



Feasibility study for end-of-life tire recycling in new tire production, Egypt

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Abstract

End-of-life tires constitute one of the biggest environmental concerns in terms of environmental pollution and resources conservation. This study aims to determine the best proportion of reclaimed rubber and crumb rubber to be added as part of the constituents used in the manufacturing of three different tire parts (tread, side wall, and inner liner) in order to produce standard products from a mix of both recycled and original ingredients. Batches were prepared into which reclaimed rubber and crumb rubber were added to the formulation of three different tire parts, in addition to one batch as reference according to the original formulation. Batches were analyzed according to national and international standards to select the optimum percentage that can be introduced in new tire formulation preparations. Results revealed that reclaimed rubber could be used as 15 parts per hundred rubber (phr) in radial tread compound and as 25 phr in either radial side wall or radial inner liner compounds. As for crumb rubber, results showed that it could be used as 10, 20 and 25 phr in radial tread, radial side wall or radial inner liner compounds respectively. Incorporating higher amounts of either reclaimed or crumb rubber would lead to violating the standards specified in vulcanized rubber tension property test and in oscillating disk cure meter test. Savings in raw material and in energy resulting from the use of reclaimed rubber was calculated: As concerns raw materials, adding 15 phr reclaimed rubber to the tread formulation would save about 7.7% of each of Styrene Butadiene Rubber (SBR), Polybutadiene and carbon black. Adding 25 phr reclaimed rubber to the side wall formulation would save about 12.8% of each of natural rubber, Polybutadiene and carbon black. Adding 25 phr reclaimed rubber to the inner liner formulation would save about 13% of each of natural rubber, SBR and carbon black. Regarding energy conservation, use of reclaimed rubber in new tires would result in a total energy conservation of 6393GJ/year. In addition to the raw material and energy conservation, the process was found to be cost-effective.

Keywords: Crumb rubber, inner liner, reclaimed rubber, side wall, tire recycling, tread

Introduction

End-of-life tires constitute one of the biggest environmental concerns in terms of environmental pollution and resources conservation [1,2]. They may cause fire hazard, trap rain water creating potential breeding grounds for mosquitoes, and occupy large volume in landfills [1,3]. Besides, they have a virtually unlimited life span and need long time for natural degradation due to the cross-linked structure of rubbers and the presence of stabilizers [4-8].

Tire ingredients include rubber (natural and synthetic), reinforcing chemicals (carbon black and silica), oils, processing aids, resins, vulcanizing agents, activators, and accelerators [9-12].

The principal alternatives for managing scrap tires are commonly referred to as the four Rs (4Rs); reduction, re-use, recycling, and energy recovery [13,14]. Reduction can be achieved by technological developments in tire design and materials that prolong the tire life span and decrease its weight [15]. However this alternative is not used in Egypt due to technical problems and big research investments. As for reuse, some markets have been developed for reusing whole scrap tires. They are reused as crash barriers in roads, car races, in maritime ports and as new tires for old cars and for carts [11].

As regards recycling, about 65-75% of tire weight is rubber (natural or synthetic) and carbon black found mainly in the tread,

sidewall, and inner liner compounds of the tire [13,16]. Recycling alternatives include retread, pyrolysis, rubber modified asphalt, compacting rubberized concrete, shredding, crumbing, and reclaiming. Crumbing is a procedure in which scrap tire is converted into "crumb rubber" through removing steel belts, bead wire, and fabrics and produce tire chips [17]. Tire chips are processed to produce finer particle sizes and super fine powder that will be able to chemically bond with the virgin rubber in the vulcanization process [18-20].

Reclaiming is a procedure in which scrap tire is converted into "reclaimed rubber" which can be mixed, processed, and vulcanized again [21,22]. The principle of reclaiming is devulcanization which consists of the cleavage of the intermolecular bonds (C-S) and/or (S-S) [18,23].

Reclaimed rubber and crumb rubber are valuable products that are used in the production of new tires [24]. They also lower power consumption as a result of shorter mixing cycles and reduction of shrinking during extrusion and calendaring [25].

On the other hand, Khait and Carr reported that reclaimed rubber could be used as alternative to virgin rubber but this would result in a reduced elasticity [26]. Ryan stated that the addition of crumb rubber to virgin rubber was found to lower its physical properties by about 10 to 15%. There is a reduction in modulus upon introduction, and such reduction is then accompanied by an increase in scorching time [27]. Stark and Wagner reported that rubber properties deteriorate in proportion to the amount of crumb rubber used. They added that the most significant changes in properties are decrease in tensile strength and dynamic properties [28].

