MASTER OF SCIENCE THESIS

DEVELOPMENT AND PRODUCTION OF A NEW PROTOTYPE TIRE AND RIM FOR REMOTE CONTROLLED MODEL RACING CARS

A.B. LAGERWEIJ

S1846477

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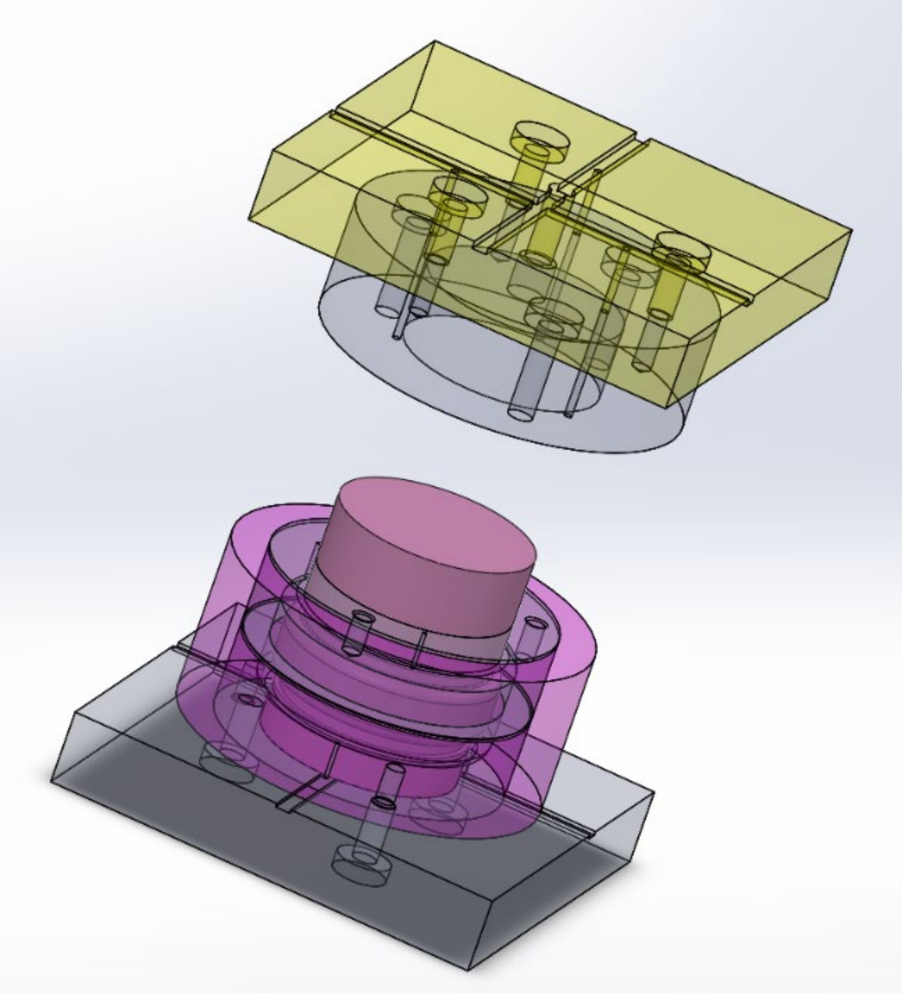

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Development and production of a new prototype tire and rim for remote controlled model racing cars

AUTHOR(S)
A.B. Lagerweij
S1846477
MSc Mechanical Engineering

GRADUATION COMMITTEE
Name of supervisors
Affiliations

prof. dr. A. Blume (Chair)
ET-ETE
dr. F. Grunert (Supervisor)
ET-ETE
dr. M.I. Abdul Rasheed (External member)
ET-AMDA

POSTAL ADDRESS
P.O. Box 217
7500 AE Enschede

WEBSITE
www.utwente.nl

PREFACE

This project started with the aim to create a way for students to produce their own tires for radio-controlled (RC) car, while also improving the ease-of-use of RC car tires. This project includes an entire design process of an RC car tire, staring with its' rim and a suitable production technology of the final product. After a long COVID19 period in which the author really missed the 'Engineering' part in his Mechanical Engineering studies, such a design project was really wanted. With a Bachelor's in Mechanical Engineering, rubber technology was not something I was really familiar with. I am very pleased with the knowledge I have acquired about designing with rubber, but also working with rubber in the labs. This project really gave me an insight in what working as an engineer could be like, researching, designing and producing solutions for a problem. This research resulted in: a compression mold to create tires, rims produced by fused deposition modelling (FDM) of PLA and rubber tires produced using the designed mold. The produced tires proved to work on the RC car, although the ease-of-use of the mold can still be improved, the general outcome of the project worked as designed.

The ambition to design and create a working product is fulfilled, but I could not have managed this without the help and supervision of my supervisors; prof. dr. A. Blume and dr. F. Grunert. Thank you for brainstorming together and keeping this project on track (pun intended). I would also like to thank my family for their support in my pursuit of the degree these last years. Lastly, I would like to thank Max Muller for his help in the design and production of the mold. Without his insights and production skills the final product would not be as it is today.

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Abstract

There are many people who drive a radio-controlled (RC) car, either for fun or professionally. The one thing that keeps these cars attached to the terrain are the tires. Tires are the connection between the road and the car, and are therefore extremely important for the performance. The tire compound is critical for the performance of the tire and also a difficult component due to the different characteristics that must be balanced. These characteristics are often described in the 'magic triangle'. Where compound design is always a compromise between: rolling resistance, wear resistance and wet grip. Designing a tire compound is a great way to get familiar with rubber compounds. This is why this is used at the University of Twente Elastomer Science & Engineering (ESE) course as an exercise for students. To actually use the compounds, they must be formed into tires that fit an RC car. This study focusses on the design and creation of RC tires from beginning to end. Rims that fit standard RC racing cars are designed that form a glue-less connection with the tires for ease of use. A mold is designed to turn the rubber compounds into tires that comply with official RC racing rules. 14 different compounds are created and characterized. These different compounds are created to serve a different purpose, focusing on grip or wear. These compounds were then used to produce tires to fit the RC car using the designed mold. The compounds are used in a real test drive to check how the material properties translate to real-world performance. The end goal is to create a package for students to create and test their own tires, linking the theoretical part of compounding to practical performance.

Chapter 1

Introduction

1.1 Aim of the project

The main goal of this project is to design a package which can be used to produce tires and rims for a remoted controlled car. To achieve this objective, multiple sub-goals are to be achieved. The first sub-goal is to design a tire and rim with a glue-less connection which fit on a standard RC car. Different rubber compounds are formulated which have difference performance goals, focusing either on wear reduction or grip improvement. Each compound is be tested for their characteristics and how they behave in the mold. The second sub-goal is to define the production of the tire and rim. For the tire this means creating a mold which can be used to vulcanize the rubber in the desired shape. For the rim this means designing a rim which can be easily 3D-printed in house as well. The third sub-goal is characterizing the formulated compounds, testing the mold and produced tires. Testing the produced tires in real driving tests would be is desirable, but this might not be possible due to the risk that the production of the tire is not sufficient. Comparing the compound characteristics to real world performance is a good way to test if it is possible to see how and if differences in compound characteristics translate to real-world performance, but this is optional and is only be performed if time permits.

