UNIVERSITI PUTRA MALAYSIA

EFFECTS OF PARTICLE SIZE AND WEIGHT PERCENTAGE OF WASTE RUBBER CRUMBS ON THE PERFORMANCE OF COMPOUNDED TYRES

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By

ADNAN ABBAS ABDULNABI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to:

The sake of Allah, my Creator and my Master,

My great teacher and messenger, Mohammed (May Allah bless and grant him and his family),

My humble effort I dedicate to my sweet and loving

Wife (Intedar)

I am grateful to her support ….

To my daughter (Dalia) and son (Redah)

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the Degree of Doctor of Philosophy

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By

ADNAN ABBAS ABDULNABI

February 2018

Chairman : Faieza Abdul Aziz, PhD
Faculty : Engineering

The problem of waste tyre disposal has become a seroius global issue as it has affected not only ecnomy, but also ecology of nations. As such, recycling provieded a powerful solution for the incresing of worn out tyres dumped into the landfills. At current, the recycled rubber produced still has vulcanized rubber structure and low blending ability with the virgin matrix composites. This behaviour limited the scope of engineering applications which could potentially involved recycled rubber material. The aim of this research was to study the effects of waste rubber modification such as size reduction on the manufacturing process of the tread of the passenger tyre. The study followed by construction of finite element code to predict the static and dynamic effects of the tyre material design and modification. Lastly, an empirical model was established to describe the effect of waste crumb rubber incorporation in tyre tread blend. In achieving the first objective Crumb Rubber (CR) modification was investigated, which was the size reduction method. A CR from ambient grinding of the ground tyre was used after it had been subjected to sieve analysis to produce six size categories of 40 μm, 150 μm, 180 μm, 250 μm, 425 μm and 600 μm. Each category was incorporated in different fractions 20 phr, 40 phr and 60 phr (10, 20, 30 wt.%) as a filler in a virgin styrene butadiene rubber (SBR) matrix to examine the effect of CR loading on the properties of the blends produced. The results revealed that the mechanical and curing properties of the tread blend had improved as the CR particle size reduced, with all of the mechanical and rheological

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properties reduction in a different manner when the CR content increased. The study revealed that the size reduction of CR could enhance the tensile strength up to 35%, and 17% for elongation at break for the finer size. To study the dynamic behavior of the tyre containing such modifyed CR, a finite element model based on Abaqus software was built as the second objective of the study. The model was used to study the effects of different particle size and content of CR on the traction, braking and slipping condition of the tyre. The parameters such as reaction force (rolling resistance), reaction moment, and pressure at footprint, stress, strain and strain energy were studied to figure out the complete behavior of the tyre at different tread properties. Finally, empirical models for tensile strength as a function of particle size and content of CR were built. Particle swarm optimization (PSO), and response surface method (RSM) based on design expert software were used. The results showed that both models have good accuracy in predicting the response, however the RSM model provided more accurate results. The statistical analysis confirmed that the effect of particle size was greater than the effect of content of CR on tensile strength of the tread.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN SAIZ ZARAH DAN PERATUSAN BERAT SISA SERBUK GETAH KE ATAS PRESTASI TAYAR BERKOMPAUN

Oleh

ADNAN ABBAS ABDULNABI

Februari 2018

Pengerusi : Faieza Abdul Aziz, PhD
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Kebelakangan ini, isu berkaitan pelupusan tayar sisa menjadi isu global yang semakin serius, ianya bukan sahaja menjejaskan ekonomi, bahkan ekologi sesebuah negara. Oleh yang demikian, kitar semula merupakan penyelesaian yang utama dalam menangani masalah pertambahan tayar buangan di tapak pelupusan. Pada masa kini, getah kitar semula yang dihasilkan masih mempunyai struktur getah tervulkan dan keupayaan penggabungan yang rendah dengan komposit matriks asli. Sifat ini menghadkan lagi bidang aplikasi kejuruteraan yang membabitkan penggunaan bahan getah kitar semula. Tujuan kajian ini adalah untuk mengkaji kesan pengubahsuaian sisa getah seperti pengurangan saiz pada proses pembuatan ke atas bunga tayar penumpang. Diikuti dengan penghasilan kod elemen tetap untuk menetukan kesan statik dan dinamik dalam reka bentuk dan pengubahsuaian bahan tayar. Dalam mencapai objektif pertama, pengubahsuaian serbuk getah (CR) telah disiasat, yang merupakan kaedah pengurangan saiz. CR dari pengisaran permukaan tayar selepas menjalani analisis ayak digunakan untuk menghasilkan enam kategori saiz 40, 150, 180, 250, 425, dan 600 μm. Kemudian, setiap kategori dicampurkan ke dalam pelbagai campuran dengan 20, 40 dan 60 phr (10, 20, 30 peratusan berat) sebagai pengisi dalam matriks getah asli stirena butadiena (SBR) untuk mengkaji kesan penambahan CR terhadap sifat-sifat campuran yang terhasil. Keputusan menunjukkan bahawa sifat mekanikal dan sifat pengawetan bagi campuran tayar bertambah baik apabila saiz zarah CR berkurang, dengan semua pengurangan sifat mekanikal dan reologi dengan cara yang berbeza apabila kandungan

CR meningkat. Tambahan lagi, pengurangan saiz CR dapat meningkatkan kekuatan regangan sehingga 35% dan pemanjangan pada takat patah sebanyak 17% untuk saiz yang lebih halus. Model elemen tetap berdasarkan perisian Abaqus dibina untuk menyiasat kesan pengubahsuaian tayar bunga terhadap sifat dinamik tayar. Model ini digunakan untuk mengkaji kesan saiz zarah yang berbeza dan kandungan CR pada daya tarikan, cengkaman dan gelinciran tayar. Parameter yang dikaji adalah seperti daya tindak balas (rintangan putaran), momen tindak balas, tekanan cetakan, tekanan, tegangan dan daya tegangan untuk mengetahui sifat-sifat keseluruhan tayar pada komposisi yang berlainan. Akhirnya, model empirikal untuk kekuatan tegangan sebagai fungsi untuk saiz zarah dan kandungan CR dibina. Kumpulan zarah optimum (PSO) dan kaedah tindakbalas permukaan (RSM) berdasarkan perisian pakar reka bentuk telah digunakan. Keputusan menunjukkan bahawa kedua-dua model mempunyai ketepatan yang baik dalam meramal tindak balas, namun begitu model RSM menunjukkan keputusan yang kurang tepat. Analisis statistik mengesahkan kesan saiz zarah adalah lebih besar daripada kesan kandungan CR terhadap kekutan regangan tapak. Bagi kaedah eksperimen terdahulu yang berkos tinggi.

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I would like to dedicate this thesis to the memory of my parents who paved the path of knowledge upon their shoulders before I became who I am now. Priceless gratitude to my wife, Intedar for her great sacrifices, understanding and patience throughout the whole of our life together, which has made this study possible. Thanks to my lovely children who have also given a lot of moral support and encouragement for the whole duration of study in Malaysia.

Adnan Abbas Alshukr

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I certify that a Thesis Examination Committee has met on 13 February 2018 to conduct the final examination of Adnan Abbas Abdulnabi on his thesis entitled "Effects of Particle Size and Weight Percentage of Waste Rubber Crumbs on the Performance of Compounded Tyres" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

6PPD	Permanax
ACOH	Glacial Acetic Acid
ASTM	American Society For Testing And Materials
C_{ij}	Rivlin coefficient
D_i	Material Compressibility
CBS	N-Cyclhexyle-2-Benzothiazyl Sulphenamide
CR	Crumb Rubber
CRI	Cure Rate Index
CTP-100	Phthalimide
DOE	Design of Experiment
DR	Devulcanized Rubber
ELT	End of Life Tyre
EPDM	Ethylene Propylene Diene Monomer
ETRMA	European Tyre & Rubber Manufacturers Association
GTR	Ground Tyre Rubber
LLDPE	Linear Low-Density Polyethylene
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MH	Maximum Torque
ML	Minimum Torque,
PSO	Particle Swarm Optimization
R	The universal gas constant
RMSE	Root Mean Square Error
RSM	Response Surface Method
SBR	Styrene Butadiene Rubber
T	The thermodynamic temperature
TCA	Trichloroacetic Acid
TMQ	Flectol
Tol	Toluene

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LIST OF NOMENCLATURES

C_{ij}	Rivlin coefficient
D_i	Material Compressibility
G	Shear modulus
I	Principal strain Invariance
ts_2	Scorch Time
ts_{90}	Curing Time
υ_x	Tyre Rolling Longitudinal Velocity
υ_y	Tyre Cornering Velocity
V_e	Cross link density
W	Elastic Strain Energy Density
wt	Crumb Rubber Content
λ	Principal Stretch Ratios
σ	Stress
σt	Tensile Strength
σ_U	Uniaxial Nominal Stress
ω	Angular Velocity
ε	Strain

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the new global ecology, the problem of waste tyres has become a central issue. Millions of worn out tyres are being thrown in the tyre graveyards every year all over the world. The worldwide number of waste tyres in storage has exceeded three billion [1]. According to a previous estimation, around 800 million of scrap tyres have been disposed of all around the globe. This amount is expected to increase by approximately two percent each year [2]. The waste tyre stockpiles growing has been attributed to the tremendous increased rate of tyers production, which had reached 1.72 billion units at the end of 2015 according to the statistics from the global industry analysis [3]. Tyers are highly engineered and have three-dimensional chemical network constructed from many dissimilar materials. Rubber (natural or synthetic) represents the matrix of the tyres composite structure, which makes up the biggest component used in tyres manufacturing as shown in Table 1.1.

Table 1.1 : Major composition of material used in tier manufacturing [3]

Ingredient	Car/passenger	Truck	Other
Rubber	47%	45%	47%
Carbon black	21.5%	22%	22%
Metal/ steel	16.5%	25%	12%
Textile	5.5%	0%	10%
Zinc Oxide	1%	2%	2%
Sulphr	1%	1%	1%
Additives	7.5	5%	6%

The rubber stabilizer materials, such as antioxidants, antiozonants and other additives present in the tyre manufacturing process lead to producing high cross-linked chemical structures rubber that is required to overcome the different operating conditions. These structures cause the waste tyre to be a non-biodegradable and non-environmentally friendly material [4]. The landfilling and mono filling were the common earlier ways of tyre disposal over the world, for example the United States and Europe reclaimed just about one-fifth of rubber hydrocarbon used at the end of the 1950s and most of the

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end of life tyers (ELT) were discarded in landfills [5]. This method of tyre disposal is undesirable because of the following reasons:

- The probability of contaminating the surrounding soil due to tyre additives leaching
- Represents negative added value because of implicit cost of transportation of tyres to the landfill sites and maintenance of the landfills to satisfy the environmental requirement.
- Tyre shape and permeability produce a long time water holding which provides sites for rodents, snakes and insects breeding [6].
- The amount of rubber and other metal contents present in the ELT makes the landfilling process represents a disposal of valuable materials.
- The landfilled ELT tyres possess fire threat danger which is difficult to be extinguished [7].