This study aims to determine the best proportion of reclaimed rubber and crumb rubber to be added as part of the constituents used in the manufacturing of three different tire parts (tread, side wall, and inner liner) in order to produce standard products from a mix of both recycled and original ingredients.

Material and methods

The study was conducted in the laboratory unit of the Transportation and Engineering Company (TRENCO) for tires production, Alexandria Governorate, Egypt.

Reclaimed rubber and crumb rubber were collected from two material recovery facilities: Chemicals Company for Reclaimed Rubber Production (MARSO) and The Egyptian Italian Company for Tires Crumb Rubber Production (EGITCO).

Batches were prepared into which reclaimed rubber and crumb rubber were added to the formulation of three different tire parts (tread part, side wall part, and inner liner part), in addition to one batch as reference according to the original formulation as follows:

1. First, concerning the incorporation of reclaimed rubber and crumb rubber in the formulation of the radial tread, nine batches were prepared. Batch number one represented the reference one with no recycled material. In batches two, three, four and five, reclaimed rubber was added as 5 phr, 10 phr, 15 phr, and 20 phr respectively.

In batches six, seven, eight and nine, crumb rubber was added as 5 phr, 10 phr, 15 phr, and 20 phr respectively.

2. Second, concerning the incorporation of reclaimed rubber and crumb rubber in the formulation of the radial side wall, nine batches were also prepared. Batch number one represented the reference one with no recycled material. In batches two, three, four and five, reclaimed rubber was added as 15 phr, 20 phr, 25 phr, and 30 phr respectively. In batches six, seven, eight and nine, crumb rubber was added as 15 phr, 20 phr, 25 phr, and 30 phr respectively.

3. Third, concerning the incorporation of reclaimed rubber and crumb rubber in the formulation of the radial inner liner, eleven batches were prepared. Batch number one represented the reference one with no recycled material. In batches two, three, four, five and six, reclaimed rubber was added as 20 phr, 25 phr, 30 phr, 35phr, and 40 phr respectively. In batches, seven, eight, nine and ten, eleven crumb rubber was added as 20 phr, 25 phr, 30 phr, 35phr, and 40 phr respectively.

Virgin raw materials were borrowed from the tire production company TRENCO and preparation as well as testing of different formulations was done in the Company pilot plant.

The above mentioned amounts in phr of both reclaimed rubber and crumb rubber were selected for the study based upon findings of Gandhi H and Kumar S [29] and of Antonio EM, [13] who reported that the best applicable phr for rubber recycling in new tire production is as follows: 5-20 phr, 15-30 phr, and 20-40 phr for tread, side wall, and inner liner respectively.

Batches were analyzed according to TRENCO testing methods and standards [30] and according to American Society for Testing and Materials (ASTM) standards [31] to select the optimum percentage that can be introduced in new tire formulation preparations. Eight tests were used to analyze the prepared batches. These are:

1. The vulcanized rubber tension property test: (reference: ASTM D-412-98a-R02) It is a stress-strain test. It gives two stress parameters (300% modulus stress value and tensile stress at break value) and one strain parameter which is the elongation percentage at break [30,31].
2. The vulcanized rubber abrasion resistance test: (reference: ASTM D-2228-02) It is a comparison test for the abrasion resistance percentage between every sample batch and the reference "original" batch. It gives abrasion resistance percentage value compared to 100% of the reference batch. This test was done for tread batches only [30,32].
3. The vulcanized rubber rebound property test: (reference: ASTM D-1045-02) It is a comparison test for the rebound property percentage between every sample batch and the reference "original" batch. It gives rebound property percentage value compared to 100% of the reference "original" batch [31,33].
4. The vulcanized rubber density "specific gravity" test:

(reference: D-148 Trencó) It gives the specific gravity value in gram per milliliter [30,34].