1.2 Thesis concepts

This thesis is constructed in four main parts. Starting with the literature study, containing the information which is of importance for the rest of the research. This information includes tire regulations, rubber production techniques and rubber compounding. The second part is the design of the rim, tire and mold. In this part multiple concepts for the mold are composed. Creating a design which could be produced and fits the existing compression molding machine brings many challenges. After each design is elaborated upon, one is extensively designed. The tire design and compound formulations are created and a matching rim is designed. These different compounds differ in performance goal: either wear minimization, grip maximization or reference. Once the 14 different compounds are derived, they are mixed in the lab. Thirdly the results are evaluated. These results consist of the material characteristics, especially characteristics which are important for tires are determined using various test methods. From these material characteristics one compound is chosen to produce in the mold. After curing the tires which are produced by the mold are evaluated, to check if the mold functions as proposed and the rubber flows correctly through the mold.. From the results and experiences, conclusions and recommendations are formulated for future research and to improve the package for the ESE course.

Chapter 2

Literature survey

2.1 General information

Before it is possible to design a tire, rim and production system for these products, more information about these products must be reviewed. Research has been done to find out what kind of standardized tires and rims are available for RC cars. By making the design fit in professional standards, it is easier to use them on an RC car that is also (semi) professional. These type of cars are generally modular, meaning (almost) every individual part can be swapped and therefore have far more replacement parts available. This ensures the longevity of the products designed in this study. Information about several production techniques for the rim and tire are reviewed and the designs altered to fit with their production technique. The performance of the tire and the flow behavior in the mold, is greatly dependent on the rubber. The compounds are divided in three groups: grip maximization, wear minimization and reference. How the tires perform in these categories is greatly dependent on the compound formulation. That is why the compound formulation of the rubber was also of interest in this literature survey.

2.2 A history of RC cars

For a more complete picture of radio - controlled (RC) cars first, a look back at the beginning is necessary. The first radio-controlled car was the nitro powered Ferrari 250LM. Nitro powered generally means that an engine is powered with a fuel which contains between 10% and 40% nitromethane, mixed with methanol. This was as early as 1966. A year later, RC cars started being commercially produced by Mardave (1). The first commercial electric car was introduced by a Japanese company, Tamiya, in 1974. Until 1979, most RC cars were focused on on-road driving (1). Only in 1979 Tamiya introduced off-road buggy's. These models used real suspension and textured rubber tires to allow the cars to drive on rougher surfaces. This was the beginning of a golden age of RC cars because the users were not restricted to smooth, paved roads anymore. The 80s also were very successful because high performance models were now available, and the sport surged in popularity. In 1979 the International Federation of Model Auto Racing (IFMAR) was established and in 1985 the first IFMAR world championship was held followed by a world championship every two years (2). This 1:10th Electric off-road championship is still seen as the most prestigious event in this sport nowadays. Not only by the hobbyists, but also by the manufacturers. It attracted the biggest brands from the industry. At the 1989 virtually every manufacturer who had a 1:10 buggy on the market was represented (1). In the 2000's the emphasis of the sport was mostly on rock crawlers. Models which could tackle very difficult terrain. One of the most recent innovations is the use of hydrogen fuel cells (3). These were designed to increase the driving range of the cars. They can run up to four times longer than electric models.

2.3 Types of tires

Since tires provide the interface between the machine and the surface, they are incredibly important. For each function there are different tires available to maximize the function's performance. In this section a quick overview of different types of tires is given to give more context what kind of tire is used in RC racing.

Firstly, the most used type of tire in the world: passenger car tires. Even with negative impact of Covid 19 on the sales of new tires, the total sales of new passenger car tires in Europe was around 250 million units (4). A passenger car tire is an incredible feat of engineering.

The RC cars are derived from real passenger cars, so are their tires as well. The mechanics of real passenger tires also play a role in the much smaller RC tires, so a better understanding of real passenger tires can support designing a better RC tire.

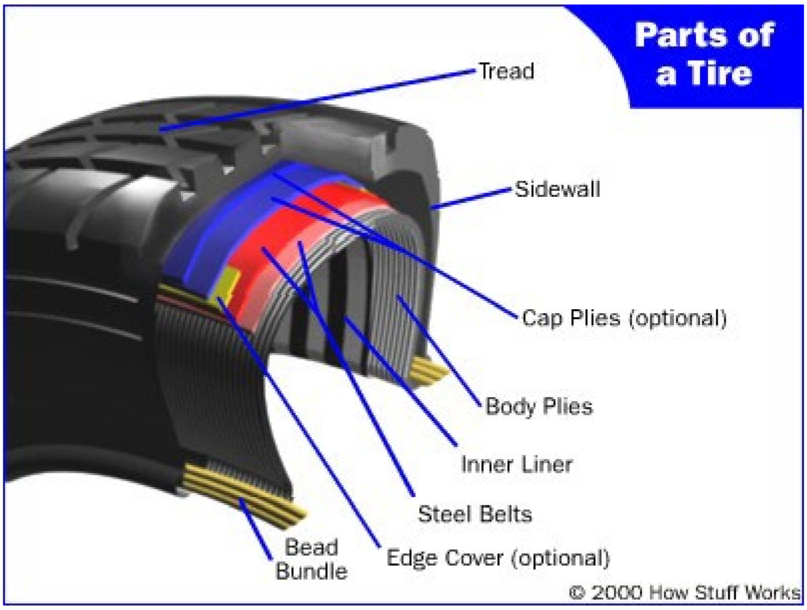

Figure 1: Parts of a passenger car tire (5)

In Figure 1 the different parts of a passenger car tire are shown. These parts are explained here.

Bead: Steel cable coated with rubber. Gives the tire the strength to stay seated around the rim and to handle the process of installing the tire one the rims

Body: Consists of several different fabrics, the most commonly used one is polyester cord. These cords are run perpendicular to the tread. These plies are coated in rubber to make sure the air inside is sealed. A tire's strength is described by the number of plies it has. Most car tires have two body plies. Jetliners for example, often have over 30 plies.

Belts: Belts made from steel are used to reinforce the area under the tread. They provide puncture resistance and help the tire stay flat so the contact with the road is maintained.

Cap plies: Some tires have cap plies, an extra layer of polyester fabric to hold everything in place. Mostly used on tires with higher speed ratings.

Sidewall: provides lateral stability for the tire, protects the body plies and keeps the air from escaping.

Tread: The tread is the contact interface with the road. Its compound is very important for the characteristics of the tire. The tread has a pattern which makes sure water can be transported out from under the tire.
The tread compound is one of the most important compounds of the tire, this compound provides the connection with the road. The parameters on which tire engineers focus mostly are: Wear, wet grip, rolling resistance, dry grip, abrasive wear resistance, ride and handling.
To elaborate more on the tread: it is generally divided into three compounds: tread caps, tread base and tread wings/sides. These different parts are shown in Figure 2.

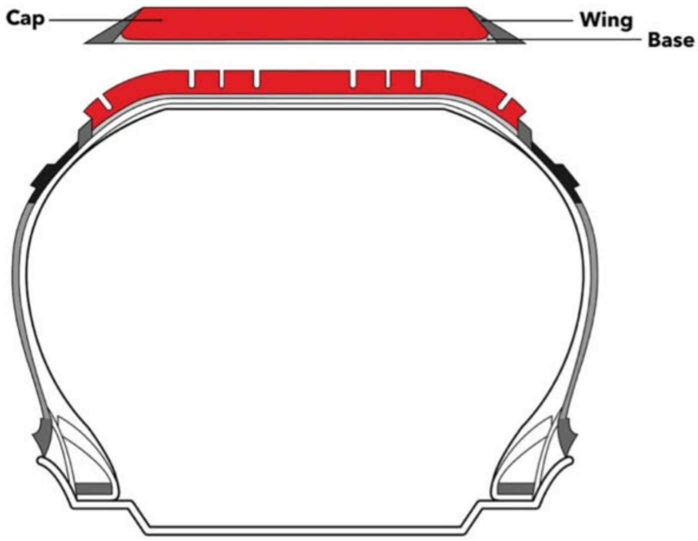

Figure 2: Parts of a tire tread (6)

The tread base creates the bonding between the tread and the tire carcass. It is designed to have a high adhesion property. The tread cap is generally made with an abrasion resistant, high grip rubber compound providing traction, low rolling resistance and high mileage.
The tread wing provides the transition from the tread and the sidewall. The wing compound is designed with adhesion to connect the tread area with the sidewall. The tread profile is designed to provide uniform wear, channel water out of the footprint and minimize noise.

