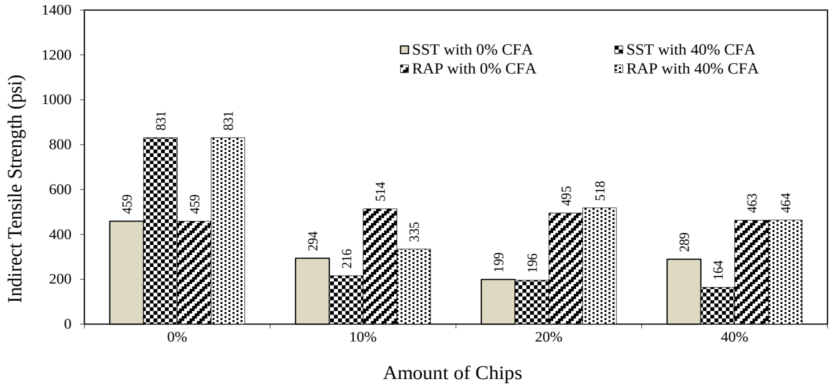
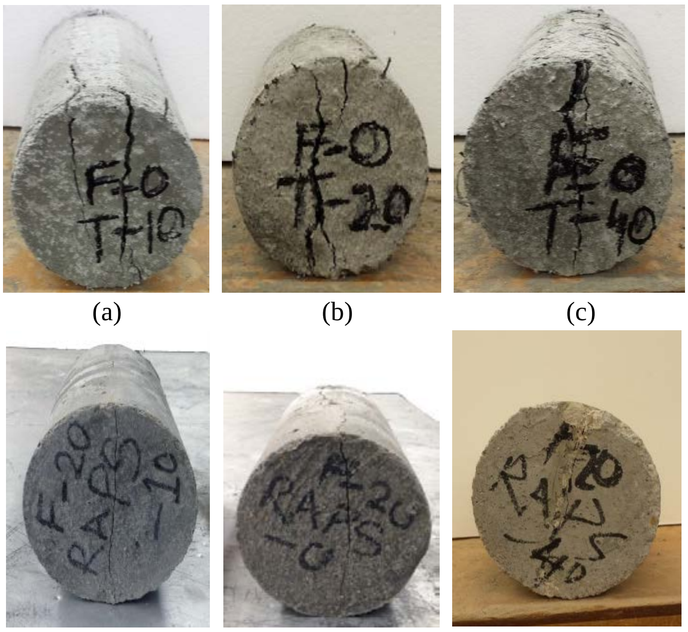


Fig. 5 IDT values of concrete containing different percentage of RAP or SST chips and CFA



(a) (b) (c)

(d) (e) (f)

Fig. 6 Photographic view of cylindrical specimens containing (a) 10% SST, (b) 20% SST, (c) 40% SST, (d) 10% RAP, (e) 20% RAP, and (f) 40% RAP after IDT testing

4.1.2 Indirect Tensile Strength (IDT)

The IDT values of specimens containing different percentage of SST chips and CFA are presented in Fig. 5. It was noted that the amount of reduction in IDT value was dependent on the amount of SST chips. For example, IDT values of cylindrical specimens containing 10%, 20% and 40% SST and 0% CFA decreased by 36%, 57% and 37%, respectively, as compared to a specimen containing no tire and no CFA. It was also observed from the failure patterns of broken specimens that the specimens with 20% and 40% SST chips had lower amount of shattering as compared to specimens with 0% or 10% SST chips (Fig. 6).

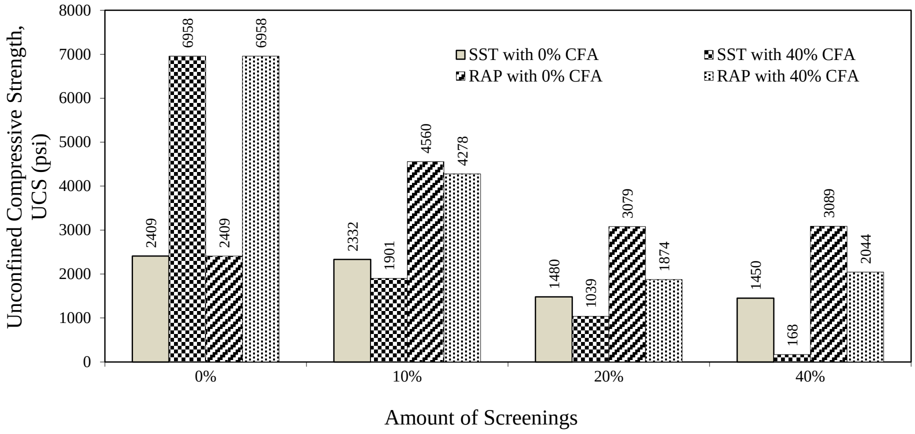


Fig. 7 UCS values of concrete containing different percentage of RAP or SST screenings and CFA