5. The vulcanized rubber density “durometer hardness” test: (reference: ASTM D-2240-03) It gives the durometer hardness value in SI unit [31,34].
6. The oscillating disk cure meter test: (R 100) (reference: ASTM D-2084-01) It is used to determine the vulcanization characteristics of vulcanizable rubber compounds. It gives two torque (stiffness) parameters in deci-newton per meter (dN.m) unit: minimum torque (L min.) which is the measure of the stiffness of the unvulcanized test specimen taken at the lowest point of the curve, and maximum torque (L max.) which is the measure of the stiffness or shear modulus of the fully vulcanized test specimen. It also gives two times parameters in minute per minute (m.m) unit: scorch time (Tsc.) which is the measure of the time at which vulcanization begins, and cure rate (C.R.) which is the measure of optimum cure based on the time to develop some percentage of the highest torque or difference in torque from the minimum [32,35].
7. Rotorless cure meter test: (MDR 2000) (reference: ASTM D-5289-95-R01) It is used to determine the vulcanization characteristics of vulcanizable rubber compounds. It gives two torque (stiffness) parameters in (dN.m) unit; minimum torque (ML) which is the measure of the stiffness of the unvulcanized test specimen taken at the lowest point of the curve and maximum torque (MH) which is the measure of the stiffness or shear modulus of the fully vulcanized test specimen. It also gives two times parameters in (m.m) unit; scorch time (Ts2) which is the measure of the time at which vulcanization begins and cure rate (T90) which is the measure of optimum cure based on the time to develop some percentage of the highest torque or difference in torque from the minimum [32,35].
8. The pre-vulcanization rubber characteristics test: (reference: ASTM D-1646-04) It is a test for measuring the time to the incipient vulcanization and the rate of cure during the early stages of vulcanization (Mooney Scorch). It gives the Pre-Vulcanization Rubber Characteristics (Mooney Scorch) value in (m.m) unit [30,31].

The previously mentioned procedures were repeated three times making an overall number of batches of 87. Results of analyses were compared with TRENCO standards for testing tires [30].

Results and discussion

Feasibility study

Properties of radial tread, radial side wall and radial inner liner prepared batches are presented in **Tables 1,2 and 3** respectively. These tire parts were prepared using different proportions of reclaimed or crumb rubber. Some properties were found to decrease as the recycled materials either reclaimed rubber or crumb rubber percentages increase:

they are 300% modulus, tensile, rebound, specific gravity, abrasion, hardness, maximum torque and Mooney scorch. Others were found to increase: elongation, minimum torque, scorch time and cure rate.

This could be due to the fact that whether recycled rubber is crumb (mechanically ground) or reclaimed (chemically or steam digested), it does not have the same physical properties as virgin natural or synthetic rubber. Recycled rubber is a blend of polymer types, chemical additives, which are present in different states of cure. For example, introducing reclaimed rubber into a rubber compound reduces the average length of rubber polymer chain. This shortening has the effect of reducing tensile strength in proportion of the amount of the reclaimed rubber added [36]. There is also a reduction in modulus upon addition of crumb rubber to virgin rubber, and such reduction is accompanied by an increase in scorching time [27].

Although a decrease or an increase in certain properties was observed, batches prepared were still within the limits specified in TRENCO specifications and safety standards of the radial tread radial side wall and radial inner liner compounds except the following ones:

1. Radial tread batches containing 20 phr reclaimed rubber and those containing 15 and 20 phr crumb rubber were not complying with the vulcanized rubber tension property and the Oscillating Disk Cure Meter Test (maximum torque parameter) specifications (**Figure 1**).
2. Radial side wall batches containing 30 phr reclaimed rubber and those containing 25 and 30 phr crumb rubber were not complying with the vulcanized rubber tension property test, as well as maximum and minimum torque parameters in the Oscillating Disk Cure Meter Test. Batches containing 30 phr reclaimed rubber, were not in acceptance with the first two tests. Batches with 30 phr crumb rubber were not in acceptance with the three tests (**Figure 2**).
3. Radial inner liner batches containing 30 or more phr recycled rubber (reclaimed or crumb), were not complying with modulus stress and tensile stress parameters (**Figure 3**).

This means that the highest amount of reclaimed rubber that could be incorporated in the formulation of radial tread compound is 15 phr, and in either radial side wall or radial inner liner formulations, it is 25 phr. As for crumb rubber, it could be used as 10, 20 and 25 phr in radial tread, radial side wall or radial inner liner compounds respectively. Incorporating higher amounts of either reclaimed or crumb rubber would lead to an off-specification product. Such results indicate also that the use of reclaimed rubber is better than crumb rubber as it allows higher percentage of recycled material to be included in the new product.

