Laboratory Investigation of Indirect Tensile Strength Using Roofing Polyester Waste Fibers in Hot Mix Asphalt

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Abstract

The vast quantity of waste materials (such as roofing polyester waste fibers) accumulating throughout the world is creating costly disposal problem. The use of these materials was proved to be economical, environmentally sound and effective in increasing the performance properties of the asphalt mixture in recent years. The primary objective of this research was to determine whether homogeneously dispersed roofing waste polyester fibers improve the indirect tensile strength (ITS) and moisture susceptibility properties of asphalt concrete mixtures containing various lengths and percentages of the fiber in various aggregate sources. The experimental design included the use of three aggregate sources, two lengths (0.635 cm (1/4 inch) and 1.270 cm (1/2 inch)) of this fiber, and two fiber contents (0.35%, and 0.50% by weight of total mixture). The results of the experiments found that, in general, the addition of the polyester fiber was beneficial in improving the wet tensile strength and tensile strength ratio (TSR) of the modified mixture, increasing the toughness value in both dry and wet conditions, and increasing the void content, the asphalt content, the unit weight, and the Marshall Stability.

Keywords: Polyester fiber; Moisture susceptibility; Waste material; Indirect tensile strength; Tensile strength ratio; Toughness; Flow

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1. Introduction

As world population continues to increase, economic and industrial growth will continue to generate increasing amounts of waste materials. Disposal methods, whatever the form, have a direct impact on the delicate balance in the physical, chemical and biological environments that constitute our global ecosystem [1-2]. For many reasons (e.g., economic), the use of waste materials in construction as partial or full replacement of virgin materials has increased. In general, previous experience showed that the use of some waste materials (such as fiber, crumb rubber and reclaimed asphalt pavement) has proven to be cost-effective, environmentally sound, and successful in improving some of the engineering properties of asphalt mixtures [3-6].

The textile industry, in the United States and other countries, generates millions of tons of fiber trim waste which goes into landfills every year. These fibers can provide high strength, good abrasion resistance, and can withstand deterioration from some chemical, mildew and rot. Several fabrics made from these fibers make excellent candidates for various civil engineering applications including pavement rehabilitation and construction.

Cotton reinforcement with fiber mesh in asphalt concrete mixtures, in both fiber and fabric forms was first attempted in 1934 [7]. The results indicated that their tensile strength was high; however, the fibers were degradable, so they did not provide the long term reinforcements that were required [7-8]. Also, metal wires were reused with the penetration of waster and asbestos was determined to be a health hazard by the Environmental Protection

Agency (EPA) at that time. Another drawback of using fiber reinforcement was that fiberglass strands cut themselves at intersections within the mixture [9-10].

Another alternative to these materials have been provided by the textile industry with the development of synthetic materials such as polyester and polypropylene. These fibers provide the same benefits that the use of natural materials, however, for a longer period of time, without known risks to the environment and human health. Some studies have been conducted on the reinforcement of surface course pavements with polyester fiber in the past [5,11-13]. Research performed in Mexico and Texas has shown that the addition of polyester fibers in asphalt concrete pavements will reduce reflective cracking [11-12]. Three primary factors should be taken into account while adding any waste product in asphalt pavement [1,13]. Initially, the life cycle cost analyses must be performed to determine the effectives of each material. A second consideration is the effect on quality and performance of the asphalt pavement. It would be poor economics indeed to incorporate waste that substantially increase the cost of the pavement and at the same time shortens the service life or increase the maintenance cost. The environmental advantages over its disposal in landfills are also considered in the utilization of waste materials.

Over 60 years ago in South Carolina, coarsely-woven cotton layers were spread between coats of asphalt to strengthen the road surface and comfort the ride [14-15]. The cotton served both as a binder for the asphalt cement and waterproof blanket to restrain water from seeping through cracks and eroding the road base. In 1976, a test site in New Jersey showed good results after one year’s time which helped in spreading this paving practice to

Georgia, Louisiana, and Texas [16]. However, the cotton fibers eventually lost strength from abrasion and rot, and the system ceased to function as membrane [16-17]. Two important functions of the fabric used in a pavement system are to readily absorb asphalt cement in order to form a strong waterproof membrane which will restrict surface water from entering the road base and be both durable and resilient under loads in order to dissipate stresses at the point of crack propagation from one pavement layer to another.

