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ENVIRONMENTAL, ECONOMIC AND TECHNICAL ASSESSMENT OF RUBBER BLENDS WITH RECYCLED RUBBER

Abstract: *Nowadays, recycled and reclaimed rubber was used as a component in rubber blends in order to save natural resources and to solve the problem of waste rubber. The composition of those blends influences the properties of rubber product, but also the consumption of natural resource, complexity of the system for the rubber blends production and therefore the product price. In this paper, The Analytic Hierarchy Process method was applied to assess rubber blends from environmental, economic, and technical perspective. Different criteria were used for the analysis of: natural resources consumption, mechanical properties of rubber blends, complexity of production system, and product price. Three various types of rubber blends were taken into consideration: virgin rubber based on styrene butadiene rubber (SBR), virgin rubber and reclaimed rubber made from whole tire, virgin rubber filled with recycled rubber powder (RRP). The obtained results show that virgin rubber and reclaimed rubber made from whole tire are the best ranked in terms of all criteria.*

Key words: Rubber blends, natural recourses, recycled rubber, reclaimed rubber, Analytic Hierarchy Process.

INTRODUCTION

Intensive development of technology requires an increasing amount of energy and natural resources, in most cases, non-renewable natural resources: coal, crude oil, natural gas, mining, etc. More than 90% of crude oil is used to make fuels such as gasoline, home heating oil, jet fuel, and diesel oil. About 4% is used by the polymer industries directly as feedstock for plastics, rubber, and chemical products.

Nowadays, crude petroleum is vital to the rubber industry. All of the synthetic raw elastomers (such as Styrene Butadiene Rubber–SBR) and the vast majority of the rubber compounding ingredients are directly dependent on petroleum as a feedstock. It is by far the most critical natural raw material for successful rubber production and fabrication [1]. Without crude oil, there would be no rubber industry as we know it today. There would be only natural rubber (NR) for the rubber base, no rubber accelerators, no effective antioxidants, no furnace carbon black reinforcement, etc. [1,3]

The most common rubber product is a tire. Over 1 billion tires are produced in the world annually. Average passenger tire has a weight of about 8 kg which consists of 1.2 kg of natural rubber; 2.3 kg of synthetic rubber; 2.4 kg of additives and 2.1 kg of synthetic carcass and steel core [1].

For production of a new tire, 23 l of crude oil equivalent for raw materials and 9 l for process energy is required [2]. Also, in tire production, energy required for natural rubber production is 8 MJ/kg, for production of synthetic rubber 110 MJ/kg, for carbon black 125 MJ/kg, for all other additives 100 MJ/kg, for fabric 45 MJ/kg, and for steel tire cord 36 MJ/kg [4].

In order to reduce consumption of natural resources, primarily crude oil, and consumption of energy, there have been increased efforts to reduce their spending by using raw materials obtained from waste. Therefore, recycled rubber derivatives are increasingly used in the rubber industry.

There are many benefits from rubber recovery: recovered rubber can cost half that of natural or synthetic rubber, producing rubber from reclaim requires less energy in the total production process than does virgin material, it conserves non-renewable petroleum products, which are used to produce synthetic rubbers, recycling activities can generate new jobs in developing countries, production rubber product from recycled rubber saves greenhouse gasses emission, etc. [2].

Recycled and reclaimed rubber is used for civil engineering applications, and ground rubber applications [5]. There are great energy and natural resource savings in production of rubber products from recycled rubber. Average required process energy for production of rubber products from virgin materials is 81 MJ/kg, while for production of rubber products from recycled materials it is 4 MJ/kg [6]. Of course, mechanical properties of rubber blends made from recycled rubber were more or less changed depending on the share of recycled rubber in the rubber blends [7, 8].

In this paper the Analytic Hierarchy Process (AHP method) was applied to assess different rubber blends from environmental, economic, and technical perspective. Four criteria were used for analysis: natural resources consumption, complexity of production system, mechanical properties of rubber blends, and product price. Three various types of rubber blends were taken into consideration: virgin rubber based on styrene butadiene rubber (SBR), virgin rubber and reclaimed rubber made from whole tire, and virgin rubber filled with recycled rubber powder (RRP).

MATERIALS AND METHODS

The Analytic Hierarchy Process

Multi-criteria decision analysis (MCDA) techniques deal with the process of making decisions in the presence of multiple objectives. Those objectives are usually conflicting, and therefore, the solution is highly dependent on the preferences of the decision-maker and must be a compromise. The benefit of MCDA is that it allows the use of both qualitative and quantitative criteria. It also allows participation of different groups of decision-makers despite the opposing goals in defining indicators and decision-making.