These findings were in accordance with Fukumoria K. et al., in Japan, who confirmed by actual road tests that tires containing about 10 phr to 15 phr of the recycled rubber in the

Table 1. Properties of radial tread containing different parts per hundred rubber (phr) either reclaimed (RR) or crumb (CR).

Phr of reclaimed rubber (RR) or crumb rubber (CR)	Tension property test			Abrasion %	Rebound %	Specific gravity g/ml	Hardness (SI unit)	Oscillating disk cure meter test				Mooney scorch (m.m)
	300% Modulus (MPa*)	Tensile (MPa*)	Elongation %					L min (dN.m) [§]	Tsc (m.m) [#]	L max (dN.m)	CR [†] (m.m)	
zero	14.6	17.8	382	100	100	1.160	72.5	11.2	2.1	55.5	3.78	44.91
5 RR	14.2	17.0	371	102	99.8	1.155	71.5	12	2.2	53.7	3.88	42.53
10 RR	13.5	16.3	366	98.8	99.0	1.155	71.5	12.3	2.22	52.7	3.90	42.02
15 RR	12.6	15.7	361	96.1	99.0	1.150	71.0	12.8	2.25	52.0	3.93	40.31
20 RR	11.7	14.7	357	91.5	97.0	1.150	71.0	13.3	2.3	51.0	3.98	39.16
5 CR	13.5	16.0	369	100.8	99.8	1.155	72.0	12.7	2.15	53.0	3.90	41.52
10 CR	12.6	15.4	362	97.7	98.8	1.155	72.0	13.2	2.2	52.0	3.93	40.98
15 CR	12.2	14.3	355	94.1	98.8	1.150	71.5	13.5	2.23	50.7	3.98	38.46
20 CR	11.6	13.8	351	89.6	98.2	1.150	69.0	13.8	2.28	48.8	4.05	36.92
specifications	Not<12	Not<15	Not<360	Not<70	Not<70	1.148-1.178	69-75	9-15	1.6-2.4	50-60	3.35-4.20	Not<30

*MPa Mega Pascal (pressure measurement unit), [§]Minimum torque in deci-neuton per meter, [#]Scorch Time in minute per minute, [†]Cure Rate

Table 2. Properties of radial side wall containing different parts per hundred rubber (phr) either reclaimed (RR) or crumb (CR).

Phr of reclaimed rubber (RR) or crumb rubber (CR)	Tension property test			Rebound %	Specific Gravity g/ml	Hardness (SI unit)	Oscillating disk cure meter test				Mooney scorch (m.m)
	300% Modulus (Kg/cm ^{2*})	Tensile (Kg/cm ^{2*})	Elongation %				L min (dN.m) [§]	Tsc (m.m) [#]	L max (dN.m)	CR [†] (m.m)	
zero	113	186	416	100.0	1.110	60.0	12.7	1.45	72.0	2.43	10.72
15 RR	107	184	423	93.3	1.105	59.0	13.5	1.48	70.3	2.48	10.57
20 RR	104	178	439	91.6	1.100	58.5	13.8	1.50	69.0	2.53	10.44
25 RR	101	174	447	89.7	1.095	58.0	14.3	1.55	67.7	2.58	10.34
30 RR	98	167	454	89.3	1.095	57.0	15.2	1.60	66.3	2.62	10.17
15 CR	105	175	431	99.2	1.105	59.0	14.0	1.47	69.8	2.50	10.29
20 CR	103	171	438	98.4	1.100	58.0	15.0	1.52	68.8	2.52	9.97
25 CR	101	166	448	97.9	1.098	57.0	15.8	1.55	67.5	2.55	9.83
30 CR	97	164	456	97.5	1.095	57.0	17.2	1.58	66.0	2.62	9.54
specifications	100-125	170-190	390-450	Not<70	1.088-1.118	57-63	10-16	1.3-1.7	67-77	2.25-2.85	7-13

*Kg/cm²: Kilogram-force per square centimeter (pressure measurement unit), [§]Minimum torque in deci-neuton per meter, [#]Scorch Time in minute per minute, [†]Cure Rate