The tread cap is the most important of the three compounds, it has the highest influence on the performance of the tire due to the fact that it is the contact point with the road. A typical tread cap consists of NR, SBR or BR as well as fillers and additives.
The fillers have some effect on the overall tire performance. Both black carbon and silica can improve the tear resistance, tensile strength and abrasion resistance, meaning both can increase wear performance and traction. Silica and silane can also improve rolling resistance with a minimum tradeoff. Carbon black is an effective filler, but cannot improve the target conflict between wear, wet and rolling resistance. However, silica and silane can improve wet performance or rolling resistance without a tradeoff on wear. High performance tires are highly silica and silane-based compounds.
Of course there are quite a lot of differences between passenger car tires and RC tires. Passenger car tires need to hold the air pressure inside, RC cars do not. Also, passenger car tires have a lot of reinforcing layers like the bead and the body plies whereas generally, RC cars are only made of one compound.

A type of tire that is most similar to that of RC cars are forklift tires. There are multiple types of forklift tires: slip on tires and solid pneumatic tires. There are two reasons why these tires are more similar to RC car. Firstly, they do not have to hold air inside of them, just like RC car tires. Secondly, forklift and RC car tires are both made using a single compound, not a blend of multiple compounds.

2.4 Professional RC racing

The goal of this research is to create a work-package for the ESE course. This work-package contains all the necessary information and materials to create RC tires, and drive with them. Therefore, an RC car is necessary. The choice for 'professional' RC cars was obvious. They provide high quality products with many standard components and connections between parts. This way it is easy to interchange tires and rims, but it is easy to replace parts in case they break. This is something that is much more limited on toy-grade RC cars.

2.4.1 RC tire design

RC racing is a world-wide phenomenon with many different classes. There are many ways to classify them all. Firstly, the classes are divided into sizes. They are displayed as 1/5, 1/8, 1/10, etc. Which just means that 1/5 is 1/5th of a regular car size. The next way to divide the classes is the powertrain: this is either powered by an internal combustion engine (ICE) or by an electric motor. Lastly, the type of body gives away the type of car. The body can take many forms, there are offroad bodies, buggies, or RC cars which resemble existing cars.

Each of these classes have different tires, because each class has different demands. The tires can be subdivided by: size, track, compound, profile and inserts. Firstly there is size. The size of the tire is proportional to that of the vehicle. A 1/10th touring car could have the following tire dimensions: outside diameter 65mm and width 26mm. The rims are mostly secured with a 12mm hex connection. Secondly the track. The track is largely determined by the surface on which the cars race

There are 4 main types of tracks which are shown in Figure 3. Slick tires are used for flatter, smoother surfaces like pavements and tarmac. Full spiked tires are used for muddy and grassy surfaces. Mini pin tires are used on carpet surfaces. Mini spiked tires are used on many different surfaces and offer good grip on most, this tire sits between the full spiked and mini pin tires.

Figure 3: Type of tire tracks, from left to right: Slick tires (7)*, Mini pin tires* (8), *mini spiked tires* (9) *and full spiked tires* (10)

Moreover, there are also on-road tires with a tread pattern and tire profile. The tire profile defines the general shape of the tire. They can be roughly categorized in square, rounded, and everything in between. A square tire has a flat crown, which is the center part of the tire tread. Due to the large contact area it has excellent forward traction. In smooth track conditions these tires also provide good traction when cornering. When the tracks start to break up, or in conditions where the car slides a lot, these tires suffer most. Square tires can slide unpredictably (11). A rounded tire is more predictable through corners and excellent in more rough conditions. While not as good in generating forward traction in smooth conditions, the rounded tire is almost universally chosen when the track is not very smooth.

Thirdly there is the compound which determines in many ways the performance of the tires. Compounds can be designed to reflect the user's needs and wishes. For example: more grip, better wear resistance, or combinations of these. Harder compounds generally offer less grip and more durability and softer compounds the other way around: more grip and less durability. Each tire manufacturer has its own compound which are confidential, and each manufacturer also has different names for their compounds.

Figure 4: Foam tire insert (12)

Lastly there is the tire insert. Store bought tires are pre-glued most of the time and have an insert which sits between the rim and the tire and is generally made from foam. An example of a foam insert can be seen in Figure 4. Inserts replace the air between the rim and the tire and can be chosen in such a way that the ride is stiffer or more flexible. In a way it is comparable to the air pressure in a regular passenger car. Most tires, except hard tires, require a foam insert. Some modifications can be done like cutting the square edge of the outside of the foam to make a softer sidewall. This can round the tire profile more, making it more consistent through corners and less likely to 'grab and roll'. Softer tires require more dense foam inserts. Inserts are not part of the present design process, there is space to use them, but they are not mandatory since the thickness of the rubber is increased. In this way foam is not necessary to reach the required stiffness

2.4.2 RC tire regulations

Just like any other professional sport, RC racing is regulated by different federations. The world governing body is the International Federation of Model Auto Racing (IFMAR). In Europe there is a sub federation: the European Federation of Radio Operated Model Automobiles (EFRA). Finally, the smallest governing body in the Netherlands is the 'Nederlandse Organisatie Modelauto Clubs' (NOMAC). The rules of these federations each comply with each other, but the smaller federations are less extensive. The European federation has fewer racing classes than the IFMAR, and the Dutch federation has fewer racing classes than the European one. This makes that the regulations for the Dutch federation have a lot less rules than the European and International ones.

Internationally, there are dozens of classes, from offroad to on-road, from internal combustion engine to electric.

NOMAC has the following classes (13):

- Internal combustion engine (ICE) circuit large scale
- ICE offroad large scale
- ICE circuit (1:8)
- ICE circuit (1:10)
- Electro circuit (1:10)

In this research the Dutch federation (NOMAC) is be used as reference to keep the rules as simple as possible. The focus on the cars is on the Electro circuit (1:10). Electric cars offer better flexibility in use, are more sustainable and cheaper than ICE cars. The terrain on which these cars in this class drive is tarmac, so that is also easy to replicate outside. Within Electro circuit (1:10) there are more sub-classes. These classes differ in the shape of the car. The following subclasses can be identified: F1 (formula one inspired cars), Fronti (front wheel drive) or Touring car modified/stock. The most common subclass is touring car. These cars are four wheel driven and all have the same electromotor.

To make racing as fair as possible, every racing class has its own set of rules. The NOMAC states the following rules regarding tires for Electro circuit (1:10) Touring car (modified). The rules regarding the tires are the following:

- Any type of rubber with a hollow chamber
- Minimum hardness of 32 Shore A
- Maximum use of 2 sets per game day
- With a wet track, Dunlop Rain Tire D20 must be used

The meaning of hollow chamber was not explained in the rulebook. Contact with NOMAC concluded it is any tire with a hollow space between the rim and tire. This space can then be filled with a foam insert. Changing these foam inserts gives more freedom to tune the behavior of the tire. Almost all 1/10 tourwagen cars have these types of tires.

2.5 Material

Why is rubber used for many types of tires? Passenger car tires are all made of rubber and some high-end RC-car tires as well. It is soft, elastic, resistant to cutting and scraping, has a high coefficient of friction and low permeability to gases. This combination of properties is perfect for tires.