One of the quite often used MCDA method is The Analytic Hierarchy Process (AHP). The AHP method is often used to solve complex decision making problems in: manufacturing industry, environmental management, waste management, power and energy industry, transportation industry, construction industry, etc. [9]. The AHP hierarchical structure allows decision makers to easily comprehend problems in terms of relevant criteria and sub-criteria. The decision procedure using the AHP method is made up of four steps [10]:

Step 1: the problem definition and determination the kind of knowledge sought;

Step 2: structure the decision hierarchy according to the goal of the decision – in the following order: the objectives, criteria in the intermediate levels, and set of the alternatives in the lowest level;

Step 3: construction of a set of pair-wise comparison matrices. Each element of the matrix in the upper level is used to compare elements in the level immediately below;

Step 4: utilization of the obtained priorities from the comparisons to weigh the priorities in the neighboring level. This process continues until the final priorities of the alternatives are obtained.

Pair-wise comparisons are used to determine the relative importance of each alternative in terms of each criterion. In order to make the pair wise comparisons, a scale indicating how many times more important, preferred or dominant one element is over another with respect to the parent element is required. This scale was introduced by Saaty [11].

Production and recycling of rubber blends

Rubber blends

In order to produce a rubber product from rubber blends, elastomer must be mixed with the ingredients as defined by the weight proportion (recipe) and after that cured. All ingredients that are added to the rubber compound intervene with rubber with the help of appropriate devices (roll mill or mixer) and become homogeneous blend called non-cured rubber [3,12]. The rubber blends consist of numbers of different components:

1. Elastomer: rubber (natural (NR) or syntetic (SBR, BR, IR, etc.)), recalimed rubber, devulcanized rubber.
2. Fillers (carbon black-N660, N330, N520, calcium carbonate, china clay, recycled rubber powder, etc.).
3. Vulcanization activators (ZnO, stearin, etc.).
4. Accelerators of vulcanization (TMDT, CBS, DMDT, Mercapto, etc.).
5. Antioxidants (TMQ, IPPD, BLE, etc.).
6. Softeners and plasticizers (rosin, oil, etc.).
7. Vulcanization retarders (DEG, Mercapto, etc.).
8. Funding for vulcanization (sulphur – S)
9. Ingredients for special purposes.

These uncured compounds are further processed through capital-intensive processes involving extruders, calendars, injection moulding machines, continuous vulcanization units, and curing presses.

Styrene Butadiene Rubber (SBR) – SBR is produced by the co-polymerization of butadiene with styrene in the approximate proportion of 3:1 by weight. Over 95% of butadiene is produced as a by-product of ethylene production from steam crackers. Both of them are derivatives of crude petroleum.

SBR is the largest volume synthetic rubber used by the rubber industry. By tonnage, SBR now represents over one-third of synthetic rubber production. Not only is SBR used in tire production, it is also used in the manufacture of conveyor belts, industrial hose, and footwear, to name a few uses. About 76% of SBR is used in tires, 15% in mechanical rubber goods, 5% in non-tire automotive, and about 4% in miscellaneous applications such as shoe soles, floor tiles, and adhesives [1].

Carbon black – Today most of the carbon black used in the rubber industry is from the furnace process, which gives a yield of 45 to 70% of theoretical carbon. About 10 million tons of furnace carbon black was produced worldwide in the year 2012, most of which was used by the rubber industry. Approximately 68% of this production is used by the tire industry, 22% goes into rubber industrial products, and 10% is used in non-rubber applications (including plastics, inks, and paints) [1].

Furnace carbon black is one of the most important compounding ingredients used in the rubber industry. It imparts such a profound improvement on cured rubber properties such as ultimate tensile strength, hardness, wear resistance, and tear resistance. Carbon black even improves the extrusion process by making the extruded rubber product smoother in appearance. By using carbon black with process oil, the rubber compound "pound volume" costs can be significantly reduced. Furnace carbon black is produced from the incomplete combustion of what is called "carbon black oil feedstock," which consists of heavy aromatic residue oils. The production of furnace carbon black is performed through the incomplete combustion of a spray of liquid oil feedstock into a mixture of natural gas and preheated air in a specially built refractory furnace at 1200 to 1600 °C [1].

Recycled rubber powder – Grinding (size reduction) is the preferred recycling route for waste tires being associated with obvious economic and social benefits. Downsizing waste tires is a technologically complicated process. It requires special machinery and equipment capable of shredding and granulating waste tires which possesses complex structure and high mechanical properties. To convert the whole tire into recycled rubber powder the related technology comprises the following steps: shredding, separation (steel, textile), granulation, and classification. Ambient grinding is usually practiced in two-roll cracker-type mill. Though termed ''ambient'' the temperature may rise up to 130 °C during milling [13-15].