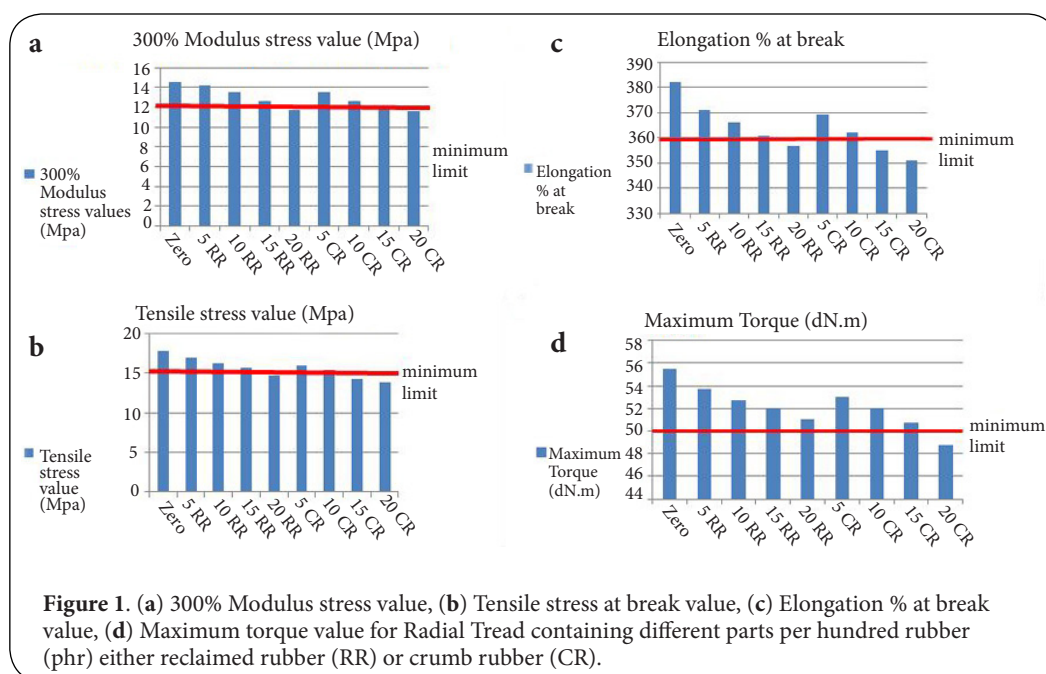
tread compound exhibit tread behavior almost equal to that for the standard type with the new rubber compound [23]. In addition, Beukering and Janssen [37] and California Integrated Waste Management Board [22] found that the recycled rubber ratio from 10 phr to 15 phr in new radial tread compound, and from 15 phr to 25 phr in radial side wall compound was reported as technically feasible, without adversely affecting the performance characteristics of tires. In Malaysia, Ismail H. et al., found that tread characteristics slightly changes with increasing recycled rubber powder. However, the maximum acceptable results were shown at 10 phr of recycled rubber powder in radial tread compound [38]. Gandhi H and Kumar S. [29] in India also found that 15 phr recycled rubber in radial

tread is applicable. Myhre M. et al., [39] and Ahmed R. et al., [15] stated that about 20 phr recycled rubber could be added to the radial side wall or radial inner liner compounds without serious effects to the physical properties of the produced tire. Similarly, the influence of recycled rubber has been tested in an inner liner compound. Concentrations up to 25 phr have been used, and the influence on the compound properties was technically accepted [40]. Adhikari B, et al., from the Indian Institute of Technology reported that about 15-20 phr of recycled rubber were used in tire inner liner compound [18]. Finally, the present study findings were in accordance with those revealed by Antonio EM [13] in Netherland, and by Klingensmith W and Rodgers B. from Ohio, USA [41] who

Table 3. Properties of radial inner liner containing different parts per hundred rubber (phr) either reclaimed (RR) or crumb (CR).

Phr of reclaimed rubber (RR) or crumb rubber (CR)	Tension property test			Rebound %	Specific gravity g/ml	Hardness (SI unit)	Oscillating disk cure meter test				Mooney scorch (m.m)
	300 % Modulus (MPa*)	Tensile (MPa*)	Elongation %				L min (dN.m) [§]	Tsc (m.m) [#]	L max (dN.m)	CR [□] (m.m)	
zero	13.4	18.7	430	100.0	1.165	64.0	12.3	1.43	70.7	2.23	37.14
20 RR	12.8	17.9	439	93.2	1.160	63.0	13.2	1.50	68.8	2.28	36.34
25 RR	12.7	17.2	442	92.9	1.160	63.0	13.7	1.53	68.0	2.32	35.84
30 RR	12.3	16.7	445	91.7	1.160	62.5	14.3	1.57	67.3	2.35	35.32
35 RR	11.7	16.0	449	90.2	1.155	62.0	14.8	1.60	66.7	2.38	35.15
40 RR	11.3	15.5	451	89.0	1.155	62.0	15.5	1.65	66.0	2.45	34.44
20 CR	12.8	17.6	436	95.2	1.160	63.5	13.3	1.50	68.3	2.30	36.03
25 CR	12.6	17.1	439	94.5	1.160	63.5	13.8	1.53	67.7	2.32	35.34
30 CR	12.1	16.5	444	93.9	1.155	63.0	14.5	1.57	67.3	2.35	35.21
35 CR	11.6	15.8	446	93.6	1.155	63.0	15.2	1.62	66.7	2.40	34.93
40 CR	10.9	15.1	450	93.3	1.155	62.5	15.7	1.63	66.0	2.42	34.81
specifications	Not<12.5	Not<17	Not<380	Not<70	1.153-1.173	59-67	9-17	1.05-1.85	65-79	1.9-2.7	Not<25