Several fabric types (such as polypropylene, polyester, polyester, glass, nylon, or melded varieties of these and other fibers) have been used in pavements to reduce reflective cracking. The major fabric materials currently used in pavements in the United States are polypropylene and polyester. During installation, the fiber must be able to withstand temperatures up to 150ºC (302ºF) and be sufficiently durable to sustain traffic after the paving process [8,18]. Since a pavement moves in several directions under mechanical and thermal stress, the multi-directional physical properties of a non-woven polyester fiber seem to be superior to the bi-axial properties of a woven material. In addition, the fiber should be lightweight, for ease in handling, and highly resistance to chemicals, mildew and fungus [13,17-18].

The primary objective of this research was to determine whether homogeneously dispersed roofing waste polyester fibers improve the indirect tensile strength (ITS) and moisture sensitivity properties of the modified asphalt mixtures. In addition, the effect of various lengths and percentages of this fiber on ITS was investigated. The second objective of this research was to determine the effects of aggregate sources on the mechanical properties of the asphalt concrete mixtures containing roofing waste polyester fibers (e.g., air voids, ITS, and toughness).

2. Experimental Process and Materials

2.1 *materials and design*

All testing procedures and equipment conformed to the standards set by the American Society for Testing and Materials (ASTM). The asphalt concrete samples prepared consisted of an AC-20 grade asphalt cement, mineral aggregate, waste polyester fibers, and an anti-strip additive (lime). Aggregates were obtained from three quarries in South Carolina Sources 1, 2 and 3. The gradations, shown in Figure 1, which followed Type I Surface Course specifications, were used in this study.

The polyester fibers were spun bond, non-woven and continuous. This commercial product trim waste was obtained from the rolls of polyesters used for roofing. Two length (0.635 and 1.270 cm or 1/4 and 1/2 inch) of this fiber were obtained using a paper shredder machine. Also, two percentages (0.35% and 0.50%) of fibers were used by the total weight of the mixture. These lengths and percentages were selected because of the similar research which has been completed in the past on fibers. Some of the characteristics of the fibers used are listed in Table 1. The abbreviation shown in Table 2 will be used in this project to discuss the results. The engineering properties of three aggregate sources 1, 2 and 3 are shown in Table 3.

The experimental design for this study is shown in Figure 2. A randomized complete block experimental design was used. There were a total of 270 Marshall specimens (50 blows/side) made and tested. All replicates were used randomly to ensure that the testing was unbiased.

2.2 Experimental testing

The optimum asphalt contents of all mixtures were obtained using the procedures described in The Asphalt Institute Manual Series Number 4 [19]. The fibers were blended with the dry aggregate and oven dried for 24 hours prior to the addition of the asphalt cement. In order to achieve the required percent air voids for these procedures (7±1%), different compactive efforts were utilized for various mixes (20 blows/side for Source 2 and 25 blows/side for sources 1 and 3).

The toughness of the mixture, shown in Figure 3, then was calculated which is defined as the area under the tensile stress-deformation curve up to a deformation of twice that incurred at maximum tensile stress. In addition, the toughness index was calculated (toughness divided by the toughness up to maximum tensile stress) [1, 15, 20-21].

3. Results and Discussions

3.1 Statistical considerations

A complete random block design was used for the statistical design because the laboratory specimens were essentially homogeneous. The effects of laboratory treatments (additional of polyester fibers) on some of the physical characteristics (e.g., ITS and TSR) of the asphalt concrete specimens were measured using Analysis of Variance (ANOVA).

Results of the ITS were compared by statistical analysis with a 5% level of significance (0.05 probability of a Type I error). For this study, there were twenty four combinations of variables (i.e., 3 aggregate sources x 2 fiber lengths x 2 fiber percentages x 2 moisture conditions).

3.2 Binder contents, unit weight and VMA

All of the fiber mixtures had a higher optimum percentage of asphalt cement than the control mixture because the additional asphalt is necessary to coat the fibers (Table 4). The proper quantity of asphalt is dependent on the absorption and the surface area of the fibers and therefore is affected not only by different concentrations of fibers but also by the different types of fibers.