Similar to the UCS results, specimens containing RAP chips showed increase in the IDT values with maximum improvement at a RAP content of 10% (Fig. 5). For example, IDT values of cylindrical specimens containing 10%, 20% and 40% RAP and 0% CFA increased by 12%, 8% and 1%, respectively, as compared to a specimen containing no RAP and no CFA. Addition of 40% CFA reduced IDT values of SST chips containing specimens. Specimens containing 10% RAP and 40% CFA reduced IDT value by approximately 35%. Addition of 40% CFA showed slight improvement in mixes containing 20% (approximately 5%) and 40% RAP (approximately 0.2%).

4.2 Effect of replacement of fine aggregate with SST or RAP screenings

4.2.1 Unconfined Compressive Strength (UCS)

The individual results of the 28-day UCS values of concrete containing SST or RAP screenings are graphically presented in Fig. 7. All the SST containing specimens tested in this study generally showed a reduction in the UCS values with an increase in the amount of tire. For example, UCS values of cylindrical specimens containing 10%, 20% and 40% SST with 0% CFA decreased respectively by 3%, 39% and 40%, as compared to a control specimen containing no tire. The decrease in the UCS values can be partially explained by weak bonding between the rubber particles and the cement matrix. Additionally, it is important to note that rubber particles are weaker in compressive strength as compared to aggregates. Since part of the aggregates is replaced by rubber particles, overall strength and density reduction is expected. It was noted that the density of cylindrical specimens containing 10%, 20% and 40% SST screenings reduced to 146.1, 139.2 and 128.9 lb/ft^3, respectively.

All the RAP containing specimens tested in this study generally showed improvement in the UCS values with an increase in the amount of RAP. For example, UCS values of cylindrical specimens containing 10%, 20% and 40% RAP with 0% CFA increased respectively by 89%, 28% and 28%, as compared to a control specimen containing no RAP.

Addition of 40% CFA degraded UCS values of both SST and RAP containing specimens (Fig. 7). For example, UCS values of mixes containing 10%, 20% and 40% RAP with 40% CFA decreased respectively by 18%, 30% and 88%, as compared to a corresponding specimen

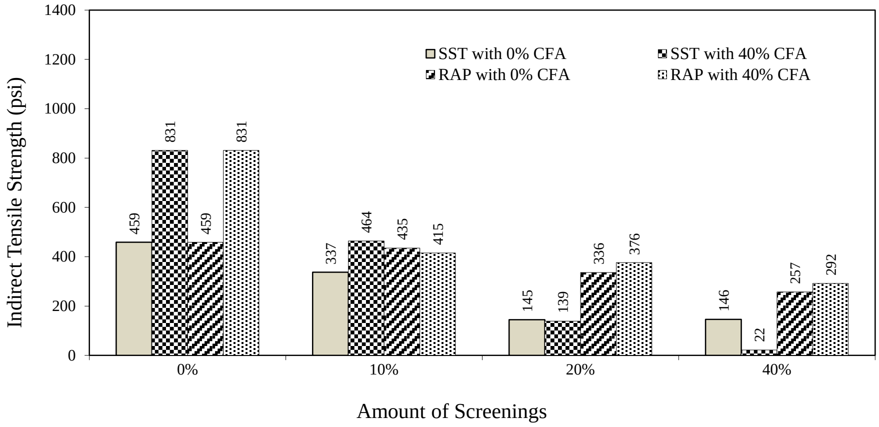


Fig. 8 IDT values of concrete containing different percentage of RAP or SST screenings and CFA

containing 0% CFA. This decrease in strength could be attributed to the weak bonding between the rubber particles and the cement-fly ash matrix. Mixes containing 10%, 20% and 40% RAP with 40% CFA showed decrease in the UCS values by approximately 6%, 39% and 34%, respectively, compared to corresponding mixes without CFA. The decrease in the compressive strength could be attributed to weak bond between the between the asphalt of RAP particles and the cement-fly ash matrix.