*MPa Mega Pascal (pressure measurement unit), [§]Minimum torque in deci-newton per meter [#]Scorch Time in minute per minute, [□]Cure Rate



stated that recycling 10 phr reclaimed or crumb rubber in new tires give successful results.

Raw material and energy conservation

Global studies on the increased demand on both raw materials and energy resources have reported that these demands will lead to material depletion and climate changes [42]. Recycling of reclaimed or crumb rubber into new tires could save raw

material and energy.

First, as concerns raw materials (Table 4), consumption of all kinds of raw materials would decrease, but emphasis will be put on SBR (Oiled Styrene Butadiene Rubber), SMR (natural rubber), Polybutadiene (1,4 cis Polybutadiene Rubber) and carbon black as they are the major ingredients used in the production of tires. Adding 15 phr reclaimed rubber to the tread formulation would save about 7.7% of each of SBR,

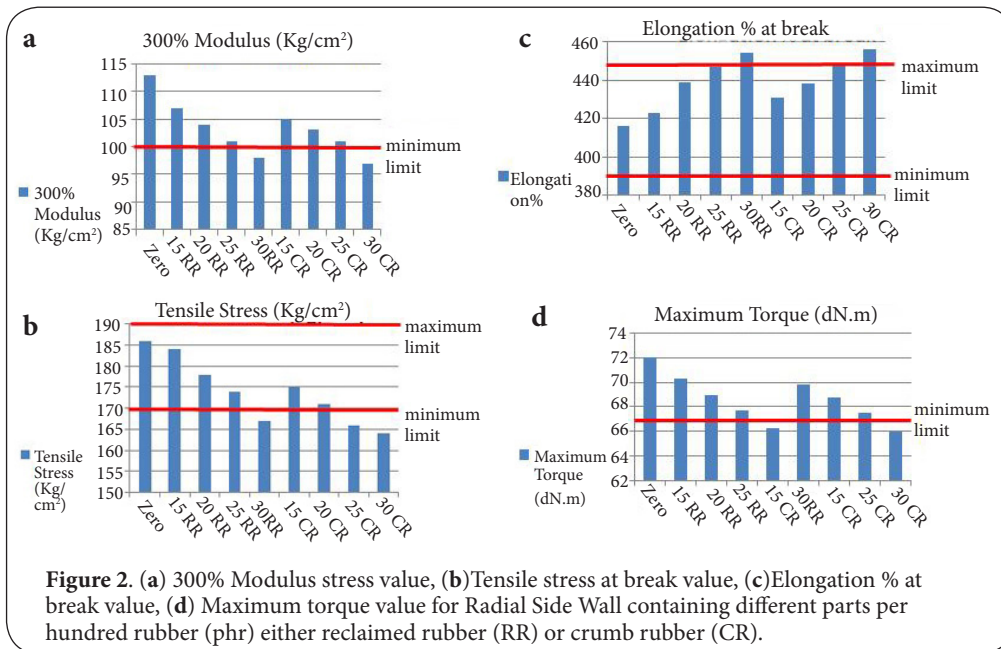


Figure 2. (a) 300% Modulus stress value, (b) Tensile stress at break value, (c) Elongation % at break value, (d) Maximum torque value for Radial Side Wall containing different parts per hundred rubber (phr) either reclaimed rubber (RR) or crumb rubber (CR).