Therefore, recycling and recovering of ELT is the best economical and ecological solution to the tyre disposal problem. Recently, legislation has driven the tyre section toward recycling and recovery. The issue of ELT treatment has received considerable critical attention during the last decade. The rate of treatment has increased rapidly as the environmental awareness has increased. A series of law and regulations have been implemented from 48 states to govern the collection, handling and disposal of the ELT [8]. As so, the rate of ELT treatment had increased from 10 percent to 80 percent during the period from 1990-2012 for the United State of America, while Europe had reported being the highest in the world at the end of 2012, by transferring around 95 percent of ELT to be recycled and recovered into materials as shown in Figure 1.1[9].

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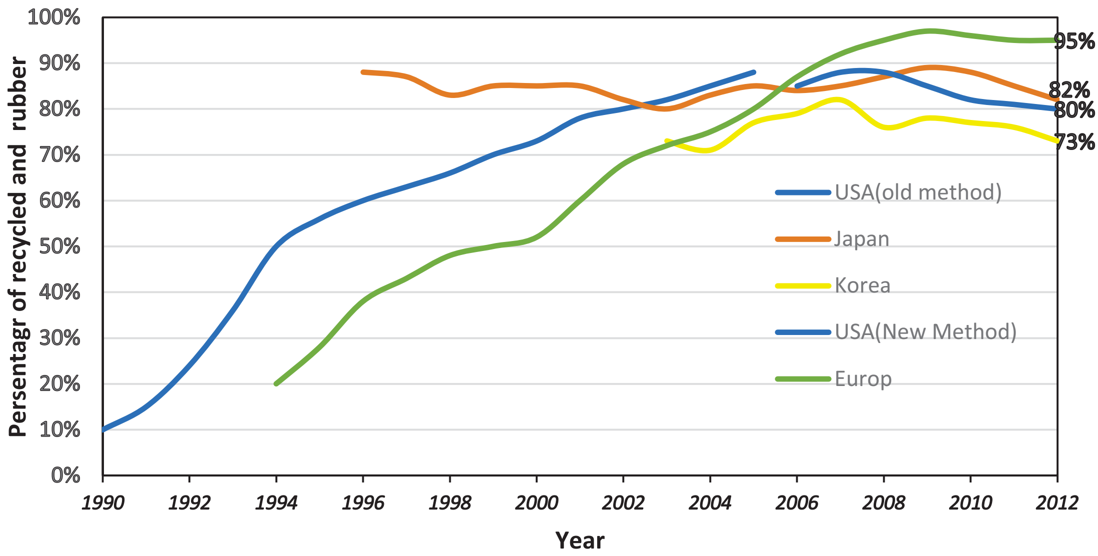

Figure 1.1 : The percentage of recycled and recovered tyres relative to the ELT [9]

According to the report published by the European Tyre & Rubber Manufacturers Association (ETRMA) in EU member states, Norway, Switzerland and Turkey [10], around 3.868 million tons of used tyres were generated in 2015. After sending 678 thousand tons for reuse, export and retreading, 3.190 million tons of ELT were sent to the recovery and recycling. The rate of recovery estimated was 92 percent, which represents one of the highest rates in recovery and recycling of ELT in the world.

It is evident from this report that, there is a global concern and urgency to minimize the amount of landfill tyres to its lowest and manageable level and moved towards a zero-waste scenario. This level had already been reached in most of the Europe states, but some efforts remained to be done through the development of the current recycling methods and find new techniques to utilize the produced recycled rubber in a different application. Although, around 50 percent of waste rubber are recycled and converted to ground rubber to use as raw materials for many applications, like civil engineering projects, new tyre production and many other rubber base applications, there is still, according to the ETRMA report [10], about 35 percent of waste tyres are used as fuel. This is harmful to the environment and this material needs to be converted for reuse or recycle, instead of using it as fuel in support of sustainability. This effort requires continuous research and developments to innovate new devulcanization and reclaiming methods in order to strategically manage and incorporate the use of crumb rubber (CR) in current applications as well as finding new engineering applications.

High-energy irradiation offers unique solutions to the problem of recycling due to its ability to induce crosslinking or scission of a wide range of material without introducing any chemical initiators. This method can possess a significant economical and ecological advantage as compared to the conventional chemical, thermal and mechanical methods which may cause many drawbacks like, noxious fumes emission, by-products peroxide degradation and high energy consumption. The three main possibilities for the use of radiation in this application are:

- Enhancing the mechanical properties and performance of recovered materials or material blends, principally through crosslinking, or through surface modification of different phases being combined.
- Treatment causing or enhancing the decomposition of polymers, particularly through chain scission, leading to the recovery of either low molecular weight mixtures, or powders, for use as chemical feedstock or additives.
- Production of advanced polymeric materials designed for environmental compatibility.

Therefore, irradiation represents an attractive solution to the problem of recycling of waste rubber in polymer composite field.

The use of numerical analysis techniques as the finite element method (FEM) has become quite a convenient and powerful tool in mechanical engineering, particularly for product design and development. Also in tyre researches, the determination of the main trends and designs is performed by means of numerical simulations and comparative evaluations. The most crucial aspect of a tyre simulation is the realistic description of the processes in the contact interface between the tyre's tread and the road surface. The frictional behaviour of this interface controls the performance of the tyre not only locally, but also globally. As such, the FEM can play a major role in tyre structural and material design process through its ability to simulate the static and dynamic performance of the tyre in different working condition.

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1.2 Problem Statement:

Every year the amount of worn out tyres are increasing over the world, however the development of the recycling process does not keep up at the same rate. Most of the recycling factories are facing real commercial problems, due to lack and limit of its products applications.

Crumb rubber is the main final product of recycling rubber factories. The main function that decides the ability of any filler to be incorporated for certain application is the active surface area[11]. This area represents the trend of filler to create crosslink with matrix materials. In general, crumb rubber has low ability to build a suitable bond with any other material, because of the strong sulphidic and carbon molecular bonds. Several surface treatments have been developed in targeting to reactivate crumb rubber surface area. The chemical activation process comprises of grafting, swelling, halogenation and addition of polymer or curing system, are examples of using chemical reaction in surface modification of CR. In addition to the chemical process, there are other numerous methods based on their physical activation such as microbial treatment and superficial devulcanization [12]. Nevertheless, all of the above methods are costly and by incorporating the process will affect the recycling factories economically.

One of the most important usages of CR is being a filler as a replacement of expensive virgin rubber matrix, this phenomenon is used in tyre tread blend as a part of manufacturing of passenger and truck tyres. The amount of CR used in this blend does not exceed 10 percent of overall weighted percentage according to the manufacturing documents of Dunlop [13]. Cheap and active methods of CR modification may lead to an increase in the amount of costless CR against high-cost virgin rubber in tread tyre blend and in other virgin polymer matrix. In addition, the allowable limit of CR particle size and content in tread compound is an important issue. However, there is lack of literature on the effect of using the particle size and content that can be incorporated in the tread of the passenger tyre.

Changing the amount of any material in tyre blends recipes are costly and time-consuming procedure. This process passing through series of activities and steps comprise internal and external tests equipment to predict the influence of this change or design in the final performance of the tyre. The other way to avoid this problem is by importing new technology from one of the tyre knowhow companies,

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which is very expensive and almost not flexible solution. The finite element code may provide a feasible improvement to the process of testing the new material design, if it is accompanied with basic laboratory mechanical test for the new design. The most crucial aspect of tyre simulation is the realistic description of the process in the contact interface between the tyre tread and road surface [14]. The dynamic behaviours of the tyres represent further challenging because it depends on many factors, such as tyre type (radial or bias-ply), tyre structure (geometry, reinforcement and tread pattern), loading condition (inflation pressure and wheel load), tyre rolling condition (traction, free rolling , braking and cornering). As such, a suitable and accurate finite element model would provide significant benefits to show the comparative interface under various tyre loading conditions [15].

In summary, the problem statements of this work can be summarized as follow:

1. The waste tyres represent a serious ecological problem and negative added cost which needs extensive support to address.
2. The existence of strong sulphidic and carbon molecular bonds causes the limit applications of crumb rubber.
3. Limited amount of cheap crumb rubber (10% of tread layer weight) is used to replace the expensive virgin rubber in tyres manufacturing application.
4. The reclaiming and devulcanizing methods needed to recycle the waste rubber are costly methods, as such there is a need to develop the current method by introducing new cost effective methods.
5. There is a need to draw a complete perception to the effect of using the particle size and content that can be used in the tread of the passenger tyre.
6. The assessment process for a new design of a tire material by using the traditional experimental methods is difficult and expensive efforts.

1.3 Objectives

The primary aim of this study is to determine experimentally the effect of crumb rubber modification on the rubber blend through one of its important application “tyre tread” as a contribution to increase its content in the tread recipe to achieve goals of reducing consumption of natural resources and supporting waste tyres recovery process, which represents eco-friendly activity. The particular objectives of this work are:

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1. To investigate the effect of CR modification such as particle size and content of waste rubber crumb on the passenger tyre tread composite material.
2. To analyze the dynamic performance of a passenger tyre tread compounded with waste rubber crumb.
3. To develop particle swarm optimization and response surface method models for the tensile strength of tyre tread containing specific particle size and weight of waste rubber crumb.

1.4 Scope of Study

This study focuses on determining of new method of modification of CR. This process, which represents the first objective, may lead to an increase in the CR loading amount in a compound recipe without affecting the final properties of the composite. The CR was incorporated in the recipe of passenger tyre tread, which has been chosen as the application to find the efficiency of the process. In this investigation, six sizs (40, 150, 180, 250, 425 and 600) µm of CR particle size was incorporated with CR loading of 10, 20 and 30 weight percentage of the total blend recipe for each category. The mechanical and rheological study for each particle size and content was performed to find the trend of each parameter. For the second objective, a finite element model of passenger tyre based on Abaqus package was built to predict the static and dynamic performance of the tyre containing the modified tread material. The material properties of the model are based on data extracted in the laboratory to analyze its performance when it becomes part of a real tyre structure. Finally, a numerical model for tensile strength of the tread compound was built. The model is created based on the data extracted from the first object by using two different methods, particle swarm algorithm and response surface method.