4.2.2 Indirect Tensile Strength (IDT)

The IDT values of specimens containing different percentages of SST or RAP screenings and CFA are presented in Fig. 8. All the specimens tested showed decrease in the IDT values with an increase in the percentage of SST screenings. For example, IDT values of cylindrical specimens containing 10%, 20% and 40% SST with 0% CFA decreased respectively by 27%, 68% and 68%, as compared to a control specimen containing no SST. All the specimens containing RAP showed decrease in the IDT values with an increase in the percentage of RAP screenings. For example, IDT values of cylindrical specimens containing 10%, 20% and 40% RAP with 0% CFA decreased respectively by 5%, 27% and 44%, as compared to a control specimen containing no RAP.

No clear trend was observed between IDT values and SST or RAP content of specimens containing 40% CFA. For example, specimens containing 10% RAP with 40% CFA improved IDT values by approximately 38%. On the other hand, addition of 40% CFA in 20% and 40% RAP containing specimens reduced IDT values by 4% and 85%, respectively. Similar trend of IDT results were reported by Ibrahim *et al*. (2014). Fig. 8 also show that IDT values of 20% and 40% RAP slightly increased (approximately 12% to 14%) with 40% CFA. However, 10% RAP with 40% CFA resulted in reduction of UCS values by approximately 5%.

4.3 Comparison of SST or RAP screenings and chips

4.3.1 Unconfined Compressive Strength (UCS)

Further, UCS results of specimens containing SST chips and screenings with 0% CFA were compared from Figs. 3 and 7, respectively. Replacement of virgin aggregate with SST screenings resulted in higher UCS values as compared to corresponding specimens prepared by replacing

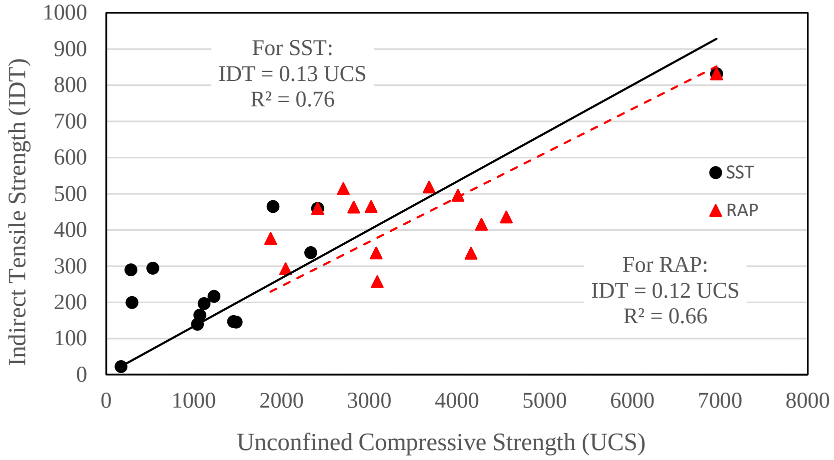


Fig. 9 Correlation between IDT and UCS values

virgin aggregate with SST chips. For example, replacement of virgin aggregates with 10% SST chips and screenings produced UCS values of 1901 and 1229 psi, respectively. UCS results of specimens containing RAP chips and screenings with 0% CFA were compared from Figs. 3 and 7, respectively. A replacement level of 10% and 40% resulted in higher UCS values for specimens containing RAP screenings as compared to corresponding specimens containing RAP chips. However, replacement level of 20% resulted in higher UCS values with RAP chips (4010 psi) as compared to RAP screenings (3079 psi).

4.3.2 Indirect Tensile Strength (IDT)

Further, IDT test results of concrete containing SST chips (Fig. 5) and screenings (Fig. 8) with 0% CFA were compared. It is evident that specimens with more than 10% SST chips resulted in higher IDT values as compared to specimens prepared by corresponding percentage of SST screenings. For example, replacement of virgin aggregates with 40% SST chips and screenings produced IDT values of 289 and 146 psi, respectively. Higher percentage of SST chips (>10%) provides reinforcement to concrete and thus producing higher IDT values. This effect was also evident from photographic views (Fig. 6) which showed comparatively lower amount of shattering in specimens containing higher percentage of SST. Specimens containing RAP chips resulted in concrete with higher IDT values as compared to corresponding specimens containing RAP screenings. For example, the IDT values of specimens containing 10% RAP chips and screenings were 514 and 435 psi, respectively. It is also interesting to note that replacement of virgin aggregates with RAP chips showed improvement in IDT values at all replacement levels.