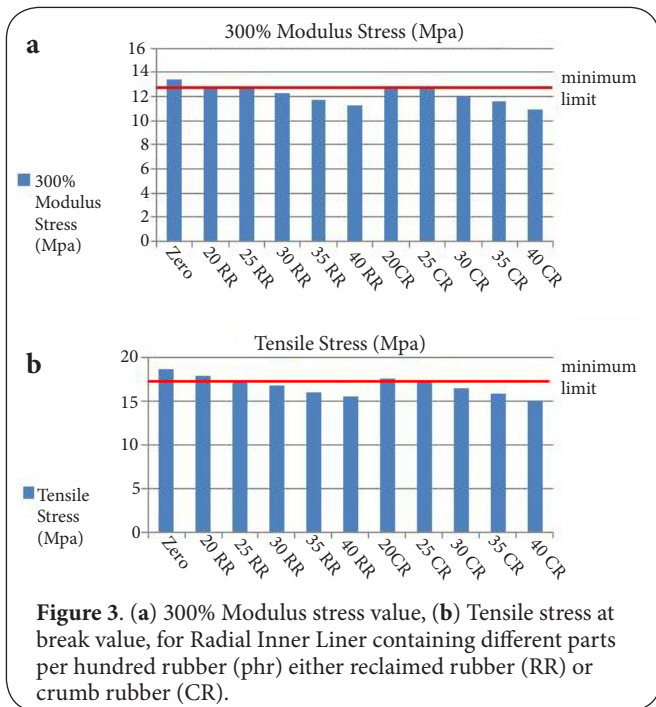


Figure 3. (a) 300% Modulus stress value, (b) Tensile stress at break value, for Radial Inner Liner containing different parts per hundred rubber (phr) either reclaimed rubber (RR) or crumb rubber (CR).

Polybutadiene and carbon black. This could lead to an annual saving of about 745,140 L.E (Table 5). Adding 25 phr reclaimed rubber to the side wall formulation would save about 12.8% of each of SMR, Polybutadiene and carbon black, leading to an annual saving of 205,349 L.E. Adding 25 phr reclaimed rubber to the inner liner formulation would save about 13% of each of SMR, SBR and carbon black, resulting in approximately 328,000 L.E. saving per year.

Second, regarding energy conservation, and as a result of raw material saving, use of reclaimed rubber in new tires would result in saving of the energy used to manufacture these raw materials, leading to a total energy conservation of 9593 GJ/year according to TRENCO production capacity (Table 6). On the other hand, the energy consumed for the production of reclaimed rubber is 32 GJ/ton [43]. By subtracting the energy used for the production of 100 tons reclaimed rubber (58.4 tons for tread, 18 tons for side wall and 23.2 tons for inner liner as shown in Table 4), total energy conservation resulting from reclaimed rubber recycling into new tires would equal 6393 GJ/year (9593GJ/y -3200 GJ/y).

Conclusion

End-of-life tires could be recycled into new tires. Reclaimed rubber could be used as 15 phr in radial tread compound and as 25 phr in either radial side wall or radial inner liner compounds. Crumb rubber could be used as 10, 20 and 25 phr in radial tread, radial side wall or radial inner liner compounds respectively. Incorporating higher amounts of either reclaimed or crumb rubber would lead to violating the standards specified in vulcanized rubber tension property test and in oscillating disk cure meter test. Savings in raw material and in energy resulting from the use of reclaimed rubber was calculated: As concerns raw materials, adding 15 phr reclaimed rubber to the tread formulation would save about 7.7% of each of Styrene Butadiene Rubber (SBR), Polybutadiene and carbon black. Adding 25 phr reclaimed rubber to the side wall formulation would save about 12.8% of each of natural rubber, Polybutadiene and carbon black. Adding 25 phr reclaimed rubber to the inner liner formulation would save about 13% of each of natural rubber, SBR and carbon black. Regarding

Table 4. Raw material conservation from reclaimed rubber (RR) recycling into new tires.