Reclaimed powder – Production of reclaimed rubber required more complex technology than production of recycled rubber powder. In the rubber recycling process by the conventional pan method, finely ground rubber powder (made from whole tire or tread) mixed with oils and reagents is heated with steam in a pressure vessel at a temperature of ~200°C for more than 5 h. Moreover, usually this process has to be followed by several procedures (refining and straining) before obtaining the final reclaimed rubber. As noted above, the reclaimed rubber obtained by this method is inferior in quality to virgin rubber. This is due to the occurrence of unselective breakage of both the cross-linking points and main chain (C-C) bonds in the rubber [13,16].

EXPERIMENTAL RESEARCH

In order to assess rubber blends with environmental, economic and technical aspects three rubber blends were developed, and assessed in terms of criteria. Four criteria were used for analysis: natural resources consumption, mechanical properties of rubber blends, complexity of production system, and product price.

Alternatives of rubber blends

For the purposes of this study the developed alternatives of rubber blends were based on SBR. These blends are used for rubber sealing products, exposed to a relatively low pressure, and low concentrations of organic acids and alcohols. The required mechanical properties of such blends are: hardness 70±5 Sh A; tensile strength 3,20±0,60 MPa; resistance to wear 450±90 mm^3/g; compression set 40±5 %.

The developed alternatives of rubber blends are presented below.

Rubber blend 1 – virgin rubber based on styrene butadiene rubber (SBR): Rubber blend 1 is made only on SBR based. In this study Rubber blend 1 presents etalon blend.

Rubber blend 2 – virgin rubber and reclaimed rubber made from whole tire: In Rubber blend 2 amount of SBR was decreased for 30% and amount of carbon black (N660) was also decreased for around 75%. Instead of these ingredients, reclaimed rubber made from whole tire (Reclaimed rubber I) was added.

Rubber blend 3 – virgin rubber filled with recycled rubber powder (RRP): In Rubber blend 4 amount of SBR was little increased for 10%, while amount of carbon black (N660) was decreased for around 75%, and rubber blend was filled 20% of SBR weight with recycled rubber powder.

Table 1. *Recipes of alternatives of rubber blends*

Ingredients (g)	Rubber blend 1	Rubber blend 2	Rubber blend 3
SBR 1502	290.00	205.00	320.00
Reclaimed rubber I	-	233.00	-
Recycled rubber powder	-	-	64.00
Stearin	3.00	5.00	4.50
ZnO	14.50	13.00	16.00
TMQ	4.00	4.20	3.50
N660	200.00	42.00	50.00
Calcium carbonate	206.00	312.00	283.00
China clay	195.00	170.00	230.00
Oil	115.00	35.00	40.00
Mercapto	6.30	8.70	9.60
TMTD	3.00	1.00	3.20
DEG	4.50		3.70
Sulfur	8.90	9.10	10.50
Rosin		12.00	12.00
Total	**1,050.20**	**1,050.00**	**1,049.50**

Criteria selection and evaluation

The selection of criteria is carried out to enable the assessment of rubber blends with the environmental, economic and technical aspects. Natural resource consumption was selected as environmental criterion, product price was selected as economic criterion, and mechanical properties of rubber blends and complexity of production system were selected as technical criteria.

Natural resources consumption – As previously outlined for the production of rubber blends and its components consume natural resources, and mostly non-renewable, such as fossil fuels. Coal is often used for electricity generation, crude oil and natural gas for the production of SBR, and other components in the rubber compound (carbon black). Those natural resources could be saved adding reclaimed rubber and recycled rubber powder into rubber blends. For the purposes of this paper, savings of natural resources is calculated based on the amount of SBR and carbon black that has been replaced with reclaimed rubber or recycled rubber powder. It was assumed that for the production of the etalon blend (Rubber blend 1), consumption of natural resources is 100%.

Mechanical properties of rubber blends – As mechanical properties of rubber blends are considered: hardness, tensile strength, elongation at break, wear, and compression set.

For this study blends were mixed in a laboratory-size mixer with a rotor speed of 50 rpm at a set temperature of 60 °C and the mixing period of 6 min. Hardness measurements were performed in accordance with ISO 7691-1, using a manual Shore durometer type A. The determination of tensile strength and elongation at break was carried out in accordance with ISO 37 on dumbbell specimen type "2". Wear resistance was performed in accordance with ISO 4649 using a Shopper cylindrical device. Compression set testing was performed according ISO 815 [17-19]. Table 2 presents results of measurement of mechanical properties of alternative rubber blends.