The compound for a tire is mostly a trade-off between rolling resistance, wet grip and wear as can be seen in Figure 5.

When developing the tire compound, one can increase the wear resistance for example, but this decreases one or both of the other characteristics (wet grip and rolling resistance).

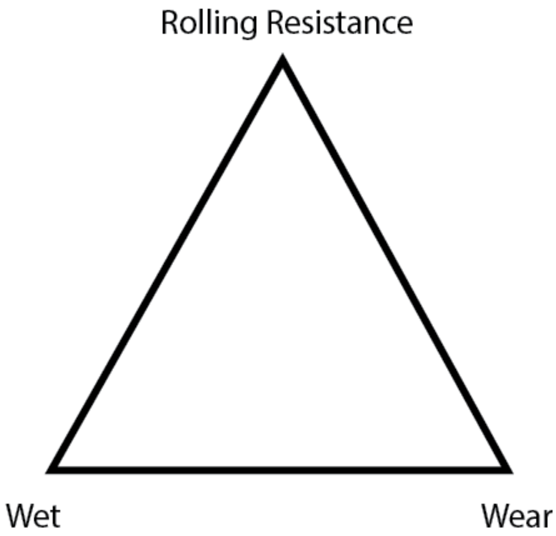

Figure 5: Triangle of tire performance

2.5.1 Grip and wear

In passenger car tires, grip, wear and rolling resistance are the most important performance factors. For RC-car tires this is mostly true, but rolling resistance is of less importance. The performance of the RC-car tire is then determined by the grip and the wear characteristics. Grip is defined as the coefficient of friction between the surface of the tire and the surface of the track. This friction depends on many factors like the roughness of the track and temperature. Two phenomena can be held responsible for friction: Indentation and molecular adhesion.

Indentation

This is where the roughness of the track excites the rubber. As rubber used for tires is viscoelastic, meaning it exhibits elastic and viscous behavior when deformed, it distorts and 'adapts' to the texture of the track's surface. When this rubber is deformed, it does not immediately return to its original shape because of hysteresis. This asymmetrical deformation of the rubber creates a reaction force opposed to the slippage, meaning it creates a friction force. A visual representation by Michelin (14) can be seen below.

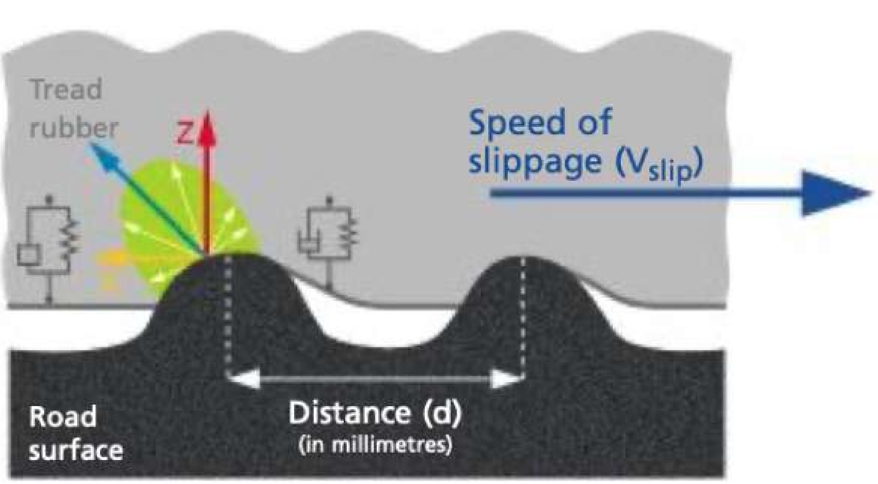

Figure 6: Indentation and grip of rubber (14)

The behavior of the rubber is comparable to a spring-damper system. When the rubber hits a bump, the spring and damper compress. The viscosity of the oil in the damper resists displacement which generates heat. After the bump, when the load is removed the spring pushes the damper back, but not to its original position, this is called hysteresis. The energy loss in the form of heat results in the asymmetrical deformation of the rubber.

Adhesion

With molecular adhesion there occurs an interaction between the tire rubber and the track which generates grip. In essence, it consists of three parts:

1. the molecular chains of rubber form bonds (or Van der Waals bonds) with the track surface.
2. The tire slides over the surface, these chains are stretched and the viscosity of the rubber resists this deformation generating ga friction force opposed to the slippage
3. The bond breaks and forms again further down the tire's surface

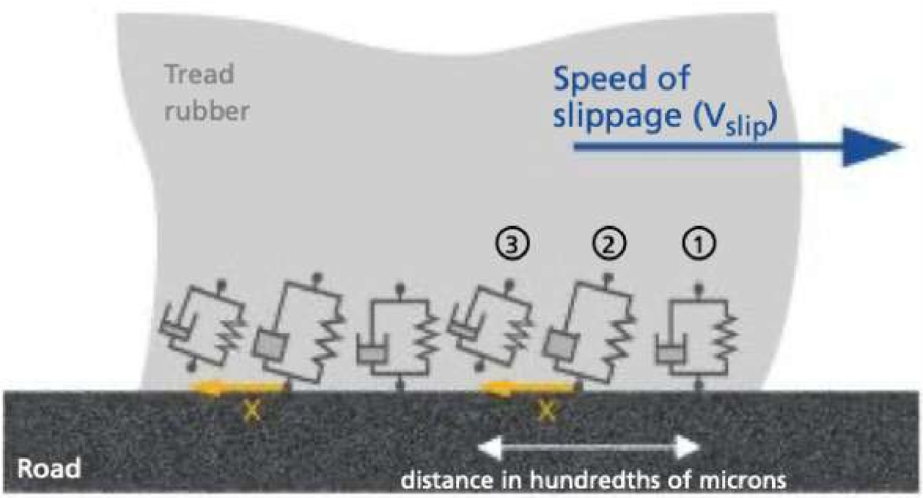

Figure 7: Molcular adhesion and grip (14)

Molecular adhesion is the reason why tires deposit rubber on the track. The molecular bonds can either break away from the track, or break away from the tire. In this case the rubber molecules are torn off the tire and remain on the track's surface.

2.6 Rubber shaping

2.6.1 Forming techniques

The focus in this research is placed on the mold design and production. To understand which properties are important and what type of mold is necessary, some information must be gathered regarding the shaping of rubber. Four general techniques can be identified when shaping rubber: Extrusion, calendaring, coating or molding.

Extrusion consists of forcing rubber through a series of screw extruders, these screws force the rubber through openings, or 'dies', these contain the final profile of the rubber. After the extrusion the rubber is vulcanized. This production technique is used mainly for products with a continuous cross-section like tubes, seals, gaskets, etc. The extrusion process is shown in Figure 8.