4.4 Comparison of UCS and IDT

To compare the tensile and compressive behavior of specimens, variation of IDT with UCS of corresponding specimens were plotted on the same graph (Fig. 9). It is evident that for both SST and RAP specimens, UCS was consistently higher followed by IDT values. Also, specimens containing RAP showed higher UCS as well as IDT strength compared to corresponding specimens containing similar percentage of SST; this is expected behavior as rubber is softer as compared to RAP. For example, 10% SST chips specimens containing 0% CFA provided a UCS and IDT value of 531 and 294 psi, respectively. On the other hand, 10% RAP chips specimens containing 0% CFA provided a UCS and IDT value of 2703 and 514 psi, respectively. The best-fit curve through all points can be represented by the following equations

$$IDT = 0.13UCS \quad (R^2 = 0.76 \text{ for SST}) \tag{1}$$

$$IDT = 0.12UCS \quad (R^2 = 0.66 \text{ for RAP}) \tag{2}$$

According to above correlations, IDT of SST and RAP can be estimated as approximately 13% and 12% of UCS, respectively. Based on the literature, the IDT is generally about 10 to 15 percent of the UCS (Kennedy *et al*. 1971, Little 1995, Sobhan and Mashnad 2003). In the current study, IDT versus UCS correlation is similar to previous studies.

5. Conclusions

This study was conducted to evaluate the feasibility of utilizing SST or RAP as an aggregate replacement and CFA as Portland cement replacement in concrete. Based on the results presented in this study following conclusions could be drawn:

- Aggregate substitution with SST chips or SST screenings was found to reduce the UCS values with an increase in the amount of SST. The decrease in the UCS values could be attributed to weak bonding between the rubber particles and the cement matrix and lower stiffness of rubber compared to virgin aggregate. However, replacement of virgin aggregate with SST screenings resulted in higher UCS values as compared to corresponding specimens prepared by replacing virgin aggregate with SST chips.
- Aggregate substitution with RAP chips or screenings showed increase in the UCS values. A replacement level of 10% and 40% resulted in higher UCS values for specimens containing RAP screenings as compared to corresponding specimens containing RAP chips.
- Aggregate substitution with SST chips or screenings was found to reduce IDT values and amount of reduction was dependent on the SST content. It is evident that specimens with more than 10% SST chips resulted in higher IDT values as compared to specimens prepared by corresponding percentage of SST screenings. This could be attributed to reinforcing effect provided by SST chips (>10%) and thus producing higher IDT values.
- Replacement of coarse aggregate with RAP chips showed increase in the IDT values with maximum improvement at a RAP content of 10%. On the contrary, replacement of fine aggregate with RAP screenings reduced the IDT values. Therefore, specimens containing RAP chips resulted in concrete with higher IDT values as compared to corresponding specimens containing RAP screenings.
- Addition of 40% CFA significantly improved the UCS values of all the mixes containing SST chips. On the other hand, 40% CFA degraded the UCS values of both SST and RAP screening containing specimens.
- Addition of 40% CFA reduced the IDT values of SST chip containing specimens. No clear trend was observed between IDT values and SST or RAP screening content of the specimens containing 40% CFA.
- Statistical analysis revealed that IDT of SST and RAP can be estimated as approximately 13% and 12% of UCS, respectively.

• Concrete mixes containing RAP and CFA could be used for low-strength construction such as driveways, sidewalks, gutters and patching.

Acknowledgments

Financial support for this study was provided through University Research Grant, College of Applied Science and Technology at Illinois State University. The material collection assistance provided by John Drew and Mike Dearing at Prairie Material located in Bloomington, Illinois, is gratefully acknowledged.

The trend, conclusions and recommendations reported in this paper reflect the behavior of concrete containing aggregates, SST, RAP and CFA used in this study. This cannot necessarily be extrapolated to other aggregates, sand, SST, RAP and CFA.

References

ASTM C 114 (2015), "Standard test methods for chemical analysis of Hydraulic Cement", Annual Book of ASTM Standards, American Society for Testing and Materials, 04.02, West Conshohocken, PA.

ASTM C 143 (2015), "Standard test method for Slump of Hydraulic-Cement Concrete", Annual Book of ASTM Standards, American Society for Testing and Materials, 04.02, West Conshohocken, PA.

ASTM C 192 (2016), "Standard practice for making and curing concrete test specimens in the laboratory", Annual Book of ASTM Standards, American Society for Testing and Materials, 04.02, West Conshohocken, PA.

ASTM C 39 (2016), "Standard test method for compressive strength of Cylindrical concrete specimens", Annual Book of ASTM Standards, American Society for Testing and Materials, 04.02, West Conshohocken, PA.

ASTM C 496 (2011), "Standard test method for splitting tensile strength of Cylindrical concrete specimens", Annual Book of ASTM Standards, American Society for Testing and Materials, 04.02, West Conshohocken, PA.