The unit weight for the fiber reinforced mixture seemed to increase as the percentage of fibers added was increased (Table 4). The statistical analysis showed that length of the fibers had no significant effect on the unit weights whereas percentage of fibers did influence this property significantly. This is due to the fact that mixtures with higher fiber percentage have higher asphalt contents which lead to a higher unit weight.

The specimens containing no fibers had lower air void contents than the mixtures containing polyester fibers at same number of blows for all the aggregate sources. It was also noted that the specimens made with 0.50% fiber contents had higher air void contents than the specimens containing 0.35% fiber contents for sources 1 and 2 (Table 5). But the statistical analysis showed no significant differences between air void contents of control samples and fiber mixtures.

The percentage of voids in the mineral aggregate (VMA) increased with an increase in percentage of fibers (Table 6). At optimum asphalt content, the control mixtures produced VMA values that were significantly lower than all of the mixtures containing fibers for all the aggregate types. The length of the fibers had no significant effect on this property of the asphalt concrete mixtures.

3.3 Flow, ITS, and Toughness

The flow values increased with an increase in the fiber content (Table 7). The statistical analysis of flow values showed that values were significantly higher for 1.270 cm (1/2 inch) long 0.50% fibers than the control specimens. This increase in flow values could be due to excessive asphalt content of fiber induced mixtures. The recommended limit was not exceeded in any case. Also, different aggregate sources did not have any statistically significant effects on the flow properties of the modified mixtures.

It was found the average mean dry ITS values of control mixtures were not significantly higher when compared to the fiber mixtures. The factorial statistical analysis of the effects due to fibers indicated that the size and percentage of fibers had no significant effect on the dry ITS. Figure 4 shows that comparison of dry ITS values for all the three aggregate sources. Different aggregate sources did not have any statistically significant effect on the dry tensile strength of the mixtures.

The comparison of wet ITS values indicated that the mean wet ITS values of all the fiber mixtures were greater than the control mixtures. Also, factorial analysis of variation shows that fiber percentage and size both affected the wet ITS value significantly. Figure 4 shows the comparison of wet ITS values for the three aggregate sources. Higher wet ITS of fiber mixtures could be related to the fact that inclusion of fibers increases the strength of the mixture because of interlocking phenomenon thus making the mixture more resistant to moisture damage. Aggregate source had no significant effect on the wet ITS values.

TSR values of control mixtures for all aggregate sources were significantly lower than that of fiber mixtures. Figure 5 shows that comparison of TSR values for all the three aggregate sources. The factorial analysis of the effects due to fiber variables indicated that the percentage and size of fibers had significant effects on TSR values. Aggregate sources had no effect on the TSR values.

The results indicated that toughness values in dry condition increased with the addition of fiber. Also, 0.35% fiber mixtures had a lower toughness than the 0.50% fiber percentages at both lengths. The dry toughness index values are shown in Table 8. The statistical analysis indicated that the differences between the control mixture and the fiber mixtures were not statistically significant in toughness values.

The control mixtures had lower toughness values in the wet condition than all of the fiber mixtures. In addition, the results indicated that wet toughness value increased with an increase in fiber length and percentage. The wet toughness indices for the fiber mixtures were higher than the control mixture. Table 8 displays that the mixture with 0.35% fibers had the highest wet toughness index for both lengths for all of the aggregate types.

Figure 6 shows the ITS/toughness values of the mixtures varying from the fiber sizes, percentages, and aggregate sources. These values are obtained as the maximum indirect tensile strengths are achieved, and related to the deformation of the testing samples. Figure 6 shows that, in the same condition, all of the wet samples have the greater deformations (smaller ITS/toughness values) than the dry ones. And it is evident that the mixture containing the larger length and/or greater percentage of the fiber (the mixture from Control to D) results in the greater deformation. These analysis results show the ITS/toughness values of the mixtures have the similar trend with their flows shown in Table 7. This shows the fiber plays a significant role in determining the sample moisture susceptibility. However, there is not a significant difference in the ITS/toughness values as using the various aggregate sources.

4. Findings and Conclusions

In this limited study, aggregate sources had no effect on any of the mechanical properties (e.g., unit weight, tensile strength, toughness, etc.) of asphalt concrete mixture. Fiber size and percentage were the only two variables which influenced almost every mechanical property of the mixtures.