1.5 Thesis Outline

This research consists of five chapters:

Chapter 1: This chapter presents a brief background on the field of waste tyre problems and recycling challenges. The chapter describes the importance of finding new reclaiming and surface activation methods for end of life tyres to ensure sustainability for the future. In addition, the research problem was highlighted and the objective of research was defined within the boundary of this work.

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Chapter 2: This chapter contains reviews of the available literature on the methods used to recycle waste tyres with emphasize on the recovery of rubber material and a brief discussion of methods used to activate and modify the CR with detailed discussion in irradiation and size reduction methods, which are the methods used in this study. This chapter also provides a literature review on the available researches in the field of tyre analysis and the main constitutive equations used to describe the hyperplastic materials.

Chapter 3: In this chapter, an elaborate discussion regarding the materials specifications, characterizations, mechanical and rheological assessment details will be covered, in addition to the process and condition of blends preparation method. This chapter also contains a detailed description of the special techniques that were carried out to build the finite element model of the passenger tyre. This part of methodology provides the Abaqus code details and boundary conditions for each step of the solution. Finally, the process of creating an empirical model for the tensile strength of the tread was described. The model was built by using the numerical algorithm based method, which is particle swarm optimization method and mathematical and statistical based method namely surface response method.

Chapter 4: The chapter is dedicated to discuss further the results and findings that emerged from the study with appropriate cause and effect for each particular outcome.

Chapter 5: A conclusion on the findings of the research will be drawn in this chapter. Finally, the recommendations for future research will be suggested.

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REFERENCES

[1] D. Hoornweg and P. Bhada-Tata, "What a waste: a global review of solid waste management," 2012.

[2] P. J. van Beukering and M. A. Janssen, "Trade and recycling of used tyres in Western and Eastern Europe," *Resources, conservation and recycling,* vol. 33, pp. 235-265, 2001.

[3] P. c. http://www.prweb.com/releases/tires_OEM/ and replacement_tire/prweb4545704.htm., Accessed on 4 March 2013.

[4] X. C. Xavier Colom, Fernando Carrillo, Pilar Casas, *New Routes to Recycle Scrap Tyres*: INTECH Open Access Publisher, 2011.

[5] B. Adhikari, D. De, and S. Maiti, "Reclamation and recycling of waste rubber," *Progress in polymer science,* vol. 25, pp. 909-948, 2000.

[6] R. H. Snyder, "Scrap Tyres Disposal and Reuse," *Society of Automotive Engineers, Inc., Warrendale, PA.,* 1998.

[7] A. O. Aderemi and A. A. Otitoloju, "An assessment of landfill fires and their potential health effects-a case study of a municipal solid waste landfill in Lagos, Nigeria," *International Journal of Environmental Protection,* vol. 2, pp. 22-26, 2012.

[8] R. M. A. RMA, "State legislation Scrap tire disposal ". *https://www.rmaorg/publications/scrap_tires/,* vol. ID=11121, 2007.

[9] E. T. a. R. M. Association, "Annual Report," 2014.

[10] ETRMA, "END-OF-LIFE TYRE REPORT," *http://www.etrma.org/,* 2015.

[11] M. Myhre and D. A. MacKillop, "Rubber recycling," *Rubber Chemistry and Technology,* vol. 75, pp. 429-474, 2002.

[12] Y. Li, S. Zhao, and Y. Wang, "Microbial desulfurization of ground tire rubber by Thiobacillus ferrooxidans," *Polymer Degradation and Stability,* vol. 96, pp. 1662-1668, 9// 2011.

[13] D. i. t. limited, "Passenger tyre tread recipe and technology," *Tyre Technology* 1989.

[14] K. Hofstetter, C. Grohs, J. Eberhardsteiner, and H. A. Mang, "Sliding behaviour of simplified tire tread patterns investigated by means of FEM," *Computers & structures,* vol. 84, pp. 1151-1163, 2006.

[15] H. Wang, I. L. Al-Qadi, and I. Stanciulescu, "Simulation of tyre–pavement interaction for predicting contact stresses at static and various rolling conditions," *International Journal of Pavement Engineering,* vol. 13, pp. 310-321, 2012.

[16] J. E. Mark, B. Erman, and M. Roland, *The science and technology of rubber*: Academic press, 2013.

© COPYRIGHT UPM

[17] M. Akiba and A. Hashim, "Vulcanization and crosslinking in elastomers," *Progress in polymer science,* vol. 22, pp. 475-521, 1997.

[18] P. Ferrão, P. Ribeiro, and P. Silva, "A management system for end-of-life tyres: A Portuguese case study," *Waste management,* vol. 28, pp. 604-614, 2008.

[19] V. Shulman, *Tyre recycling* vol. 15: iSmithers Rapra Publishing, 2004.

[20] M. Myhre, S. Saiwari, W. Dierkes, and J. Noordermeer, "Rubber recycling: chemistry, processing, and applications," *Rubber chemistry and technology,* vol. 85, pp. 408-449, 2012.

[21] S. Li, J. Lamminmäki, and K. Hanhi, "Effect of ground rubber powder and devulcanizates on the properties of natural rubber compounds," *Journal of Applied Polymer Science,* vol. 97, pp. 208-217, 2005.

[22] G. Tao, Q. He, Y. Xia, G. Jia, H. Yang, and W. Ma, "The effect of devulcanization level on mechanical properties of reclaimed rubber by thermal-mechanical shearing devulcanization," *Journal of Applied Polymer Science,* vol. 129, pp. 2598-2605, 2013.

[23] S. Rooj, G. C. Basak, P. K. Maji, and A. K. Bhowmick, "New route for devulcanization of natural rubber and the properties of devulcanized rubber," *Journal of Polymers and the Environment,* vol. 19, pp. 382-390, 2011.

[24] W. X. C. I. C, "industrial grade acetoacetic trichloroacetic acetic acid " *https://whsxyhg.en.alibaba.com*.

[25] R. Kohler and J. O'NEILL, "New technology for the devulcanization of sulfur-cured scrap elastomers," *Rubber World,* vol. 216, 1997.

[26] B. Maxwell, "Process of reclaiming rubber and refining reclaimed rubber," ed: Google Patents, 1979.

[27] O. Dementienko, O. Kuznetsova, A. Tikhonov, and E. Prut, "The effect of dynamic vulcanization on the properties of polymer-elastomer blends containing crumb rubber," *Polymer Science Series A,* vol. 49, pp. 1218-1225, 2007.

[28] B. Diao, A. I. Isayev, and V. Y. Levin, "Basic Study of Continuous Ultrasonic Devulcanization of Unfilled Silicone Rubber," *Rubber Chemistry and Technology,* vol. 72, pp. 152-164, 1999.

[29] S. L. Zhang, Z. X. Zhang, Z. X. Xin, K. Pal, and J. K. Kim, "Prediction of mechanical properties of polypropylene/waste ground rubber tire powder treated by bitumen composites via uniform design and artificial neural networks," *Materials & Design,* vol. 31, pp. 1900-1905, 4// 2010.

[30] M. Mouri, N. Sato, H. Okamoto, M. Matsushita, K. Fukumori, H. Honda, *et al.*, "New continuous recycling technology for vulcanized rubbers," *PAPERS-AMERICAN CHEMICAL SOCIETY DIVISION OF RUBBER CHEMISTRY,* 1999.

© COPYRIGHT UPM

[31] J. Shi, H. Zou, L. Ding, X. Li, K. Jiang, T. Chen, *et al.*, "Continuous production of liquid reclaimed rubber from ground tire rubber and its application as reactive polymeric plasticizer," *Polymer Degradation and Stability,* vol. 99, pp. 166-175, 2014.
[32] K. Fukumori, M. Matsushita, H. Okamoto, N. Sato, Y. Suzuki, and K. Takeuchi, "Recycling technology of tire rubber," *JSAE Review,* vol. 23, pp. 259-264, 4// 2002.
[33] A. A. Phadke, A. K. Bhattacharya, S. K. Chakraborty, and S. K. De, "Studies of Vulcanization of Reclaimed Rubber," *Rubber Chemistry and Technology,* vol. 56, pp. 726-736, 1983.
[34] A. A. Phadke and S. K. De, "Use of cryoground reclaimed rubber in natural rubber," *Conservation & Recycling,* vol. 9, pp. 271-280, 1986/01/01 1986.
[35] R. Eckart, "Cryogenics advances ground rubber technology," *Modern Tire Dealer,* 1980.
[36] A. A. Phadke, S. K. Chakraborty, and S. K. De, "Cryoground Rubber-Natural Rubber Blends," *Rubber Chemistry and Technology,* vol. 57, pp. 19-33, 1984.
[37] A. Phadke, A. Bhowmick, and S. De, "Effect of cryoground rubber on properties of NR," *Journal of applied polymer science,* vol. 32, pp. 4063-4074, 1986.
[38] S. K. De, A. Isayev, and K. Khait, *Rubber recycling*: CRC Press, 2005.
[39] A. Bani, G. Polacco, and G. Gallone, "Microwave-induced devulcanization for poly(ethylene–propylene–diene) recycling," *Journal of Applied Polymer Science,* vol. 120, pp. 2904-2911, 2011.
[40] C. H. Scuracchio, D. A. Waki, and M. L. C. P. da Silva, "Thermalanalysis of ground tire rubber devulcanized by microwaves," *Journal of Thermal Analysis and Calorimetry,* vol. 87, pp. 893-897, 2007.
[41] Y. J. Hong, K. M. Jeong, P. Saha, J. Suh, and J. K. Kim, "Processing and characterization of microwave and ultrasonically treated waste-EPDM/LDPE polymer composites," *Polymer Engineering & Science,* vol. 55, pp. 533-540, 2015.
[42] A. Zanchet, L. N. Carli, M. Giovanela, R. N. Brandalise, and J. S. Crespo, "Use of styrene butadiene rubber industrial waste devulcanized by microwave in rubber composites for automotive application," *Materials & Design,* vol. 39, pp. 437-443, 8// 2012.
[43] S. Seghar, N. Ait Hocine, V. Mittal, S. Azem, F. Al-Zohbi, B. Schmaltz, *et al.*, "Devulcanization of styrene butadiene rubber by microwave energy: Effect of the presence of ionic liquid," *Express Polym. Lett,* vol. 9, pp. 1076-1086, 2015.
[44] V. Pistor and A. J. Zattera, "Degradation kinetics of ethylene propylene diene terpolymer residues devulcanized by microwaves," *Journal of Elastomers & Plastics,* vol. 46, pp. 69-83, 2014.