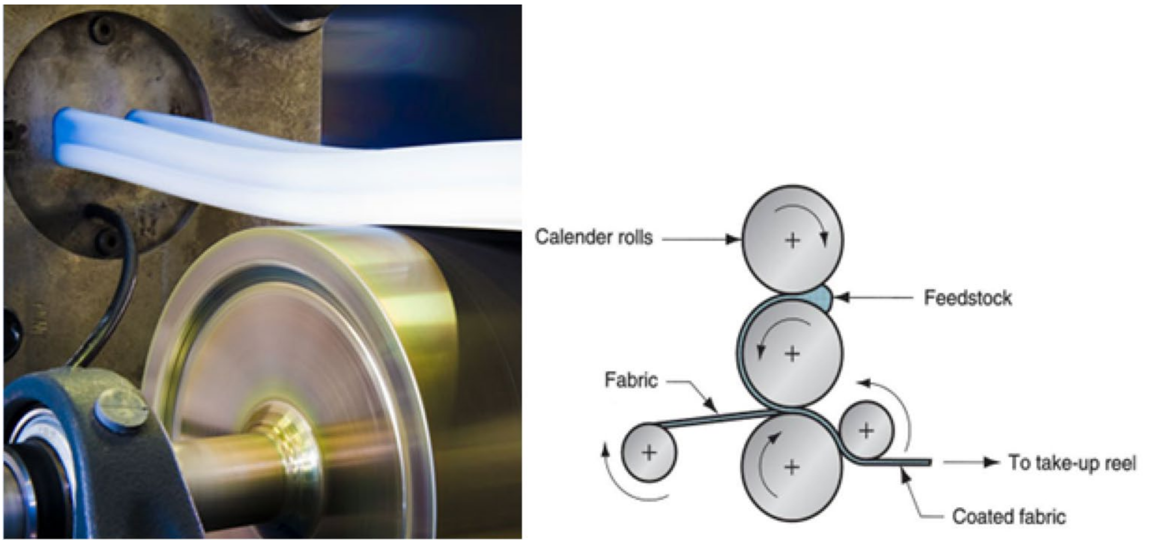

Figure 8: Left: Rubber extrusion (15) *right: rubber calendering* (16)

Calendering is a process by which rubber is pressed into textiles (fabric, cloth, etc.) to make composite sheets. A calendaring machine consists of two or more rolls that revolve in opposite direction. The calendering process is schematically shown in Figure 8.

Coating uses the calendering process to apply a coat of rubber, this is used for passenger car tires, waterproof tent cloths, conveyor belts, etc.

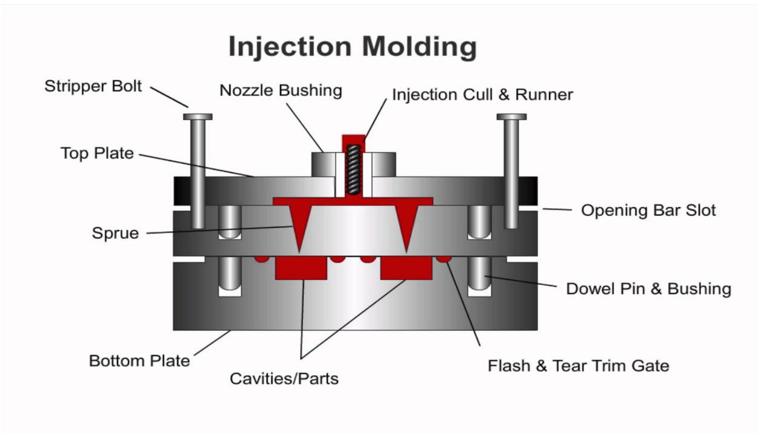

Figure 9: Rubber injection molding (17)

Finally, there is molding. Molding can be subdivided into: injection molding compression molding and transfer molding. Injection molding is a process where heated, unvulcanized rubber is injected into a closed mold under high pressure.

It can be used with a wide range of rubbers and can create a lot of different geometries. Some advantages of injection molding are: Low material waste, fast cycle times and high dimensional tolerances. However, the setup costs are very high.

Compression molding is an older and more simple technique. Using heat and pressure the rubber is shaped into the form of the mold. The pressure is achieved using the compression of the mold. The vulcanization also takes place in the mold, after vulcanization the product is removed from the mold. For simple parts the mold consists of two plates: the cavity side and the core side.

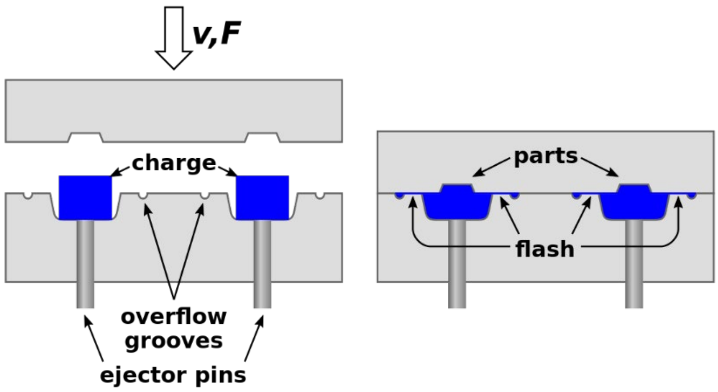

Figure 10: Rubber compression molding (18)

Some advantages of compression molding are: low waste, lower costs than injection molding, larger parts than injection molding and stiffer materials can be used for the product. The processing times are slower however.

Finally, there is transfer molding. The rubber is cut and weighed into pre-forms. The difference between compression molding and transfer molding is that the rubber is not put directly into the cavity of the mold. Rather, it is compressed and injected into the mold through a runner and gate system. Multiple cavities can be used this way, so the manufacturing time is lower than that of compression molding. However, it creates some more material waste due to the runner and gate system. The rubber in the runner and gate system is also vulcanized and can therefore not be used again after.

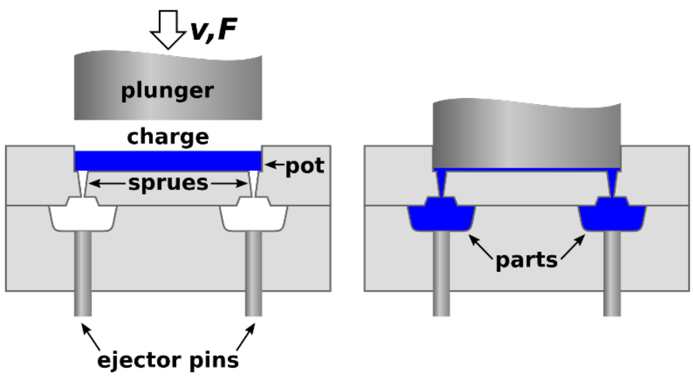

Figure 11: Rubber transfer molding (19)

Chapter 3

Experimental

3.1 Radio-controlled car

To test the tires, an RC car was purchased to design the rim and tire for. The choice for this car is the Himoto Nascada 1/10. This platform offers a wide range of replaceable parts, every part is replaceable or upgradable. The car is built for on-road driving and has a top speed of 45 km/h (20). This way it is possible to reach the limit of the car's grip. If a slower car is chosen, this limit might not be reached.

Figure 12: The Himoto Nascada 1/10 used as basis of this project (20)

3.2 Materials

The compound is an important part of the puzzle because it relates to the performance of the product as well as to the production. One can change the compound if the flow properties inside of the mold are not correct , for example: if the viscosity of the compound is too high, not every part of the mold might be reached and the product's demands not met. 14 different compounds are created to show the different characteristics of compounds. These 14 compounds are subdivided into three groups: Maximize grip, minimize wear and a somewhat experimental butyl rubber compound. Within these three groups the only variable is the filler type and loading. An overview of the compound formulations can be seen in subchapter 3.3.1. A compound formulation can be broken down into multiple categories, each category is treated in this chapter.

3.2.1 Polymer

The largest part of the characteristics of the final rubber are determined by the polymer itself. So the compound formulation starts with the choice of polymer. This is done by first looking at car tires, typically, three different polymers are used (for the elastomers) in car tires: NR, NBR, SBR and BR. This is the starting point for the polymer choice, because in essence the car tire and RC tire fulfill the same goal. A patented butyl rubber (IIR) compound formulation was found in literature, a simplified version of this is also made as a reference. The polymer choice starts by stating the most important characteristics for the two groups (grip maximization and wear minimization).

In literature, one patent was found regarding the compound formulation of RC car tires (21). This patent was reviewed and the compound formulation was simplified so it can be created with the available materials. The polymer which is used is chlorobutyl 1066 (HIIR). These compounds will be called 'reference compounds' from now on.