Table 2. *Mechanical properties of alternatives of rubber blends*

Mechanical properties	Rubber blend 1	Rubber blend 2	Rubber blend 3
Hardness (Sh A)	70	68	67
Tensile strength (MPa)	3.50	3.15	3.15
Elongation at break (%)	200	180	160
Wear (mm^3/g)	450	495	500
Compression set (%)	40	35	38

The results of those mechanical properties were agglomerated in one criterion, and 9-level scale established in the AHP method [10] (1 - Worst, 9 - Best) was used for the assessment of this criterion.

Complexity of production system – Based on the above described technology for the production of SBR, carbon black, recycled and reclaimed rubber, the complexity of production of developed alternatives of rubber blends was assessed. For the purpose of this study complexity of production system of etalon blend (Rubber blend 1) was taken as 100%.

Product price – Criterion Product price was calculated based on the current market price of components and their share in the considered rubber blends.

Table 3 presents the values of selected environmental, economic, and technical criteria.

Table 3. *Calculated values of selected environmental, economic, and technical criteria.*

Criteria	Rubber blend 1	Rubber blend 2	Rubber blend 3
Natural resources consumption (%)	100.00	70.00	90.00
Mechanical properties of rubber blends	9	7	6
Complexity of production system (%)	100.00	130.00	70.00
Product price (€/kg)	0.795	0.649	0.702

The hierarchical structure

According to the AHP procedure, the hierarchical structure is constructed. Figure 1 shows the hierarchical structure considered in the selection of a rubber blends, based on selected criteria.

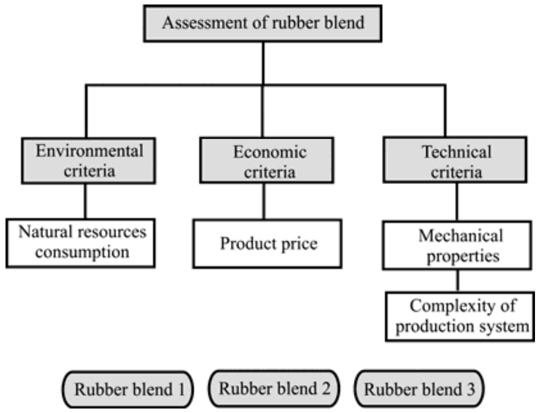

Figure 1. *The hierarchical structure for selection of rubber blends*

RESULTS AND DISCUSSION

In order to assess rubber blends, the procedure of AHP method was used. Following the pair-wise criteria, the criteria weight with respect to the goal: assessment of rubber blends was obtained. As mention above, the highest priority is given to natural resource consumption. The obtained results show that Rubber blend 2 (virgin rubber and reclaimed rubber made from whole tire) is best ranked in terms of all criteria with ranking priority of 51.8% (Figure 2), because the biggest savings of natural resources and a minimal product price.

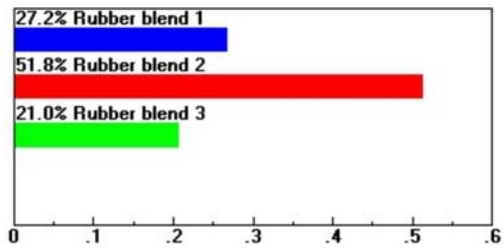

Figure 2. *Scenario ranking for evaluated indicators weight*

4.1. Sensitivity analysis

The last step of the decision process of the AHP method is the sensitivity analysis, where the input data of criteria weighting are slightly modified in order to observe their impact on the results. If the ranking of alternatives does not change, the results are said to be robust [20]. The sensitivity analysis was performed to assess the influence of individual criteria to the alternatives of rubber blends.

A sensitivity analysis was performed for borderline cases criteria weighting, because of subjectivity of the pair-wise comparison of criteria. The following cases were examined:

- Case 1: All criteria have an equal weighting factor of 25%.
- Case 2: Technical criteria Mechanical properties of rubber blends and Complexity of production system have a weighting factor of 70%, while others have a weighting factor of 30%.
- Case 3: Criteria Natural resource consumption and Mechanical properties of rubber blends have a weighting factor of 70%, while others have a weighting factor of 30%.
- Case 4: Criteria Mechanical properties and Product price have a weighting factor of 70%, while others have a weighting factor of 30%.
- Case 5: Criteria Natural resource consumption and Product price have a weighting factor of 70%, while others have a weighting factor of 30%.