© COPYRIGHT UPM

[45] V. Pistor, C. H. Scuracchio, P. J. Oliveira, R. Fiorio, and A. J. Zattera, "Devulcanization of ethylene-propylene-diene polymer residues by microwave—Influence of the presence of paraffinic oil," *Polymer Engineering & Science,* vol. 51, pp. 697-703, 2011.
[46] M. Khavarnia and S. O. Movahed, "Butyl rubber reclamation by combined microwave radiation and chemical reagents," *Journal of Applied Polymer Science,* vol. 133, 2016.
[47] S. Gunasekaran, R. Natarajan, A. Kala, and R. Jagannathan, "Dielectric studies of some rubber materials at microwave frequencies," 2008.
[48] F. D. B. d. Sousa and C. H. Scuracchio, "The role of carbon black on devulcanization of natural rubber by microwaves," *Materials Research,* vol. 18, pp. 791-797, 2015.
[49] Z. Shugao, Z. Ping, C. Yonghua, L. Xiaohong, and Z. Junxue, "Study on Microwave Devulcanization of Nonpolar Vulcanizates [J]," *CHINA RUBBER INDUSTRY,* vol. 5, 1999.
[50] P. Garcia, F. de Sousa, J. de Lima, S. Cruz, and C. Scuracchio, "Devulcanization of ground tire rubber: Physical and chemical changes after different microwave exposure times," *Express Polym. Lett,* vol. 9, pp. 1015-1026, 2015.
[51] A. Pelofsky, "Rubber reclamation using ultrasonic energy," ed: Google Patents, 1973.
[52] H. Y. Okuda M., " JP 62121741 patent," 1987.
[53] W. Feng and A. I. Isayev, "High-power ultrasonic treatment of butyl rubber gum: Structure and properties," *Journal of Polymer Science Part B: Polymer Physics,* vol. 43, pp. 334-344, 2005.
[54] W. Feng and A. I. Isayev, "Blends of ultrasonically devulcanized tire-curing bladder and butyl rubber," *Journal of Materials Science,* vol. 40, pp. 2883-2889, 2005.
[55] S. Ghose, A. I. Isayev, and E. von Meerwall, "Effect of ultrasound on thermoset polyurethane: NMR relaxation and diffusion measurements," *Polymer,* vol. 45, pp. 3709-3720, 5// 2004.
[56] J. L. Massey, J. C. Parr, T. A. Wagler, E. von Meerwall, C. K. Hong, and A. I. Isayev, "Ultrasound devulcanization of unfilled natural rubber networks, studied via component molecular mobility," *Polymer International,* vol. 56, pp. 860-869, 2007.
[57] C. H. Scuracchio, R. E. S. Bretas, and A. I. Isayev, "Blends of PS with SBR Devulcanized by Ultrasound: Rheology and Morphology," *Journal of Elastomers & Plastics,* vol. 36, pp. 45-75, 2004.
[58] X. Sun and A. I. Isayev, "Ultrasound devulcanization: comparison of synthetic isoprene and natural rubbers," *Journal of Materials Science,* vol. 42, pp. 7520-7529, 2007.
[59] V. V. Yashin and A. I. Isayev, "The effect of polydispersity on structure of ultrasonically treated rubbers," *Polymer,* vol. 45, pp. 6083-6094, 8/5/ 2004.

© COPYRIGHT UPM

[60] A. I. Isayev, "paper presented at a meeting of the Rubber Division, ACS,Cleveland.," 1995.
[61] L. H. Thompson and L. K. Doraiswamy, "Sonochemistry: Science and Engineering," *Industrial & Engineering Chemistry Research,* vol. 38, pp. 1215-1249, 1999/04/01 1999.
[62] W. C. Warner, "Methods of Devulcanization," *Rubber Chemistry and Technology,* vol. 67, pp. 559-566, 1994.
[63] M. Sabzekar, M. P. Chenar, S. M. Mortazavi, M. Kariminejad, S. Asadi, and G. Zohuri, "Influence of process variables on chemical devulcanization of sulfur-cured natural rubber," *Polymer Degradation and Stability,* vol. 118, pp. 88-95, 8// 2015.
[64] G. K. Jana and C. K. Das, "Recycling natural rubber vulcanizates through mechanochemical devulcanization," *Macromolecular Research,* vol. 13, pp. 30-38, 2005.
[65] G. K. Jana, R. N. Mahaling, T. Rath, A. Kozlowska, M. Kozlowski, and C. K. Das, "Mechano-chemical recycling of sulfur cured natural rubber," *POLIMERY-WARSAW-,* vol. 52, p. 131, 2007.
[66] S. Yamashita, N. Kawabata, S. Sagan, and K. Hayashi, "Reclamation of vulcanized rubbers by chemical degradation. V. Degradation of vulcanized synthetic isoprene rubber by the phenylhydrazine–ferrous chloride system," *Journal of Applied Polymer Science,* vol. 21, pp. 2201-2209, 1977.
[67] N. Kawabata, B. I. Okuyama, and S. Yamashita, "Reclamation of vulcanized rubber by chemical degradation. XV. Degradation of vulcanized synthetic isoprene by the phenylhydrazine–iron (II) chloride system," *Journal of Applied Polymer Science,* vol. 26, pp. 1417-1419, 1981.
[68] V. Rajan, W. Dierkes, R. Joseph, and J. Noordermeer, "Science and technology of rubber reclamation with special attention to NR-based waste latex products," *Progress in polymer science,* vol. 31, pp. 811-834, 2006.
[69] K. Hamanoue, H. Teranishi, M. Okamoto, Y. Furukawa, S. Tagawa, and Y. Tabata, "Photochemical reactions of N-vinylcarbazole in the binary solvent of benzonitrile and nitrobenzene," *Journal of Polymer Science: Polymer Chemistry Edition,* vol. 18, pp. 91-100, 1980.
[70] D. De, S. Maiti, and B. Adhikari, "Reclaiming of rubber by a renewable resource material (RRM). II. Comparative evaluation of reclaiming process of NR vulcanizate by RRM and diallyl disulfide," *Journal of applied polymer science,* vol. 73, pp. 2951-2958, 1999.
[71] D. De, B. Adhikari, and S. Maiti, "Reclaiming of rubber by a renewable resource material. Part 1. Reclaiming of natural rubber vulcanizates," *Journal of Polymer Materials,* vol. 14, pp. 333-342, 1997.

© COPYRIGHT UPM

[72] K. A. J. Dijkhuis, *Recycling of Vulcanized EPDM-rubber: Mechanistic Studies Into the Development of a Continuous Process Using Amines as Devulcanization Aids*: University of Twente [Host], 2008.
[73] A. Jalilvand, I. Ghasemi, M. Karrabi, and H. Azizi, "An investigation on the EPDM devulcanization in co-rotating twin screw extruder by response surface methodology," *Progress in Rubber, Plastics and Recycling Technology,* vol. 24, p. 33, 2008.
[74] V. Rajan, W. Dierkes, J. Noordermeer, and R. Joseph, "Comparative investigation on the reclamation of NR based latex products with amines and disulfides," *Rubber chemistry and technology,* vol. 78, pp. 855-867, 2005.
[75] V. Rajan, W. Dierkes, R. Joseph, and J. Noordermeer, "Recycling of NR based cured latex material reclaimed with 2, 2′-dibenzamidodiphenyldisulphide in a truck tire tread compound," *Journal of applied polymer science,* vol. 102, pp. 4194-4206, 2006.
[76] D. De, A. Das, D. De, B. Dey, S. C. Debnath, and B. C. Roy, "Reclaiming of ground rubber tire (GRT) by a novel reclaiming agent," *European Polymer Journal,* vol. 42, pp. 917-927, 2006.
[77] D. De, D. De, and G. Singharoy, "Reclaiming of ground rubber tire by a novel reclaiming agent. I. Virgin natural rubber/reclaimed GRT vulcanizates," *Polymer Engineering & Science,* vol. 47, pp. 1091-1100, 2007.
[78] S. Yamashita, "Reclaimed rubber from rubber scrap," *Int Polym Sci Technol,* vol. 8, pp. 77-93, 1981.
[79] V. V. Rajan, W. K. Dierkes, R. Joseph, and J. W. M. Noordermeer, "Science and technology of rubber reclamation with special attention to NR-based waste latex products," *Progress in Polymer Science,* vol. 31, pp. 811-834, 9// 2006.
[80] M. A. L. Verbruggen, *Devulcanization of EPDM Rubber: A Mechanistic Study Into a Successful Method*, 2007.
[81] K. A. J. Dijkhuis, I. Babu, J. S. Lopulissa, J. W. M. Noordermeer, and W. K. Dierkes, "A Mechanistic Approach to EPDM Devulcanization," *Rubber Chemistry and Technology,* vol. 81, pp. 190-208, 2008.
[82] P. Sutanto, F. L. Laksmana, F. Picchioni, and L. P. B. M. Janssen, "Modeling on the kinetics of an EPDM devulcanization in an internal batch mixer using an amine as the devulcanizing agent," *Chemical Engineering Science,* vol. 61, pp. 6442-6453, 10// 2006.
[83] M. Van Duin, J. W. Noordermeer, M. A. Verbruggen, and L. Van Der Does, "Method for devulcanizing rubber with an amine," ed: Google Patents, 2005.
[84] R. D. Myers, P. Nicholson, J. B. Macleod, and M. E. Moir, "Rubber devulcanization process," ed: Google Patents, 1997.