The asphalt content of all the fiber induced mixtures was found to be higher than the control mixtures. This is due to the fact that more asphalt binder is required to coat the fiber strands in the mixture. The unit weights of the mixtures with fibers were higher than the control mixtures.

All the fiber induced asphalt mixtures had higher air voids than the control mixtures. The mixtures with 0.635 cm (1/4 inch) length and 0.35% fibers had higher air voids that the ones with 1.270 cm length and 0.50% fibers. And %VMA value increased as the percentage of fibers added was increased in the asphalt mixture.

Marshall mix design indicated that the stability of mixtures containing fibers was lower than those of the control mixtures. Specimens containing 1.270 cm (1/2 inch) long fiber mixtures had lower stability values than the 0.635 cm (1/4 inch) long fiber mixtures. Flow values increased with the increase in fiber length and percentage.

The dry ITS values of the mixtures containing fibers were lower than the control mixtures. These values were lower for 1.270 cm (1/2 inch) and 0.50% fiber mixtures. But the statistical analysis indicated that this difference was not statistically significant. The wet ITS values of the fiber induced asphalt mixtures were found to be statistically higher than the controls indicating that the use of polyester fibers decreased the moisture susceptibility of mixtures

Tensile strength ratios for all fiber induced mixtures were significantly higher than those of the controls. The toughness and toughness indices in both dry and wet conditions were found to be statistically higher with the increase in fiber content.

In summary, the research findings show that the addition of waste roofing polyester fibers in asphalt concrete mixture improves some of the engineering properties such as ITS, toughness and TSR. In addition, decrease in susceptibility to moisture and higher flow values were noticed by the addition of fibers. Also, 0.635 cm (1/4 inch) long fibers with 0.50% content proved to be the best combination since this mixture provided the highest dry and wet ITS, TSR and toughness values.

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Table 1

Physical characteristics of non-woven polyester fibers

Test Properties	Typical Values
Weight, gm/m^2	180
Tensile Strength, daN/5 cm	68
Elongation-at-Break, %	38
Tear Strength, N	75.6
Thermal Sensitivity, ºC	240ºC (softens); 265ºC (melts)

Note: 1 daN (deca-Newton) = 10 Newton

Table 2
Name designated for fiber additive

Fiber Type	Name	Length (cm)	% Fiber by total weight of mix
0.635 cm & 0.35%	A	0.635	0.35
0.635 cm & 0.50%	B	0.635	0.50
1.270 cm & 0.35%	C	1.270	0.35
1.270 cm & 0.50%	D	1.270	0.50
Control	Control	no fiber	

Table 3
Engineering properties of the aggregate sources 1, 2, and 3

Aggregate Source	LA Abrasion Loss (%)	Absorption (%)	Specific Gravity			Sand Equivalent	Hardness
			Dry (bulk)	SSD (bulk)	Apparent		
1	51	0.70	2.650	2.660	2.690	76	5
2	48	0.80	2.610	2.640	2.670	70	6
3	26	0.50	2.610	2.620	2.640	60	6

Table 4
Optimum asphalt contents and unit weights for all mixtures

Fiber Type	Source 1		Source 2		Source 3	
	O.A.C (%)	Unit Weight (kg/m^3)	O.A.C (%)	Unit Weight (kg/m^3)	O.A.C (%)	Unit Weight (kg/m^3)
Control	6.7	2318	5.9	2323	6.2	2315
A	6.9	2305	6.4	2313	7.2	2307
B	7.0	2291	6.4	2302	7.0	2305
C	7.1	2286	7.0	2291	7.2	2294
D	7.3	2281	7.5	2278	7.5	2289

Note: O.A.C. = optimum asphalt content

Table 5
Air voids of all mixtures

Fiber Type	Source 1			Source 2			Source 3		
	Mean (%)	St.d (%)	C.V.	Mean (%)	St.d (%)	C.V.	Mean (%)	St.d (%)	C.V.
Control	5.7	0.065	0.894	5.1	0.020	0.394	5.1	0.031	0.309
A	6.6	0.095	0.861	6.4	0.096	0.761	6.1	0.043	0.621
B	6.7	0.057	0.854	6.6	0.051	0.754	6.7	0.053	0.788
C	6.6	0.039	0.532	6.3	0.093	0.991	6.5	0.086	0.654
D	6.8	0.098	0.699	6.4	0.076	0.897	6.5	0.078	0.912