Results obtained by sensitivity analysis are presented in Fig. 3. In the Case 1 when all criteria have an equal weighting factor, Rubber blend 2 ranked the first with priority ranking of 40.30%. The same results were obtained in Cases 3, 4 and 5: Rubber blend 2 ranked the first. Only in the Case 2 when technical criteria Mechanical properties of rubber blends and Complexity of production system have a weighting factor of 70%, Rubber blend 1 ranked the first with priority ranking of 35.40% because of lower level of complexity of production system and the best mechanical properties of the rubber blend.

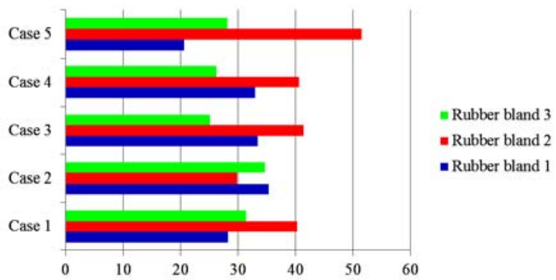

Figure 3. *Results of sensitivity analysis*

The main findings of the above sensitivity analysis are:

1. Rubber blend 2 (virgin rubber and reclaimed rubber made from whole tire) is the most stable solution under whatever criteria weighting. Moreover, it ranks first under equal criteria weighting and when priority is given to the group of criteria, whether they are environmental, or economic.

2. Rubber blend 1 (virgin rubber based on SBR) ranked the first in case when priority was given to technical criteria.

3. Rubber blend 3 (virgin rubber filled with recycled rubber powder) is never ranked first in any criteria weighting.

CONCLUSION

The production of rubber blends is highly dependent of non-renewable natural and energy resources. In order to reduce consumption of natural and energy resources, there have been increased efforts to reduce their spending by using waste raw materials obtained from waste. For that reason, recycled rubber derivatives are used as raw materials in rubber production.

In order to assess rubber blends from environmental, economic and technical aspects, we applied the Analytic Hierarchy Process. Assessment of rubber blends was done with special attention to consumption of natural resource, because the production price and mechanical characteristics of the product are no longer the primary criteria, due to rapid consumption of non-renewable natural resources in the rubber production.

Three various types of rubber blends were taken into consideration: virgin rubber based on styrene butadiene rubber, virgin rubber with reclaimed rubber made from whole tire, and virgin rubber filled with recycled rubber powder. We used four different criteria for the analysis: as environmental criteria - natural resources consumption, as economic – product price, and as technical – mechanical properties of rubber blends and complexity of production system.

The obtained results show that the best ranking alternative is Rubber blend 2 (virgin rubber and reclaimed rubber made from whole tire) with priority ranking of 51.80%. Conducted sensitivity analysis also showed that in 80% of cases Rubber blend 2 ranked the first, while Rubber blend 1 (virgin rubber based on styrene butadiene rubber) ranked the first in case when priority was given to technical criteria.

From the obtained results it can be concluded that in case of rubber products which do not require a material with exceptional mechanical characteristics, it is economically and environmentally justifiable to use recycled rubber derivatives in rubber blends.

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BIOGRAPHY

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OCENA GUMENIH SMEŠA SA RECIKLIRANOM GUMOM SA EKONOMSKOG, TEHNIČKOG I ASPEKTA ŽIVOTNE SREDINE

Petar Đekić, Goran Radenković, Biljana Milutinović, Gordana Stefanović

Apstrakt: *Danas se, u cilju uštede prirodnih resursa i rešavanja problema otpadne gume. kao komponenta u gumenim smešama sve češće koristi reciklirani gumeni prah, kao i regenerat. Sastav tih smeša utiče na svojstva proizvoda od gume, ali i potrošnju prirodnog resursa, složenost sistema za proizvodnju gume, a samim tim i cenu proizvoda. U ovom radu predstavljena je analiza različitih gumenih smeša sa tehničkog, ekonomskog i aspekta životne sredine. Analiza je izvršena korišćenjem metode analitičkog hijerarhijskog procesa. Za analizu su korišćena četiri kriterijuma: potrošnja prirodnih resursa, mehanička svojstva gumenih smeša, složenost sistema proizvodnje i cena proizvoda. Za potrebe ovog istraživanja razvijene su tri različite vrste gumenih smeša: smeša na bazi stiren butadien kaučuka, smeša na bazi stiren butadien kaučuka i regenerata dobijenog od celog pneumatika i smeša na bazi stiren butadien kaučuka punjena recikliranim gumenim prahom. Dobijeni rezultati pokazuju da je smeša na bazi stiren butadien kaučuka i regenerata dobijenog od celog pneumatika najbolje rangirana u pogledu svih kriterijuma.*

Ključne reči: Gumene smeše, prirodni resursi, reciklirana guma, regenerat, metoda analitičkog hijerarhijskog procesa.