For grip maximization the following characteristics were deemed most important: Cold flexibility, impact resilience and glass transition temperature. Cold flexibility helps to increase grip if the temperature in the tires are not high yet. A higher impact resilience increases the amount of energy the rubber absorbs, this can also indicate higher grip levels. The glass transition temperature is mainly of importance for colder temperatures, having a lower grass transition temperature ensures that the rubber has grip even at low temperatures. This group of compounds is called 'grip compounds' from now on. For wear minimization the following characteristic was deemed most important: Abrasion resistance. This group of compounds is called 'wear compounds' from now on.

One demand that must be adhered to is the minimum hardness of 32 Shore A. This demand is stated by the NOMAC. If this demand is not met, it is not possible to use the designed tires in an official race.

1: excellent **6: very bad**	**NR**	**IR**	**IIR**	**SBR**	**BR**	**NBR**	**EPDM**	**ACM**	**CR**	**ECO**	**CSM**	**FKM**
Tensile strength (no filler)	1	2	4	5	6	5	5	6	3	4	5	5
Tensile strength (with silica)	1	2	3	2	4	2	3	3	2	3	3	3
Elongation at break	1	1	2	2	3	2	3	4	2	3	3	3
Abrasion resistance (with silica)	4	4	4	3	1	2	3	4	3	3	3	4
Tear resistance	2	2	3	3	5	3	3	3	2	3	3	4
Impact resilience	2	2	6	3	1	3	3	4	3	3	4	5
Cold flexibility	2	2	2	3	2	3	2	5	3	3	5	5
Heat resistance	5	5	3	4	4	3	2	2	3	2	3	1
Ozone resistance	4	4	2	3	2	3	1	2	2	1	2	1
UV resistance	4	4	2	3	3	3	1	2	2	1	2	1
Oil resistance	6	6	6	5	6	1	4	1	2	1	2	1
Inflammability	6	6	6	6	6	6	6	6	2	2	3	3
Gas permeability	5	5	1	4	4	2	4	3	3	1	3	3

Figure 13: Overview of polymer properties (22)

An overview of the polymer properties is shown in Figure 13. Using these properties and other practical considerations like availability and processability.

The polymer which is the base for the grip compounds is NR. As can be seen in Figure 13, NR has a very good impact resilience, cold flexibility and a glass transition temperature (Tg) of around -70 °C (23) The polymer used is called natural rubber RSS1. Ribbed Smoked Sheets (RSS) is made from high quality natural rubber latex. These rubber sheets are used in the production of tires. Natural rubber is harvested in the form of latex from the rubber tree.

The polymer which is the base for the wear compounds is BR. From Figure 13 it can be seen that BR has a very good abrasion resistance. Buna CB 24 is a high-cis polybutadiene (BR). This is a synthetic rubber formed from the polymerization of 1,3-butadiene (24). It has a high resistance to wear and is used in the production of tires. The catalyst used in the production affects the type of polybutadiene, since it can polymerize in three different ways: Cis, trans and vinyl. The type of BR used has a high cis content.

The polymer which is the foundation for the reference compounds is butyl rubber, more specifically; chlorobutyl 1066. Chlorobutyl is a chlorinated copolymer of isobutylene and isoprene. This chlorine makes it cure faster, more heat stable and more compatible with other rubbers than standard butyl (25).

3.2.2 Filler

As filler material carbon black (CB) is used. This acts as a reinforcement in the rubber matrix. The amount of reinforcement depends on the surface area and the structure of the CB. The grade of CB is explained with a number, N220 for example. The first number is the surface area grade. The higher the number, the lower the reinforcement. Meaning N100 has a high surface area and is highly reinforcing and N900 has a low surface area and is not very reinforcing. Generally; N100-300 are difficult to disperse, have a high compression set and dynamic energy loss. N700-900 have a low compression set and dynamic energy loss (26).

As an alternative, silica and silane could be used as reinforcement in the rubber. Using silica and silane instead of carbon, however, increases the complexity of the compound formulation, so the use of carbon black as reinforcing filler is preferred.

Two different types of CB is used in the compounds: N330 and N660. Each with different filler loadings: 15/35/55 PHR. PHR stands for parts per hundred rubber. This is a way to describe the contents of a rubber content based on 100 parts of polymer. So, a total of 6 grip compounds will be produced. The wear and butyl rubber compounds only use 35 and 55 PHR of filler loadings, because a lower (15 PHR) filled load would make the compounds very sticky and hard to process. So these two compound groups have 4 different compounds each. This makes a total of 14 compounds which are produced and tested.

To make the compound naming more clear, future abbreviations that will be used are summarized in Table 1. For example, a compound based on NR, with 15 PHR of carbon black N330 is abbreviated to: NR15-330.

Table 1: Compouding abbrevations

Polymer type	Filler type	Filler load (PHR)
NR	N330, N660	15 / 35 / 55
BR	N330, N660	35 / 55
HIIR	N330, N660	35 / 55

3.2.3 Plasticizers

Plasticizers are low-volatile fluids which are highly compatible to the rubber matrix. Generally these are mineral oils, esters, phosphates, ether and thioether. These plasticizers increase the mobility of the polymer chains which in its turn: lowers viscosity > improves processing and makes for easier mixing. The three different polymers are all compatible with TDAE. Treated Distillate Aromatic Extracts (TDAE) is a processing oil with a high aromatic content.

3.2.4 Anti-degradants

Anti-degradants are an ingredient used to deter the aging of rubber products. They include antioxidants and antiozonants, since the aging of rubber is largely by oxygen. Types of rubber that easily interact with oxygen can be improved by adding a chemical antioxidant to prevent the oxidation. One can also use a physical anti-degradant like wax, this provides a layer on the surface of the rubber product to prohibit the contact between the rubber and oxygen. Since aging is not really of importance in this research, not much anti-degradants is used in the compounds. The grip and wear compounds only use 6PPD, an antiozonant and antioxidant.

3.2.5 Vulcanization system

NR, BR and IIR all are compatible with a sulfur vulcanization system, because all three polymers are unsaturated polymers, meaning the polymers have double bonds in their backbone as opposed to saturated polymers, which only have single bonds in their backbone. A vulcanization system typically consists of sulfur, activators and accelerators (27). A common activator is zinc oxide (ZnO), which is often combined with fatty acids such as stearic acid to become more soluble. The accelerator is used to increase the rate and degree of vulcanization. So in all three compound groups, Sulfur and zinc oxide (ZnO) is used. The choice of accelerator however differs.

For the grip compounds, based on NR, MBTS is used as accelerator. The ratio between the sulfur and the accelerator (S/A) has a great influence on the overall vulcanization. In a research by Boonkerd and Deeprasertkul the effect of the S/A ratio in NR compounds was studied (28). The activator, zinc oxide (ZnO) was present in the compound by 8 PHR. Four different accelerators were used: DCBS, CBS, MBTS and TBzTD. CBS, MBTS and TBzTD are available at the university. MBTS is chosen as accelerator due to the fact that at a reasonable S/A ratio of around 1.17 – 1.92 the tensile strength is already very high and there are also a lot of polysulfidic bonds formed. A higher density of polysulfidic bonds is preferred for the tire's life expectancy. When polysulfidic bonds break they form di- and monosulfidic bonds. But, at the beginning of the race, the tire is still softer and has more grip.