Note: St.d = standard deviation; C.V. = coefficient of variation

Table 6

Voids in the mineral aggregate of all mixtures

Fiber Type	Source 1			Source 2			Source 3		
	Mean (%)	St.d (%)	C.V.	Mean (%)	St.d (%)	C.V.	Mean (%)	St.d (%)	C.V.
Control	14.6	0.192	0.877	14.9	0.020	0.394	15.1	0.031	0.309
A	16.7	0.151	0.910	15.9	0.096	0.761	16.2	0.043	0.621
B	16.8	0.130	0.777	16.4	0.051	0.754	16.8	0.053	0.788
C	17.1	0.349	0.897	16.9	0.076	0.991	17.1	0.086	0.654
D	17.4	0.114	0.665	17.3	0.076	0.897	17.4	0.078	0.912

Note: St.d = standard deviation; C.V. = coefficient of variation

Table 7
Flows of all mixtures

Fiber Type	Source 1			Source 2			Source 3		
	Mean (1/100cm)	St.d (1/100cm)	C.V.	Mean (1/100cm)	St.d (1/100cm)	C.V.	Mean (1/100cm)	St.d (1/100cm)	C.V.
Control	22.61	0.653	0.896	24.89	0.536	0.877	23.11	0.622	0.89
A	30.22	0.566	0.894	32.26	0.376	0.897	30.22	0.29	0.843
B	35.05	0.488	0.796	35.31	0.310	0.881	33.53	0.404	0.861
C	37.60	0.572	0.769	34.80	0.376	0.889	35.31	0.34	0.986
D	37.85	0.462	0.875	36.32	0.330	0.911	35.81	0.312	0.976

Note: St.d = standard deviation; C.V. = coefficient of variation

Table 8

Toughness/toughness index values of all mixtures

Designated Name	Source 1		Source 2		Source 3	
	Dry	Wet	Dry	Wet	Dry	Wet
Control	12.8/2.4	5.5/2.2	13.2/2.3	5.9/2.1	13.5/2.2	5.5/2.1
A	12.9/2.5	8.8/2.6	13.8/2.5	8.9/2.9	13.8/2.4	8.2/2.9
B	14.1/2.5	9.7/2.4	14.3/2.4	9.7/2.4	14.3/2.6	9.5/2.3
C	14.5/2.5	9.6/2.6	14.6/2.4	9.8/2.8	14.8/2.6	9.9/2.9
D	15.3/2.4	9.5/2.4	15.2/2.4	10.2/2.3	15.1/2.5	9.9/2.6