Manufactured compound (number of batches/year)	Name	Virgin raw material consumed						Saving in raw material	
		without RR			with RR				
		phr	Kg/batch	Kg/year	phr	Kg/batch	Kg/year	in Kg/year	as % raw material
Tread (3000)	SBR 1712	85.00	119.54	358620	85.00	110.34	331020	27600	7.70
	Polybutadiene	15.00	21.1	63300	15.00	19.47	58410	4890	7.73
	Carbon black	65.00	91.41	274230	65.00	84.38	253140	21090	7.69
	Others	14.90	20.95	62850	14.90	19.34	58020	--	--
	Reclaimed rubber	0.00	0	0	15.00	19.47	58410	--	--
	Total	179.90	253		194.90	253			
Side wall (600)	SMR 20	55.00	75.72	45432	55.00	66.04	39624	5808	12.78
	Polybutadiene	45.00	61.95	37170	45.00	54.04	32424	4746	12.77
	Carbon black	50.00	68.83	41298	50.00	60.04	36024	5274	12.77
	Others	20.70	28.5	17100	20.70	24.86	14916	--	--
	Reclaimed rubber	0.00	0	0	25.00	30.02	18012	--	--
	Total	170.70	235		195.70	235			
Inner liner (700)	SMR 20	70.00	106.48	74536	70.00	92.61	64827	9709	13.03
	SBR 1712	30.00	45.63	31941	30.00	39.69	27783	4158	13.02
	Carbon black	47.50	72.25	50575	47.50	62.85	43995	6580	13.01
	Others	19.48	29.63	20741	19.48	25.77	18039	--	--
	Reclaimed rubber	0.00	0	0	25.00	33.08	23156	--	--
	Total	166.98	254		191.98	254			

Table 5. Cost-Benefit analysis for the use of reclaimed rubber in new tire manufacturing.

Parts of the tire	Material	Saving in tons per year	Average price L.E. per ton	Annual saving L.E.
Radial tread	SBR 1712	27.60	15,000	414,000
	Polybutadiene	4.89	20,000	97,800
	Carbon black	21.09	15,000	316,350
	Others	4.83	7,000	33,810
	Reclaimed rubber	-58.41	2,000	-116,820
	Total			745,140
	Radial side wall	SMR 20	5.81	20,000
Polybutadiene		4.75	20,000	94,920
Carbon black		5.27	15,000	15,005
Others		2.18	7,000	15,288
Reclaimed rubber		-18.01	2,000	-36,024
Total				205,349
Radial inner liner	SMR 20	9.71	20,000	194,180
	SBR 1712	4.16	15,000	62,370
	Carbon black	6.58	15,000	98,700
	Others	2.71	7,000	18,963
	Reclaimed rubber	-23.16	2,000	-46,312
	Total			327,901

Table 6. Energy conservation from raw material saving resulting from reclaimed rubber recycling into new tires.

Raw material	Energy consumed for production (GJ/ton)	Saving in raw material (ton/year)*	Energy saved (GJ/year)
SMR	16 [44]	15.5	248
SBR	130 [45]	31.8	4134
Polybutadiene	108 [46]	9.6	1037
Carbon black	126.5 [47,48]	33	4174
Total			9593

*computed from Table 4 as follows:

- saving in SMR=5.8+9.7=15.5 tons
- saving in SBR=27.6+4.2=31.8 tons
- saving in Polybutadiene=4.9+4.7=9.6 tons
- saving in carbon black=21.1+5.3+6.6=33.0 tons

energy conservation, use of reclaimed rubber in new tires would result in a total energy conservation of 6393GJ/year. In addition to the raw material and energy conservation, the process was found to be cost-effective.

Competing interests

The authors declare that they have no competing interests

Authors' contributions

Authors' contributions	KMF	RAH	GAI	HME	ODE
Research concept and design	✓	✓	✓	✓	--
Collection and/or assembly of data	✓	--	--	--	--
Data analysis and interpretation	✓	✓	--	--	--
Writing the article	✓	✓	--	--	--
Critical revision of the article	✓	✓	✓	✓	✓
Final approval of article	✓	✓	✓	✓	✓
Statistical analysis	✓	✓	--	--	--

Acknowledgement

The authors would like to thank responsible persons in TRENCO that gave the permission for using the company pilot plant for performing the practical part of the present research.

Publication history

Senior Editor: Mallikarjuna Nadagouda, US Environmental Protection Agency, USA.

EIC: Robert Boyd Harrison, University of Washington, USA.

Received: 03-Sep-2014 Final Revised: 16-Oct-2014

Accepted: 24-Oct-2014 Published: 29-Oct-2014

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Citation:

Feriha KM, Hussein RA, Ismail GA, El-Naggar HM and El-Sebaie OD. **Feasibility study for end-of-life tire recycling in new tire production, Egypt.** *J Environ Eng Ecol Sci*. 2014; **3**:5.
<http://dx.doi.org/10.7243/2050-1323-3-5>