© COPYRIGHT UPM

[85] N. Kawabata, S. Yamashita, and Y. Furukawa, "Reclamation of Vulcanized Rubbers by Chemical Degradation. IX. Oxidative Degradation of cis-1, 4-Polyisoprene by Phenylhydrazine-Iron (II) Chloride System," *Bulletin of the Chemical Society of Japan,* vol. 51, pp. 625-628, 1978.
[86] P. P. Nicholas, "The Scission of Polysulfide Crosslinks in Scrap Rubber Particles through Phase Transfer Catalysis," *Rubber Chemistry and Technology,* vol. 55, pp. 1499-1515, 1982.
[87] P. P. Nicholas, "Devulcanized rubber composition and process for preparing same," ed: Google Patents, 1979.
[88] A. M. Joseph, B. George, K. Madhusoodanan, and R. Alex, "THE CURRENT STATUS OF SULPHUR VULCANIZATION AND DEVULCANIZATION CHEMISTRY: DEVULCANIZATION," 2016.
[89] D. Campbell and B. Saville, "Current principles and practices in elucidating structure in sulfur vulcanized elastomers," in *Proceeding of the international rubber conference. Brighton, UK*, 1967, pp. 1-14.
[90] D. Campbell, "Structural characterization of vulcanizates part X. Thiol- disulfide interchange for cleaving disulfide crosslinks in natural rubber vulcanizates," *Journal of Applied Polymer Science,* vol. 13, pp. 1201-1214, 1969.
[91] B. Saville and A. Watson, "Structural characterization of sulfur-vulcanized rubber networks," *Rubber chemistry and technology,* vol. 40, pp. 100-148, 1967.
[92] Y. Onouchi, S. Inagaki, H. Okamoto, and J. Furukawa, "Reclamation of scrap rubber vulcanizates III: reclamation of crushed tire scrap with dimethylsulfoxide," *Int Polym Sci Technol,* vol. 55, pp. 58-62, 1982.
[93] V. M. Makarov and V. Drozdovskiĭ, *Reprocessing of tyres and rubber wastes: recycling from the rubber products industry*: Ellis Horwood, 1991.
[94] J. G. Bryson, "Reclaim oil for digester process for rubber reclaiming," ed: Google Patents, 1979.
[95] S. Ramarad, M. Khalid, C. Ratnam, A. L. Chuah, and W. Rashmi, "Waste tire rubber in polymer blends: A review on the evolution, properties and future," *Progress in Materials Science,* vol. 72, pp. 100-140, 2015.
[96] O. Grigoryeva, A. Fainleib, J. Grenet, and J. Saiter, "Reactive compatibilization of recycled polyethylenes and scrap rubber in thermoplastic elastomers: chemical and radiation-chemical approach," *Rubber Chemistry and Technology,* vol. 81, pp. 737-752, 2008.
[97] S. H. Lee, Z. X. Zhang, D. Xu, D. Chung, G. J. Oh, and J. K. Kim, "Dynamic reaction involving surface modified waste ground rubber tire powder/polypropylene," *Polymer Engineering & Science,* vol. 49, pp. 168-176, 2009.

© COPYRIGHT UPM

[98] R. Bagheri, M. Williams, and R. Pearson, "Use of surface modified recycled rubber particles for toughening of epoxy polymers," *Polymer Engineering & Science,* vol. 37, pp. 245-251, 1997.
[99] A. E. o. Wisconsin, *technical information on Tirecycle,* 2002.
[100] A. Amash, U. Giese, and R. Schuster, "Interphase grafting of reclaimed rubber powder," *Kautschuk Gummi Kunststoffe,* vol. 55, pp. 218-218, 2002.
[101] M. Rezaei Abadchi, A. Jalali Arani, and H. Nazockdast, "Partial replacement of NR by GTR in thermoplastic elastomer based on LLDPE/NR through using reactive blending: Its effects on morphology, rheological, and mechanical properties," *Journal of Applied Polymer Science,* vol. 115, pp. 2416-2422, 2010.
[102] J. L. Zhang, H. X. Chen, C. M. Ke, Y. Zhou, H. Z. Lu, and D. L. Wang, "Graft polymerization of styrene onto waste rubber powder and surface characterization of graft copolymer," *Polymer bulletin,* vol. 68, pp. 789-801, 2012.
[103] A. Tolstov, O. Grigoryeva, A. Fainleib, I. Danilenko, A. Spanoudaki, P. Pissis*, et al.*, "Reactive Compatibilization of Polyethylene/Ground Tire Rubber Inhomogeneous Blends via Interactions of Pre-Functionalized Polymers in Interface," *Macromolecular Symposia,* vol. 254, pp. 226-232, 2007.
[104] M. M. Hassan, G. A. Mahmoud, H. H. El-Nahas, and E.-S. A. Hegazy, "Reinforced material from reclaimed rubber/natural rubber, using electron beam and thermal treatment," *Journal of Applied Polymer Science,* vol. 104, pp. 2569-2578, 2007.
[105] S. H. Lee, A. M. Shanmugharaj, V. Sridhar, Z. X. Zhang, and J. K. Kim, "Preparation and characterization of polypropylene and waste tire powder modified by allylamine blends," *Polymers for Advanced Technologies,* vol. 20, pp. 620-625, 2009.
[106] A. M. Shanmugharaj, J. K. Kim, and S. H. Ryu, "Modification of rubber surface by UV surface grafting," *Applied Surface Science,* vol. 252, pp. 5714-5722, 6/15/ 2006.
[107] F. Smith, E. Daniels, and A. Teotia, "Testing and evaluating commercial applications of new surface-treated rubber technology utilizing waste tires," *Resources, conservation and recycling,* vol. 15, pp. 133-144, 1995.
[108] S. Sato, Y. Honda, M. Kuwahara, H. Kishimoto, N. Yagi, K. Muraoka*, et al.*, "Microbial scission of sulfide linkages in vulcanized natural rubber by a white rot basidiomycete, ceriporiopsis s ubvermispora," *Biomacromolecules,* vol. 5, pp. 511-515, 2004.
[109] K. Rose and A. Steinbüchel, "Biodegradation of natural rubber and related compounds: recent insights into a hardly understood catabolic capability of microorganisms," *Applied and Environmental Microbiology,* vol. 71, pp. 2803-2812, 2005.

© COPYRIGHT UPM

[110] J. Jose, S. Satapathy, A. Nag, and G. Nando, "Modification of waste polypropylene with waste rubber dust from textile cot industry and its characterization," *Process Safety and Environmental Protection,* vol. 85, pp. 318-326, 2007.
[111] J. K. Kim and J. W. Park, "The biological and chemical desulfurization of crumb rubber for the rubber compounding," *Journal of applied polymer science,* vol. 72, pp. 1543-1549, 1999.
[112] M. Löffler, "Microbial surface desulfurization of scrap rubber crumb-a contribution towards material recycling of scrap rubber," *Kautsch. Gummi Kunstst,* vol. 48, p. 454, 1995.
[113] M. Chritiansson, B. Stenberg, L. R. Wallenberg, and O. Holst, "Reduction of surface sulphur upon microbial devulcanization of rubber materials," *Biotechnology Letters,* vol. 20, pp. 637-642, 1998.
[114] R. A. Romine and M. F. Romine, "Rubbercycle: a bioprocess for surface modification of waste tyre rubber," *Polymer degradation and stability,* vol. 59, pp. 353-358, 1998.
[115] A. Singh, "Chemical and biochemical aspects of activated oxygen: singlet oxygen, superoxide anion, and related species," *CRC Handbook of free radicals and antioxidants in Biomedicine. CRC Press, Inc., Boca Raton, Florida,* vol. 1, pp. 17-28, 1989.
[116] G. Burillo, R. L. Clough, T. Czvikovszky, O. Guven, A. Le Moel, W. Liu, *et al.*, "Polymer recycling: potential application of radiation technology," *Radiation Physics and Chemistry,* vol. 64, pp. 41-51, 2002.
[117] J. Scheirs, "Rubber tyre recycling," *Polymer Recycling: Wiley Series in Polymer Science. New York: John Wiley and Sons,* pp. 410-456, 1998.
[118] F. G. Smith, E. J. Daniels, and A. P. S. Teotia, "Testing and evaluating commercial applications of new surface-treated rubber technology utilizing waste tires," *Resources, Conservation and Recycling,* vol. 15, pp. 133-144, 1995/11/01/ 1995.
[119] X. Zhang, X. Zhu, M. Liang, and C. Lu, "Improvement of the properties of ground tire rubber (GTR)-filled nitrile rubber vulcanizates through plasma surface modification of GTR powder," *Journal of Applied Polymer Science,* vol. 114, pp. 1118-1125, 2009.
[120] M. M. Hassan, G. A. Mahmoud, H. H. El- Nahas, and E. S. A. Hegazy, "Reinforced material from reclaimed rubber/natural rubber, using electron beam and thermal treatment," *Journal of Applied Polymer Science,* vol. 104, pp. 2569-2578, 2007.
[121] K. F. El-Nemr and A. M. Khalil, "Gamma irradiation of treated waste rubber powder and its composites with waste polyethylene," *Journal of Vinyl and Additive Technology,* vol. 17, pp. 58-63, 2011.

© COPYRIGHT UPM

[122] F. Cataldo, O. Ursini, and G. Angelini, "Surface oxidation of rubber crumb with ozone," *Polymer Degradation and Stability,* vol. 95, pp. 803-810, 2010/05/01/ 2010.
[123] P. Fan and C. Lu, "Surface graft copolymerization of poly(methyl methacrylate) onto waste tire rubber powder through ozonization," *Journal of Applied Polymer Science,* vol. 122, pp. 2262-2270, 2011.
[124] A. Chapiro, "General consideration of the radiation chemistry of polymers," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 105, pp. 5-7, 1995.
[125] W. M. Z. W. Y. Jamaliah Sharif, Khairul Zaman Hj Mohd Dahlan, Mansor Hj Ahmad, "Preparation and properties of radiation crosslinked natural rubber/clay nanocomposites," *Polymer Testing,* vol. 24, pp. 211-217, 2005.
[126] J. O. D. DJT Hill, MCS Perera, PJ Pomery "High energy radiation effects on halogenated butyl rubbers," *Polymer,* vol. 36, pp. 4185-4192, 1995.
[127] R. L. C. Guillermina Burillo, Tibor Czvikovszky, Olgun Guven, Alain Le Moel, Weiwei Liu, Ajit Singh, Jingtian Yangh, Traian Zaharescu, "Polymer recycling: potential application of radiation technology," *Radiation Physics and Chemistry,* vol. 64, pp. 41-51, 2002.
[128] R. A. CK Radhakrishnan, G Unnikrishnan, , "Thermal, ozone and gamma ageing of styrene butadiene rubber and poly (ethylene-co-vinyl acetate) blends," *Polymer degradation and stability,* vol. 91, pp. 902-910, 2006.
[129] N. Z. AV Telnov, Yu A Khokhlov, NP Sitnikov, ML Smetanin, VP Tarantasov, DN Shadrin, IV Shorikov, AL Liakumovich, FK Miryasova, "Radiation degradation of spent butyl rubbers," *Radiation Physics and Chemistry,* vol. 63, pp. 245-248, 2002.
[130] J. K. K. AM Shanmugharaj, Sung Hun Ryu, , "UV surface modification of waste tire powder: characterization and its influence on the properties of polypropylene/waste powder composites," *Polymer testing,* vol. 24, pp. 739-745, 2005.
[131] E. L. R. Sonnier, L. Clerc, A. Bergeret, JM Lopez-Cuesta, "Polyethylene/ground tyre rubber blends: Influence of particle morphology and oxidation on mechanical properties," *Polymer Testing,* vol. 26, pp. 274-281, 2007.
[132] S. R. MM Abou Zeid, A.A. Nada, AM Khalil, RH. Hilal, "Effect of gamma irradiation on ethylene propylene diene terpolymer rubber composites," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 266, pp. 111-116, 2008.
[133] M. Ş. Bağdagül Karaağaç, Veli Deniz, Olgun Güven, "Recycling of gamma irradiated inner tubes in butyl based rubber compounds," *Nuclear Instruments and Methods in Physics*

© COPYRIGHT UPM

Research Section B: Beam Interactions with Materials and Atoms, vol. 265, pp. 290-293, 2007.