Note: Toughness unit = N/mm

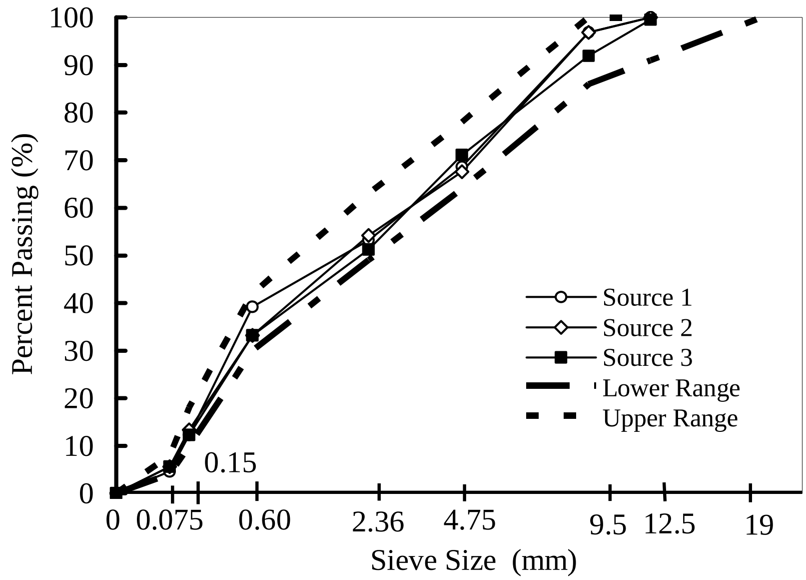
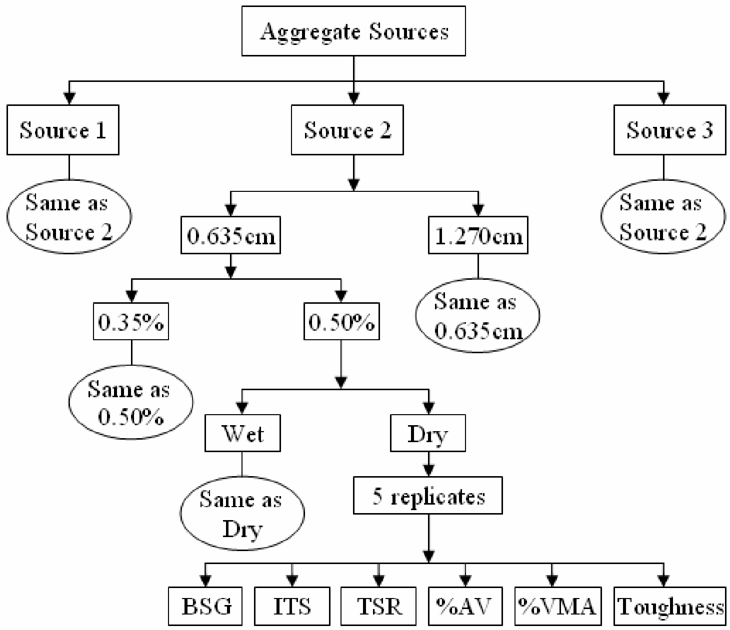


Fig. 1 Gradation curves for Sources 1, 2, and 3 (SCDOT Type I surface source)



Legend:

BSG: bulk specific gravity; ITS: indirect tensile strength; TSR: tensile strength ratio; %AV: percent air voids; %VAM: voids in mineral aggregate