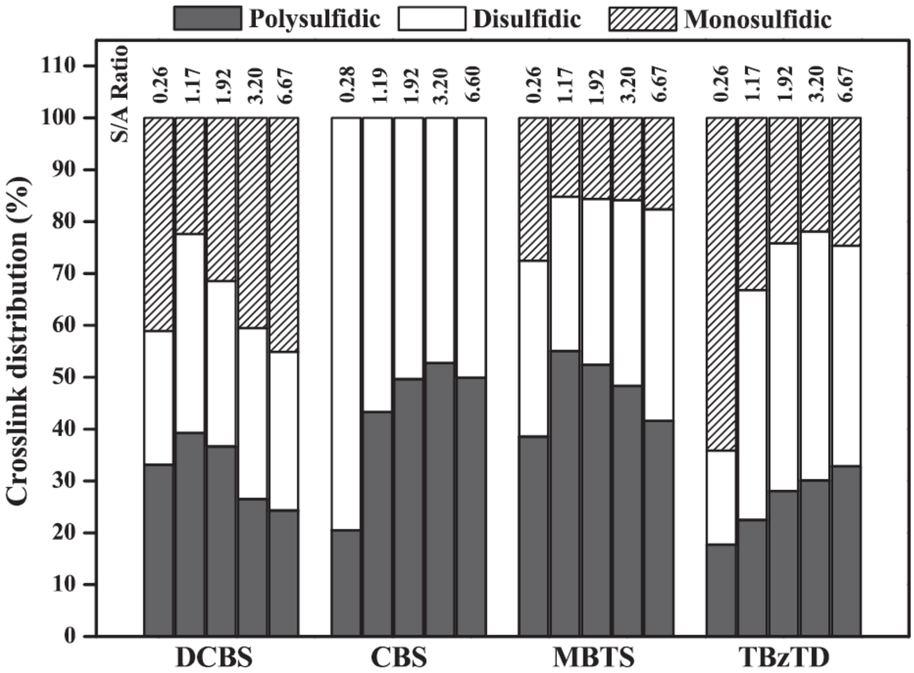

Figure 14: Crosslink distribution in relation to the type of accelerator and S/A ratio (28)

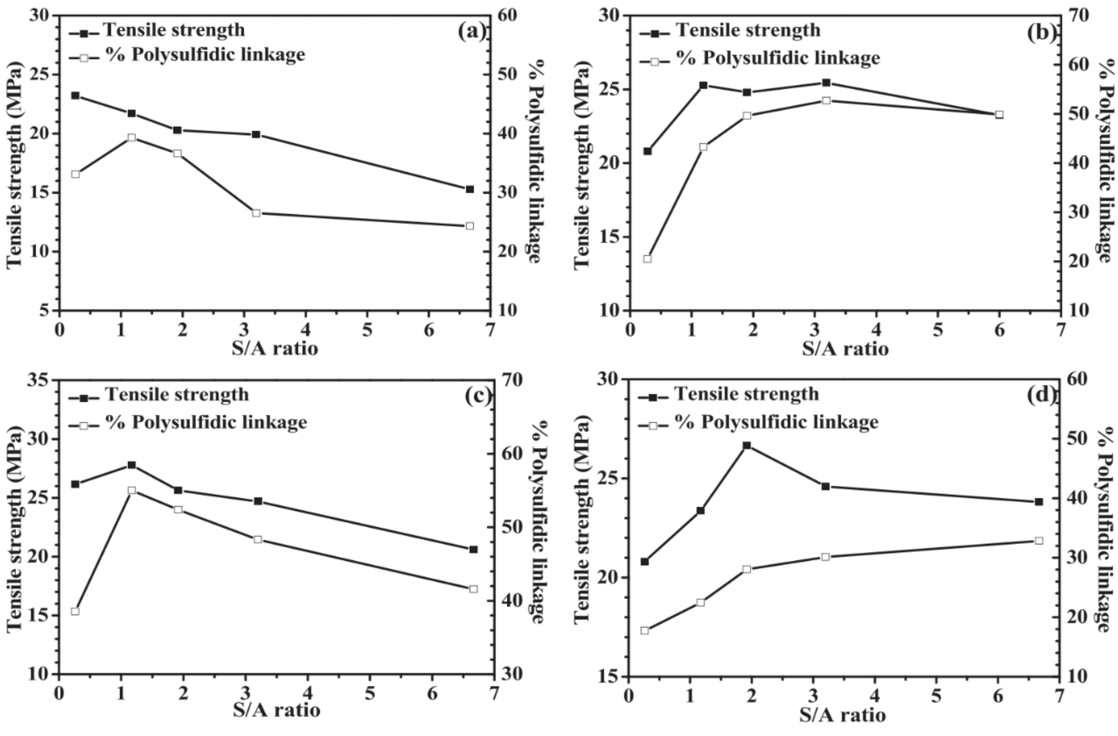

Figure 15: Tensile properties of NR compounds cured with various S/A ratios at 155°C using (a) DCBS, (b) CBS, (c) MBTS,and (d) TBzTD as the accelerator (28)

Depending on the accelerator, the ratio of S/A which gives the highest tensile strength can be found in Figure 15.

MBTS is also used in the reference compounds. When ZnO is used to crosslink chlorobutylrubber, carbon-carbon bonds are formed. These bonds results in a compound with a very stable crosslink system (27, 29).

3.3 Compound and sample preparation

Now all the ingredients of the different compounds are known, the compound formulation can be finalized and produced into actual rubber. One starts with the conversion of PHR to grams, so all the different materials can be weighed, after which they are mixed and cured.

3.3.1 Compound formulations

In Table 2 the compound formulation of the reference compound with increasing carbon black content can be found. The compound formulations of the grip compounds can be found in

Table 3. This is the only compound with 15 PHR of carbon black, the other compound groups have a minimum carbon black content of 35 PHR. Finally, the compound formulation of the wear compounds is listed in Table 4.

Table 2: Compound formulation of reference compounds (four in total)

Ingredients	PHR
HIIR (Chlorobutyl 1066)	100
Carbon black N330/N660	35/55
Aromatic oil (TDAE)	5
Activator Zinc Oxide	6
Stearic acid	1.5
Accelerator MBTS	1
Sulphur	0.1
PEG-4000	1

Table 3: Compound formulation of grip compounds (six in total)

Ingredients	PHR
NR (RSS1)	100
Carbon black N330/N660	15/35/55
Aromatic oil (TDAE)	10
Activator: Zinc Oxide	3.5
Stearic acid	1.5
Accelerator: MBTS	1.5
Sulfur	2.5
6PPD	1.5

Table 4: Compound formulation of wear compounds (four in total)

Ingredients	PHR
BR (CB24)	100
Carbon black N330/N660	35/55
Aromatic oil (TDAE)	15
Activator Zinc Oxide	3
Stearic acid	1
Accelerator TBBS	1.5
TBzTD	0.2
Sulphur	1.5
6PPD	1.5

3.3.2 Mixing procedures

The compounds are mixed using a Brabender 350S. All compounds are mixed in a two stage mixing process, both these stages are mixed in the internal mixer. In the first stage, the masterbatch is created, this must cool down before the second stage can be carried out This is an important step because the rubber has lots of heat after mixing. If the vulcanization system is mixed in immediately after the first mixing stage, there is a chance the material starts to vulcanize inside the mixer. In the second stage the vulcanization system is mixed together with the master batch. The mixing procedures which are created were first tested on a test batch of rubber. The mixing procedures of the different compounds can be seen in Table 5, Table 6 and Table 7.