[134] E. L. C. Sandra R Scagliusi, Ademar B Lugao, "Effect of gamma radiation on chlorobutyl rubber vulcanized by three different crosslinking systems," *Radiation Physics and Chemistry,* vol. 81, pp. 1370-1373, 2012.

[135] M.-C. M. Marković Gordana, Jovanović Vojislav, Samardžija-Jovanović Suzana, Budinski-Simendić Jaroslava, "The effect of gamma radiation on the ageing of sulfur cured NR/CSM and NBR/CSM rubber blends reinforced by carbon black," *Chemical Industry and Chemical Engineering Quarterly,* vol. 15, pp. 291-298, 2009.

[136] R. S. Ratnam Chantara Thevy, Khalid Mohd, Noraini, "Effect of Pre-Irradiation of Waste Tire Dust on the Properties of Ethylene Vinyl Acetate/Waste Tire Dust Blend (EVA/WTD) Blends," *Journal of Composite and Biodegradable Polymers,* vol. 1, pp. 16-22, 2013.

[137] M. M. Hassan, N. A. Badway, M. Y. Elnaggar, and E. S. A. Hegazy, "Effects of peroxide and gamma radiation on properties of devulcanized rubber/polypropylene/ethylene propylene diene monomer formulation," *Journal of Applied Polymer Science,* vol. 131, 2014.

[138] M. M. Hassan, R. O. Aly, S. E. Abdel Aal, A. M. El-Masry, and E. S. Fathy, "Mechanochemical devulcanization and gamma irradiation of devulcanized waste rubber/high density polyethylene thermoplastic elastomer," *Journal of Industrial and Engineering Chemistry,* vol. 19, pp. 1722-1729, 9/25/ 2013.

[139] M. A. Zeid, Rabie, ST, Nada, AA, Khalil, AM, Hilal, RH, "Effect of gamma irradiation on ethylene propylene diene terpolymer rubber composites," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 266, pp. 111-116, 2008.

[140] M. M. Hassan and M. Y. E. Nagwa A Badway, El-Sayed A Hegazy, "Thermo-mechanical properties of devulcanized rubber/high crystalline polypropylene blends modified by ionizing radiation," *Journal of Industrial and Engineering Chemistry,* vol. 19, pp. 1241-1250, 2013.

[141] S. K. Tariq Yasin, Muhammad Shafiq, Rohama Gill, "Radiation crosslinking of styrene–butadiene rubber containing waste tire rubber and polyfunctional monomers," *Radiation Physics and Chemistry,* vol. 106, pp. 343-347, 2015.

[142] R. Sonnier, E. Leroy, L. Clerc, A. Bergeret, and J. M. Lopez-Cuesta, "Polyethylene/ground tyre rubber blends: Influence of particle morphology and oxidation on mechanical properties," *Polymer Testing,* vol. 26, pp. 274-281, 4// 2007.

[143] O. V. Gordana Marković, Milena Marinović-Cincović , Vojislav Jovanović, Suzana Samaržija-Jovanović , Jaroslava Budinski-Simendić "Composites based on waste rubber powder and rubber blends: BR/CSM," *Composites Part B: Engineering,* vol. 45, pp. 178-184, 2013.
[144] R. Sonnier, E. Leroy, L. Clerc, A. Bergeret, and J. M. Lopez-Cuesta, "Compatibilisation of polyethylene/ground tyre rubber blends by γ irradiation," *Polymer Degradation and Stability,* vol. 91, pp. 2375-2379, 2006/10/01/ 2006.
[145] M. M. Hassan, N. A. Badway, A. M. Gamal, M. Y. Elnaggar, and E.-S. A. Hegazy, "Studies on mechanical, thermal and morphological properties of irradiated recycled polyamide and waste rubber powder blends," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 268, pp. 1427-1434, 2010.
[146] E. Abdel-Bary, A. Dessouki, E. El-Nesr, and M. Hassan, "Radiation-induced graft copolymerization of some vinyl monomers onto waste rubber powder," *Polymer—Plastics Technology and Engineering,* vol. 36, pp. 241-256, 1997.
[147] S. Ramarad, C. T. Ratnam, M. Khalid, and A. L. Chuah, "Improving the properties of reclaimed waste tire rubber by blending with poly (ethylene- co- vinyl acetate) and electron beam irradiation," *Journal of Applied Polymer Science,* vol. 132, 2015.
[148] T. Amari, N. J. Themelis, and I. K. Wernick, "Resource recovery from used rubber tires," *Resources Policy,* vol. 25, pp. 179-188, 1999.
[149] S. Z. M. Meysami, and C. Tzoganakis, "Effect of incorporation of devulcanized rubber," *ANTEC,* 2010.
[150] D. Mangaraj, "Rubber recycling by blending with plastics," *Rubber Recycling,* 2004.
[151] H. Manuel, "Standards for rubber granulates and powders," *KGK. Kautschuk, Gummi, Kunststoffe,* vol. 54, pp. 101-105, 2001.
[152] J. A. Szilard, "Reclaiming rubber and other polymers," 1973.
[153] R. Swor, L. Jensen, and M. Budzol, "Ultrafine recycled rubber," *Rubber Chemistry and Technology,* vol. 53, pp. 1215-1225, 1980.
[154] D. Gibala and G. R. Hamed, "Cure and Mechanical Behavior of Rubber Compounds Containing Ground Vulcanizates. Part I-Cure Behavior," *Rubber chemistry and technology,* vol. 67, pp. 636-648, 1994.
[155] M. Kluppel, A. Kuhrcke, and R. Schuster, "Recycling of scrap rubber in technical elastomers," *Kautschuk Gummi Kunststoffe,* vol. 50, pp. 373-379, 1997.

[156] M. S. Sobhy, M. M. M. Mahdy, M. A. K. El-Fayoumi, and E. M. Abdel-Bary, "Effect of waste rubber powder in SBR formulations on the swelling of different organic solvents," *Polymer Testing,* vol. 16, pp. 349-362, 1997/08/01/ 1997.
[157] C. Jacob, P. De, A. Bhowmick, and S. De, "Recycling of EPDM waste. I. Effect of ground EPDM vulcanizate on properties of EPDM rubber," *Journal of applied polymer science,* vol. 82, pp. 3293-3303, 2001.
[158] G. Mathew, R. Singh, N. Nair, and S. Thomas, "Recycling of natural rubber latex waste and its interaction in epoxidised natural rubber," *Polymer,* vol. 42, pp. 2137-2165, 2001.
[159] S. C. Han and M. H. Han, "Fracture behavior of NR and SBR vulcanizates filled with ground rubber having uniform particle size," *Journal of applied polymer science,* vol. 85, pp. 2491-2500, 2002.
[160] H. Ismail, R. Nordin, and A. Noor, "Cure characteristics, tensile properties and swelling behaviour of recycled rubber powder-filled natural rubber compounds," *Polymer Testing,* vol. 21, pp. 565-569, 2002.
[161] H. Ismail, R. Nordin, and A. M. Noor, "The comparison properties of recycle rubber powder, carbon black, and calcium carbonate filled natural rubber compounds," *Polymer-Plastics Technology and Engineering,* vol. 41, pp. 847-862, 2002.
[162] C. Jacob, A. Bhowmick, P. De, and S. De, "Studies on ground EPDM vulcanisate as filler in window seal formulation," *Plastics, rubber and composites,* vol. 31, pp. 212-219, 2002.
[163] H. Ismail, R. Nordin, and A. M. Noor, "The effects of recycle rubber powder (RRP) content and various vulcanization systems on curing characteristics and mechanical properties of natural rubber/RRP blends," *Iranian Polymer Journal,* vol. 12, pp. 373-380, 2003.
[164] C. Jacob, A. Bhowmick, P. De, and S. De, "Utilization of powdered EPDM scrap in EPDM compound," *Rubber chemistry and technology,* vol. 76, pp. 36-59, 2003.
[165] O. Kuznetsova, L. Zhorina, and E. Prut, "Blends based on ground tire rubber," *Polymer science. Series A, Chemistry, physics,* vol. 46, pp. 151-159, 2004.
[166] S. Li, J. Lamminmäki, and K. Hanhi, "Effect of ground rubber powder on properties of natural rubber," in *Macromolecular Symposia*, 2004, pp. 209-216.
[167] K. Ravichandran and N. Natchimuthu, "Vulcanization characteristics and mechanical properties of natural rubber–scrap rubber compositions filled with leather particles," *Polymer international,* vol. 54, pp. 553-559, 2005.
[168] J. Lamminmäki, S. Li, and K. Hanhi, "Feasible incorporation of devulcanized rubber waste in virgin natural rubber," *Journal of materials science,* vol. 41, pp. 8301-8307, 2006.