Fig. 2 Flowchart of experimental design

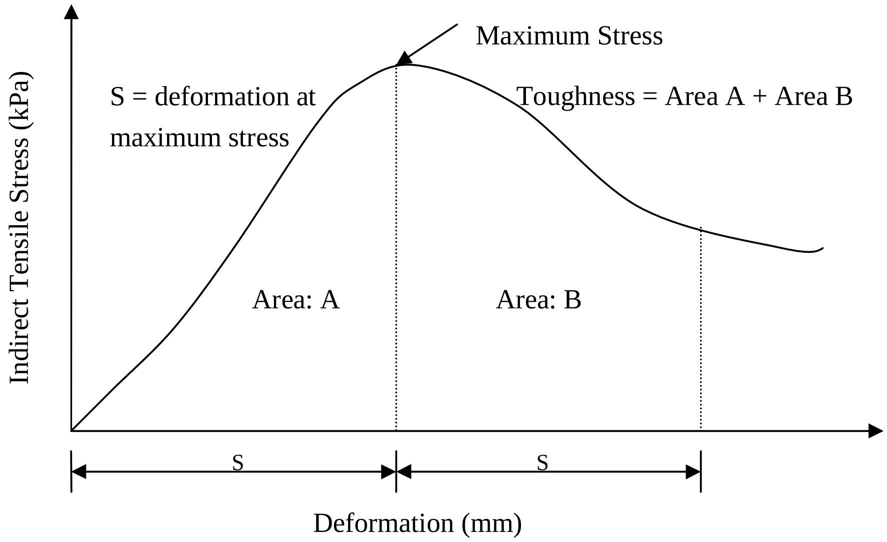


Fig. 3 Definition of toughness

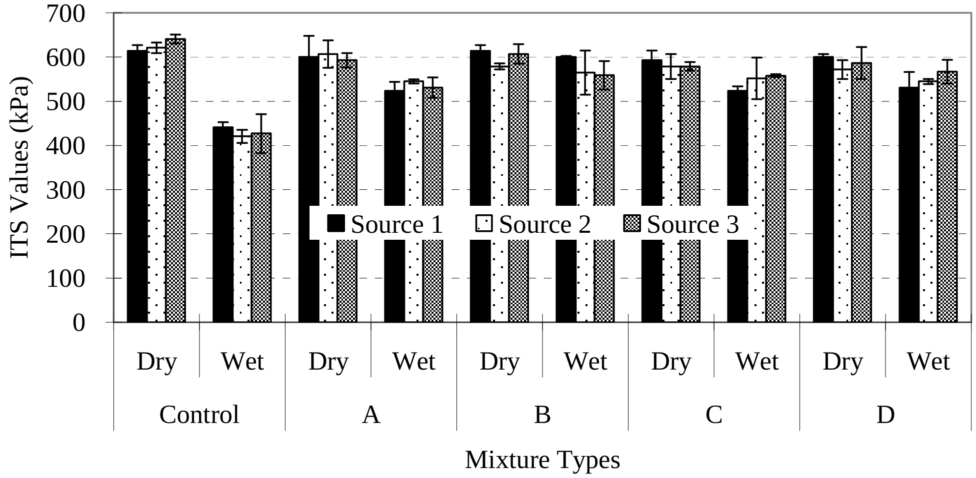


Fig. 4 ITS values of all mixtures

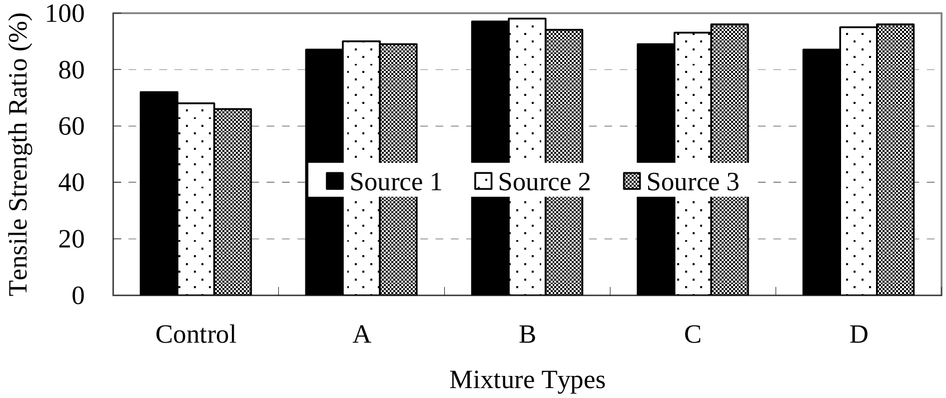


Fig. 5 TSR values of all mixtures

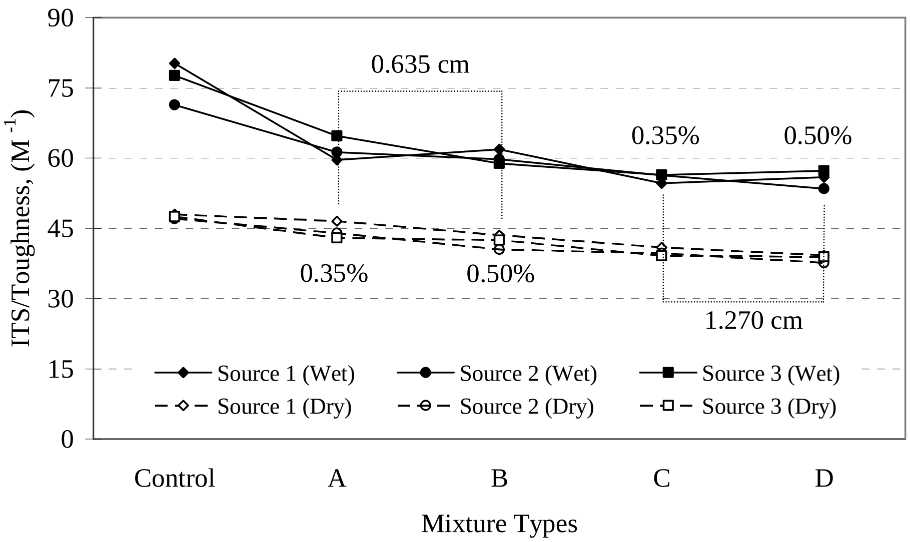


Fig. 6 ITS/Toughness values of all mixtures