Bilodeau, A. and Malhotra, V.M. (2000), "High-volume fly ash system: Concrete solution for sustainable development", *ACI Mater. J*., **97**(M6), Jan-Feb 2000.

Cook, J.E. (1981), "A ready-mixed concrete company's experience with class C ash", Report No. 163, National Ready-Mix Concrete Association, Silver Spring, Maryland.

Crouch, L.K., Hewitt, R. and Byard, B. (2007), "High Volume Fly Ash Concrete", *Proceedings of the World of Coal Ash (WOCA)*, Northern Kentucky, 1-14

Eldin, N.N. and Senouci, A.B. (1993), "Rubber-tire practices as concrete aggregate," *J. Mater. Civil Eng*., **5**(4), 478-496.

Epps, J.A. (1994), "Uses of recycled rubber tires in highways", *Synthesis of Highway Practice, 198*, Transportation Research Board, National Research Council, Washington, DC.

Gupta, S. (2015), "Use of triangular membership function for prediction of compressive strength of concrete containing nanosilica", *Cogent Eng*., 2:1025578, 1-11.

Hernandez-Olivares, F., Barluenga, G., Bollati, M. and Witoszek, B. (2002), "Static and dynamic behavior of recoiled tyre rubber-filled concrete", *Cement Concrete Res*., **32**(10), 1587-1595.

Huang, B., Shu, X. and Burdette, E.G. (2005), "Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement", *J. Transport. Res. Board*, **1929**(1), 37-45.

Huang, B., Shu, X. and Burdette, E.G. (2006), "Mechanical properties of concrete containing recycled asphalt pavements", *Mag. Concrete Res*., **58**(5), 313-320.

Ibrahim, A., Mahmoud, E., Khodair, Y. and Patibandla, V. (2014), "Fresh, mechanical, and durability characteristics of self-consolidating concrete incorporating recycled Asphalt pavements", *J. Mater. Civil Eng.*, **26**(4), 668-675.

Kennedy, T.W., Moore, R.K. and Anagnos, J.N. (1971), "Estimations of indirect-tensile strengths for cement-treated materials", *Highway Res. Record*, **351**, 112-114.

Khatib, Z.K. and Bayomy, F.M. (1999), "Rubberized Portland cement concrete", *J. Mater. Civil Eng.*, **11**(3), 206-213.

Lee, H.S., Lee, H., Moon, J.S. and Jung, H.W. (1998), "Development of tire-added latex concrete", *ACI Mater. J.*, **95**(4), 356-364.

Li, G., Stubblefield, M.A., Garrick, G., Eggers, J., Abadie, C. and Huang, B. (2004), "Development of waste tire modified concrete", *Cement Concrete Res.*, **34**(12), 2283-2289.

Little, D.N. (1995), *Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime*, Dubuque, Kendall/Hunt.

Naik, T.R. and Ramme, B.W. (1990), "Effects of high-lime fly ash content on water, time of set and compressive strength of concrete", *ACI Mater. J.*, **87**(6), 619-626.

Naik, T.R., Ramme, B.W. and Tews, J.H. (1994), "Use of high volumes of class C and class F fly ash in concrete", *Cement, Concrete Aggregates*, CCAGPD, **16**(1), 12-20.

Oikonomou, N., Stefanidou, M. and Mavridou, S. (2006), "Improvement of the bonding between rubber tire particles and cement paste in cement products", *Proceedings of the 15th Conference of the Technical Chamber of Greece*, Alexandroupoli, Greece, 234-242.

Okafor, O.F. (2010), "Performance of recycled asphalt pavement as coarse aggregate in concrete", *Leonardo Electro. J. Practices Tech.*, **17**, 47-58.

Siddique, R. and Naik, T.R. (2004), "Properties of concrete containing scrap-tire rubber-an overview", *Waste Manage.*, **24**(6), 563-569.

Snelson, D.G., Kinuthia, J.M., Davies, P.A. and Chang, S.R. (2009), "Sustainable construction: Composite use of tyres and ash in concrete", *Waste Manage.*, **29**(1), 360-367.

Sobhan, K. and Mashnad, M. (2003), "Fatigue behavior of a pavement foundation with recycled aggregate and waste HDPE strips", *J. Geotech. Geoenvir. Eng.*, **129**(7), 630-638.

Topcu, I.B. (1995). "The properties of rubberized concretes", *Cement Concrete Res.*, **25**(2), 304-310.

Yilmaz, A. and Degrimenci, N. (2009), "Possibility of using waste tire rubber and fly ash with Portland cement as construction materials", *Waste Manage.*, **29**(5), 1541-1546.

CC