© COPYRIGHT UPM

[169] H. Ismail, N. F. Omar, and N. Othman, "Effect of carbon black loading on curing characteristics and mechanical properties of waste tyre dust/carbon black hybrid filler filled natural rubber compounds," *Journal of Applied Polymer Science,* vol. 121, pp. 1143-1150, 2011.
[170] L. N. Carli, O. Bianchi, R. S. Mauler, and J. S. Crespo, "Accelerated aging of elastomeric composites with vulcanized ground scraps," *Journal of Applied Polymer Science,* vol. 123, pp. 280-285, 2012.
[171] D. Charlton, J. Yang, and K. Teh, "A review of methods to characterize rubber elastic behavior for use in finite element analysis," *Rubber chemistry and technology,* vol. 67, pp. 481-503, 1994.
[172] K. H. Meyer, G. v. Susich, and E. Valko, "Die elastischen Eigenschaften der organischen Hochpolymeren und ihre kinetische Deutung," *Kolloid-Zeitschrift,* vol. 59, pp. 208-216, 1932.
[173] K. Meyer, G. v. SUSlCH, and E. Valko, "Kolloid-Z. 59, 208 (1932);" KH MEYER and C," *FERRI: Helv. chim. Acta,* vol. 18, p. 570, 1935.
[174] E. Guth and H. Mark, "Internal molecular statitics, especially in chain molecules," *Mh Chem,* vol. 65, pp. 93-121, 1934.
[175] W. Kuhn, Kolloidzschr "The shape of fibrous molecules in solution," vol. 68, 1934.
[176] L. Treloar, "The elasticity and related properties of rubbers," *Reports on progress in physics,* vol. 36, p. 755, 1973.
[177] L. R. G. Treloar, *The physics of rubber elasticity*: Oxford University Press, USA, 1975.
[178] S. L. Rosen, *Fundamental principles of polymeric materials*: Wiley, 1982.
[179] M. Shaw and E. Young, "Rubber elasticity and fracture," *Journal of engineering materials and technology,* vol. 110, pp. 258-265, 1988.
[180] I. Fried and A. R. Johnson, "Nonlinear computation of axisymmetric solid rubber deformation," *Computer Methods in Applied Mechanics and Engineering,* vol. 67, pp. 241-253, 1988.
[181] P. J. Flory and J. Rehner Jr, "Statistical mechanics of cross-linked polymer networks I. Rubberlike elasticity," *The Journal of Chemical Physics,* vol. 11, pp. 512-520, 1943.
[182] H. M. James and E. Guth, "Theory of the elastic properties of rubber," *The Journal of Chemical Physics,* vol. 11, pp. 455-481, 1943.
[183] F. T. Wall, "Statistical thermodynamics of rubber. II," *The Journal of Chemical Physics,* vol. 10, pp. 485-488, 1942.
[184] L. Treloar, "The elasticity of a network of long-chain molecules. I," *Transactions of the Faraday Society,* vol. 39, pp. 36-41, 1943.

© COPYRIGHT UPM

[185] F. W. Sears, "An introduction to thermodynamics, the kinetic theory of gases, and statistical mechanics," 1956.
[186] B. Kim, S. B. Lee, J. Lee, S. Cho, H. Park, S. Yeom*, et al.*, "A comparison among Neo-Hookean model, Mooney-Rivlin model, and Ogden model for chloroprene rubber," *International Journal of Precision Engineering and Manufacturing,* vol. 13, pp. 759-764, 2012.
[187] R. Rivlin, "Large elastic deformations of isotropic materials. IV. Further developments of the general theory," *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* vol. 241, pp. 379-397, 1948.
[188] M. Mooney, *Journal of Applied Physics,* vol. 11, 1940.
[189] R. Ogden, "Large deformation isotropic elasticity-on the correlation of theory and experiment for incompressible rubberlike solids," in *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 1972, pp. 565-584.
[190] H.-G. Kilian, "Equation of state of real networks," *Polymer,* vol. 22, pp. 209-217, 2// 1981.
[191] E. M. Arruda and M. C. Boyce, "A three-dimensional constitutive model for the large stretch behavior of rubber elastic materials," *Journal of the Mechanics and Physics of Solids,* vol. 41, pp. 389-412, 1993.
[192] W. Kuhn and F. Grün, "Beziehungen zwischen elastischen Konstanten und Dehnungsdoppelbrechung hochelastischer Stoffe," *Kolloid-Zeitschrift,* vol. 101, pp. 248-271, 1942.
[193] A. Isihara, N. Hashitsume, and M. Tatibana, "Statistical Theory of Rubber- Like Elasticity. IV.(Two- Dimensional Stretching)," *The Journal of Chemical Physics,* vol. 19, pp. 1508-1512, 1951.
[194] V. Biderman, "Calculation of rubber parts," *Rascheti na prochnost,* vol. 40, 1958.
[195] A. Gent and A. Thomas, "Forms for the stored (strain) energy function for vulcanized rubber," *Journal of Polymer Science,* vol. 28, pp. 625-628, 1958.
[196] L. J. Hart-Smith, "Elasticity parameters for finite deformations of rubber-like materials," *Zeitschrift für angewandte Mathematik und Physik ZAMP,* vol. 17, pp. 608-626, 1966.
[197] K. Valanis and R. Landel, "The Strain- Energy Function of a Hyperelastic Material in Terms of the Extension Ratios," *Journal of Applied Physics,* vol. 38, pp. 2997-3002, 1967.
[198] A. G. James, A. Green, and G. Simpson, "Strain energy functions of rubber. I. Characterization of gum vulcanizates," *Journal of Applied Polymer Science,* vol. 19, pp. 2033-2058, 1975.
[199] R. Ball, M. Doi, S. Edwards, and M. Warner, "Elasticity of entangled networks," *Polymer,* vol. 22, pp. 1010-1018, 1981.
[200] P. J. Flory, "Network Structure and the Elastic Properties of Vulcanized Rubber," *Chemical reviews,* vol. 35, pp. 51-75, 1944.

© COPYRIGHT UPM

[201] B. Erman and P. J. Flory, "Relationships between stress, strain, and molecular constitution of polymer networks. Comparison of theory with experiments," *Macromolecules,* vol. 15, pp. 806-811, 1982.
[202] P. J. Flory and B. Erman, "Theory of elasticity of polymer networks. 3," *Macromolecules,* vol. 15, pp. 800-806, 1982.
[203] A. Gent, "A new constitutive relation for rubber," *Rubber chemistry and technology,* vol. 69, pp. 59-61, 1996.
[204] O. Yeoh, "Characterization of elastic properties of carbon-black-filled rubber vulcanizates," *Rubber chemistry and technology,* vol. 63, pp. 792-805, 1990.
[205] G. Heinrich and M. Kaliske, "Theoretical and numerical formulation of a molecular based constitutive tube-model of rubber elasticity," *Computational and Theoretical Polymer Science,* vol. 7, pp. 227-241, // 1997.
[206] M. Kaliske and G. Heinrich, "An extended tube-model for rubber elasticity: statistical-mechanical theory and finite element implementation," *Rubber Chemistry and Technology,* vol. 72, pp. 602-632, 1999.
[207] M. Shariff, "Strain energy function for filled and unfilled rubberlike material," *Rubber chemistry and technology,* vol. 73, pp. 1-18, 2000.
[208] C. Miehe, S. Göktepe, and F. Lulei, "A micro-macro approach to rubber-like materials—Part I: the non-affine micro-sphere model of rubber elasticity," *Journal of the Mechanics and Physics of Solids,* vol. 52, pp. 2617-2660, 11// 2004.
[209] R. Marlow, "A general first-invariant hyperelastic constitutive model," *Constitutive Models for Rubber,* pp. 157-160, 2003.
[210] J. Padovan and O. Paramadilok, "Transient and steady state viscoelastic rolling contact," *Computers & Structures,* vol. 20, pp. 545-553, 1985.
[211] J. Padovan and R. Kennedy, "Three-Dimensional Traveling Load Finite Element," SAE Technical Paper 0148-7191, 1986.
[212] R. Kennedy and J. Padovan, "Finite element analysis of a steady-state rotating tire subjected to point load or ground contact," *Tire Science and Technology,* vol. 15, pp. 243-260, 1987.
[213] J. Padovan, "Finite element analysis of steady and transiently moving/rolling nonlinear viscoelastic structure—I. Theory," *Computers & structures,* vol. 27, pp. 249-257, 1987.
[214] J. Oden, T. Lin, and J. Bass, "A finite element analysis of the general rolling contact problem for a viscoelastic rubber cylinder," *Tire science and technology,* vol. 16, pp. 18-43, 1988.
[215] L. Faria, J. Bass, J. Oden, and E. Becker, "A three-dimensional rolling contact model for a reinforced rubber tire," *Tire Science and Technology,* vol. 17, pp. 217-233, 1989.

© COPYRIGHT UPM

[216] J. Padovan, A. Kazempour, F. Tabaddor, and B. Brockman, "Alternative formulations of rolling contact problems," *Finite elements in analysis and design,* vol. 11, pp. 275-284, 1992.
[217] A. Goldstein, "Finite element analysis of a quasi-static rolling tire model for determination of truck tire forces and moments," *Tire Science and Technology,* vol. 24, pp. 278-293, 1996.
[218] B. Kao and M. Muthukrishnan, "Tire transient analysis with an explicit finite element program," *Tire Science and Technology,* vol. 25, pp. 230-244, 1997.
[219] M. Koishi, K. Kabe, and M. Shiratori, "Tire cornering simulation using an explicit finite element analysis code," *Tire Science and Technology,* vol. 26, pp. 109-119, 1998.
[220] P. Campanac, K. Nonami, and D. Duhamel, "Application of the vibration analysis of linear systems with time-periodic coefficients to the dynamics of a rolling tyre," *Journal of sound and vibration,* vol. 231, pp. 37-77, 2000.
[221] M. Shiraishi, H. Yoshinaga, A. Miyori, and E. Takahashi, "Simulation of dynamically rolling tire," *Tire Science and Technology,* vol. 28, pp. 264-276, 2000.
[222] K. Kabe and M. Koishi, "Tire cornering simulation using finite element analysis," *Journal of Applied Polymer Science,* vol. 78, pp. 1566-1572, 2000.
[223] E. Doğan and M. P. Saka, "Optimum design of unbraced steel frames to LRFD–AISC using particle swarm optimization," *Advances in Engineering Software,* vol. 46, pp. 27-34, 2012.
[224] A. C. M. Maxfield and L. Fogel, "Artificial intelligence through a simulation of evolution," *Biophysics and Cybernetics Systems: Proceedings of the Second Cybernetics Sciences. Spartan Books, Washington DC, EE. UU,* 1965.
[225] M. Dorigo, V. Maniezzo, A. Colorni, and V. Maniezzo, "Positive feedback as a search strategy," 1991.
[226] J. H. Holland, "Genetic algorithms," *Scientific american,* vol. 267, pp. 66-72, 1992.
[227] K. Price, R. M. Storn, and J. A. Lampinen, *Differential evolution: a practical approach to global optimization*: Springer Science & Business Media, 2006.
[228] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," in *Micro Machine and Human Science, 1995. MHS'95., Proceedings of the Sixth International Symposium on*, 1995, pp. 39-43.
[229] R. C. Eberhart, Y. Shi, and J. Kennedy, "Swarm Intelligence (The Morgan Kaufmann Series in Evolutionary Computation)," 2001.
[230] M. Clerc and J. Kennedy, "The particle swarm-explosion, stability, and convergence in a multidimensional complex space," *IEEE transactions on Evolutionary Computation,* vol. 6, pp. 58-73, 2002.

© COPYRIGHT UPM

[231] Y. Del Valle, G. K. Venayagamoorthy, S. Mohagheghi, J.-C. Hernandez, and R. G. Harley, "Particle swarm optimization: basic concepts, variants and applications in power systems," *IEEE Transactions on evolutionary computation,* vol. 12, pp. 171-195, 2008.
[232] P. Agrawal, S. Kaur, H. Kaur, and A. Dhiman, "Analysis and synthesis of an ant colony optimization technique for image edge detection," in *Computing Sciences (ICCS), 2012 International Conference on*, 2012, pp. 127-131.
[233] D. Lavanya and S. Udgata, "Swarm intelligence based localization in wireless sensor networks," *Multi-Disciplinary Trends in Artificial Intelligence,* pp. 317-328, 2011.
[234] J. Kennedy and R. E. P. S. Optimization, "Ieee int," in *Conf. on Neural Networks*, 1995.
[235] I. Uriarte, E. Zulueta, T. Guraya, M. Arsuaga, I. Garitaonandia, and A. Arriaga, "CHARACTERIZATION OF RECYCLED RUBBER USING PARTICLE SWARM OPTIMIZATION TECHNIQUES," *Rubber Chemistry and Technology,* vol. 88, pp. 343-358, 2015.
[236] P. Thakral, V. Arora, S. Kukreti, and A. Bakhshi, "In-silico engineering of intrinsically conducting copolymers using particle swarm optimization algorithm," 2013.
[237] A. K. Bakhshi, V. Kapoor, and P. Thakral, "Molecular Engineering of Electrically Conducting Polymers Using Artificial Intelligence Methods," in *Applications of Metaheuristics in Process Engineering*, J. Valadi and P. Siarry, Eds., ed Cham: Springer International Publishing, 2014, pp. 289-314.
[238] Y. Cao, Z. X. Deng, J. Li, and H. Liu, "Multi-Parameter Optimization Algorithm of Frequency-Dependent Model for Viscoelastic Damping Material," in *Advanced Materials Research*, 2010, pp. 416-420.
[239] Y. Li and C. Xueli, "Silicone Rubber Tensile Performance Test Methods Based on Particle Swarm Optimization," *Bulletin of Science and Technology,* vol. 7, p. 032, 2013.
[240] T. Tilford, M. Ferenets, J. E. Morris, A. Krumme, S. Pavuluri, P. R. Rajaguru*, et al.*, "Application of Particle Swarm Optimisation to Evaluation of Polymer Cure Kinetics Models," *Journal of Algorithms & Computational Technology,* vol. 4, pp. 121-146, 2010.
[241] J. McGraw, "The synthetic rubber manual," *Elastomer product information supporting rubber industry,* vol. 82, 2008.
[242] J.-B. Donnet, *Carbon black: science and technology*: CRC Press, 1993.
[243] U. Niyogi, "Polymer Additives and Compounding," *Polym. Sci,* pp. 1-30, 2007.
[244] U. K. Niyogi, "Additives for rubbers," ed, 2007.

[245] A. International, "Standard Practice for Rubber Materials Equipment and Procedures for Mixing Standard Compounds and Preparing Standard Vulcanized Sheets," 2001.
[246] Annual Book of ASTM Standards, "Standard Test Method for Rubber Property Vulcanization Using Oscillating Disk Cure Meter1," *Vol 09.01.,* vol. , October 2001.
[247] A. de Bever, "Dynamic behaviour of rubber and rubberlike materials," ed: WFW-report, 1992.
[248] A. International, "Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers Tension," January 2003.
[249] ASTM International, "Standard Test Method for Rubber Property Abrasion Resistance Rotary Drum Abrader," *2001*.
[250] D. C. Drucker, "A definition of stable inelastic material," DTIC Document1957.
[251] R. B. Simpson, *Rubber basics*: iSmithers Rapra Publishing, 2002.
[252] C. C. T. Zaharescu, S. Jipa, R. Setnescu, "Assessment on radiochemical recycling of butyl rubber," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 185, pp. 360-364, 2001.
[253] W. H. W. Brendan Rodgers, Scott Solis, , William Klingensmith, , *Rubber compounding*: Wiley Online Library, 2004.
[254] S. P. Vinita Dubey, NBSN Rao,, "Research trends in the degradation of butyl rubber," *Journal of analytical and applied pyrolysis,* vol. 34, pp. 111-125, 1995.
[255] H.-S. M. Andrzej G. Chmielewski, Shamshad Ahmed, "Progress in radiation processing of polymers," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* vol. 236, pp. 44-54, 2005.
[256] C. Prouillac and G. Rima, "Radiation Chemistry: from basics to applications in material and life sciences," *Radiation Chemistry: from basics to applications in material and life sciences,* pp. 281-293, 2008.
[257] T. Zaharescu, "Radiation Effects on Polymer-Based Systems," in *Thermal Degradation of Polymer Blends, Composites and Nanocomposites*, ed: Springer, 2015, pp. 121-155.
[258] D. W. Chunde Wu, Jinchu Fan, Liansheng Wang, "Photosonochemical degradation of trichloroacetic acid in aqueous solution," *Chemosphere,* vol. 44, pp. 1293-1297, 2001.
[259] S. D. Amit Kumar Naskar, Anil K Bhowmick, , "Surface chlorination of ground rubber tire and its characterization," *Rubber chemistry and technology,* vol. 74, pp. 645-661, 2001.
[260] A. A. E. H. Félix A López, Francisco J Alguacil, Teresa A Centeno, Belen Lobato, Belen, "Kinetics of the Thermal Degradation of Granulated Scrap Tyres: a Model-free Analysis," *Materials Science,* vol. 19, pp. 403-408, 2013.

© COPYRIGHT UPM

[261] S. Singh, C. Wu, and P. T. Williams, "Pyrolysis of waste materials using TGA-MS and TGA-FTIR as complementary characterisation techniques," *Journal of Analytical and Applied Pyrolysis,* vol. 94, pp. 99-107, 2012.
[262] M. M. Hassan, N. A. Badway, M. Y. Elnaggar, and E.-S. A. Hegazy, "Thermo-mechanical properties of devulcanized rubber/high crystalline polypropylene blends modified by ionizing radiation," *Journal of Industrial and Engineering Chemistry,* vol. 19, pp. 1241-1250, 2013.
[263] X. Colom and J. Canavate, Carrillo, F, Suñol, JJ, "Effect of the particle size and acid pretreatments on compatibility and properties of recycled HDPE plastic bottles filled with ground tyre powder," *Journal of applied polymer science,* vol. 112, pp. 1882-1890, 2009.
[264] W. Klingensmith and K. Baranwal, "Recycling of rubber: An overview," *Rubber World,* vol. 218, pp. 41-46, 1998.
[265] T. Sreeja and S. Kutty, "Studies on acrylonitrile butadiene rubber/reclaimed rubber blends," *Journal of elastomers and plastics,* vol. 34, pp. 145-155, 2002.
[266] T. Sreeja and S. Kutty, "Cure characteristics and mechanical properties of natural rubber/reclaimed rubber blends," *Polymer-Plastics Technology and Engineering,* vol. 39, pp. 501-512, 2000.
[267] D. Systèmes, "Abaqus documentation," *Providence, RI, United States,* 2012.
[268] J. Y. Wong, *Theory of ground vehicles*: John Wiley & Sons, 2008.
[269] K. Narasimha Rao, R. K. Kumar, and P. Bohara, "A sensitivity analysis of design attributes and operating conditions on tyre operating temperatures and rolling resistance using finite element analysis," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 220, pp. 501-517, 2006.
[270] M. H. R. Ghoreishy, "A state of the art review of the finite element modelling of rolling tyres," *Iranian Polymer Journal,* vol. 17, pp. 571-597, 2008.
[271] S. Chae, M. El-Gindy, M. Trivedi, I. Johansson, and F. Öijer, "Dynamic response predictions of a truck tire using detailed finite element and rigid ring models," *ASME Paper No. IMECE2004-61111,* 2004.
[272] A. Ök, S. Özüpek, and E. Becker, "Crack simulation in pneumatic tyres using the finite element method," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 221, pp. 157-166, 2007.
[273] T. Tang, D. Johnson, R. E. Smith, and S. D. Felicelli, "Numerical evaluation of the temperature field of steady-state rolling tires," *Applied Mathematical Modelling,* vol. 38, pp. 1622-1637, 2014.

© COPYRIGHT UPM

[274] K. Captain, A. Boghani, and D. Wormley, "Analytical tire models for dynamic vehicle simulation," *Vehicle System Dynamics,* vol. 8, pp. 1-32, 1979.
[275] Y.-P. Chang, M. El-Gindy, and D. Streit, "Influence of tyre loading and inflation pressure on standing waves phenomenon using PAM-SHOCK," *International Journal of Heavy Vehicle Systems,* vol. 10, pp. 86-111, 2003.
[276] K. M. Marshek, H. H. Chen, R. B. Connell, and R. Hudson, "Experimental determination of pressure distribution of truck tire-pavement contact," *Transportation Research Record,* vol. 1070, pp. 9-13, 1986.
[277] K. Narasimha Rao and R. K. Kumar, "Simulation of tire dynamic behavior using various finite element techniques," *International Journal for Computational Methods in Engineering Science and Mechanics,* vol. 8, pp. 363-372, 2007.
[278] V. Dorsch, A. Becker, and L. Vossen, "Enhanced rubber friction model for finite element simulations of rolling tyres," *Plastics, rubber and composites,* vol. 31, pp. 458-464, 2002.
[279] M. Ghoreishy, "Steady state rolling analysis of a radial tyre: comparison with experimental results," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 220, pp. 713-721, 2006.
[280] M. Ghoreishy, "Finite element analysis of steady rolling tyre with slip angle: Effect of belt angle," *Plastics, rubber and composites,* vol. 35, pp. 83-90, 2006.
[281] R. N. Jazar, "Vehicle dynamics," *Theory and Applications. Riverdale, NY: Springer Science+ Business Media,* 2008.
[282] J. M. Bland and D. G. Altman, "Agreement between methods of measurement with multiple observations per individual," *Journal of biopharmaceutical statistics,* vol. 17, pp. 571-582, 2007.
[283] I. E. Frank and R. Todeschini, *The data analysis handbook* vol. 14: Elsevier, 1994.
[284] G. Smith, "Probability and Statistics in Civil Engineering Collins," ed: London, 1986.
[285] F. Pimentel-Gomes, "Course of experimental statistics," *Piracicaba: Nobel,* 2000.
[286] S.-E. Inc., "Design-Expert software user’s guide, Technical manual," vol. v10, 2016.

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