Table 5: Mixing procedure of reference compounds

<table>
<tr><th colspan="2">First stage</th><th colspan="2">Second stage</th></tr>
<tr><td colspan="2">Rotor speed: 50 RPM
Initial temperature: 70 °C
Fill factor: 0.70</td><td colspan="2">Roto speed: 60 RPM
Initial temperature: 50 °C
Fill factor: 0.65</td></tr>
<tr><td>Steps</td><td>Time</td><td>Steps</td><td>Time</td></tr>
<tr><td>Add polymer</td><td>00:00</td><td>Add masterbatch</td><td>00:00</td></tr>
<tr><td>Add ZnO, PEG-4000, stearic acid and ½ of carbon black</td><td>01:00</td><td>Add cure system</td><td>00:30</td></tr>
<tr><td>Add ½ of carbon black and oil</td><td>02:00</td><td>Mixing</td><td>00:45 – 03:00</td></tr>
<tr><td>Increase speed manually until the temperature is around 145 °C</td><td>03:15 – 05:00</td><td></td><td></td></tr>
</table>

Table 6: Mixing procedure of grip compounds

First stage		Second stage	
Rotor speed: 70 RPM Initial temperature: 70 °C Fill factor: 0.73		Roto speed: 70 RPM Initial temperature: 70 °C Fill factor: 0.68	
Steps	Time	Steps	Time
Add polymer	00:00	Add masterbatch	00:00
Add 6PPD	01:00	Add cure system	00:30
Add carbon black and oil	02:00	Mixing	00:45 – 03:00
Add activator	03:00		
Increase speed manually until the temperature is around 135 °C	03:15 – 05:00		

Table 7: Mixing procedure of wear compounds

First stage		Second stage	
Rotor speed: 70 RPM Initial temperature: 70 °C Fill factor: 0.70		Roto speed: 70 RPM Initial temperature: 70 °C Fill factor: 0.65	
Steps	Time	Steps	Time
Add polymer	00:00	Add masterbatch	00:00
Add ZnO, stearic acid and ½ of carbon black	02:00	Add cure system	00:30
Add ½ of carbon black and oil	03:00	Mixing	00:45 – 03:00
Increase speed manually until the temperature is around 145 °C	03:15 – 05:00		

3.4 Characterizations

When the compounds are mixed, their properties can be measured. Knowing the material characteristics can help with choosing which compound is most suitable to be used in the mold, but also to compare to real life performance. All the tests mentioned in this chapter are performed at room temperature (RT) unless mentioned otherwise.

3.4.1 Mooney viscosity

Since rubbers behave as a non-Newtonian fluid, there is no simple relationship between molecular weight and the viscosity. Using a Mooney viscometer the Mooney viscosity of the rubber is characterized using the torque required to rotate a rotor. The tests are performed on an Alpha technologies MV 2000. The results of these tests give more information about the flow behavior of the rubber in the mold. The Mooney viscosity is measured at 100 °C, for 4 minutes. This way it is possible to derive the viscosity during processing and some assumptions can be made about the processibility of each of the rubber compounds. All tests are performed according to ISO 289-1 (30)

3.4.2 Curing behavior

The cure behavior of the compounds was tested using a TA technologies Rubber Process Analyzer (RPA). The cure behavior of the rubber is important when vulcanizing the rubber later in the mold. The optimum cure time is taken as vulcanization time to obtain optimum physical properties. Usually, the best time for vulcanization of the rubber compound is at 90% (t_{c90}) or 95% (t_{c95}) of the maximum torque measured. The rise in torque is assumed to be proportional to the rise in crosslink density. In this study, t_{c90} is used as vulcanization time. The experiments are carried out using a strain of 0.5 degrees and a frequency of 1.67 Hz.

3.4.3 Tensile strength

The tensile strength of the compounds is tested on a Zwick Tensile tester with a speed of 500mm/min. For statistical relevance every test is performed with at least 5 samples. A dumbbell test specimen is used, with a thickness of 2 mm. The information that is collected from these experiments are the maximum tensile strength and elongation at break. All tests are performed according to ISO 37 (31).

3.4.4 Hardness

The hardness of rubbers is expressed as Shore hardness, named after its inventor. Shore hardness, using either Shore A or shore D is preferred for rubbers. Shore A is commonly used for 'softer' rubbers and Shore D for harder rubbers. The Shore hardness is measured using a Durometer. The value is determined by the penetration of the Durometer indenter into the sample. The indentation reading can change over time, so the indentation time can also be of importance alongside the hardness number. In this study, the Shore A hardness is measured. All tests are performed according to ISO 868 (32).

3.4.5 Rebound

Rubber is highly elastic, when it is deformed under an external force, it can be restored to its original shape after removing the external force. When it turns to its original shape, it also produces a reaction force. The magnitude of this force depends on the difference in resilience properties between rubbers. Using a Zwick 5109 rebound tester, the resilience can be characterized. Resilience is given as the ratio between returned energy and impact energy. This test is performed at room temperature and at 60 °C, this temperature is relatable to that of the working temperature of a passenger car tire. All tests are performed according to ISO 4662 (33).

3.4.6 Abrasion

To evaluate the abrasion resistance of the compounds, the DIN abrader can be used. By abrading a rubber sample over an abrasive sheet for a set distance and speed. By using a reference sample the influence of the abrasive sheet is compensated. All tests are performed according to ISO 4649 (34)

Using a reference compound it is possible to calculate the relative volume loss. The relative volume loss (ΔV_{rel}) is given by the following formula:

$$\Delta V_{\mathrm{rel}} = \frac{\Delta m_{\mathrm{t}} \Delta m_{\mathrm{const}}}{\rho_{\mathrm{t}} \Delta m_{\mathrm{r}}}$$

Where

Δmt	is the mass loss, in milligrams of the test rubber piece;
$\Delta mconst$	is the defined value of the mass loss, in milligrams, of the reference compound test piece;
ρt	is the density, in milligrams per cubic millimeter, of the test rubber;
Δmr	is the mass loss, in milligrams of the reference compound test piece.

Chapter 4

Results and discussion

4.1 Tire design

With the production technique (compression molding) in mind, it is possible to design the tire. The tire's design is based on a storebought tire, but altered to fit the demands: ensure a glue-less connection to the rim, must be produced with compression molding and can be used without inserts. To accommodate for this, the thickness of the tire is increased compared to store bought tires, this makes it possible to use the tire without inserts. Sharp corners and undercuts are minimized, as well as small wall thicknesses. This ensures the tire can still be removed without damaging it. A more uniform thickness across the tire also helps with the vulcanization of the rubber, decreasing differences in how the material cures in the mold. The final design of the tire can be seen in Figure 17. A cross-sectional view of the tire and rim assembly can be seen in Figure 16. These designs are created with Solidworks.

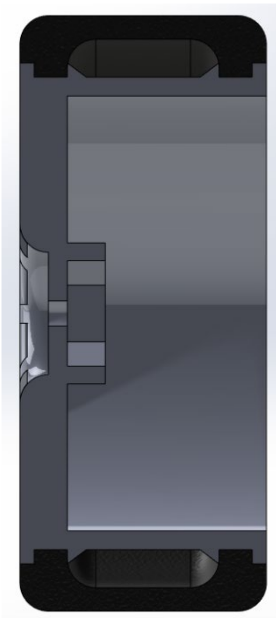

Figure 16: Cross section of tire and rim assembly

Figure 17: 3D view of tire design

The tire design does not have a tread profile. This is because a tread profile is useful for removing water when the track is wet. When racing in the wet, racers are obligated to use predetermined rain tires, so a tread is disregarded. This rule is obliged by the NOMAC (13)

4.2 Mold Concepts

The design of the mold is the most crucial part off this study. The mold has the function to not only force the rubber into the right geometry, but also to cure it. There are multiple forming techniques, methods to transfer the rubber into the desired shape. These different working principles are elaborated upon in chapter 2.6. It is chosen to design a mold which is based on compression molding. Extrusion is not possible because of the geometry of the finished product. Out of the molding techniques, injection molding is not possible to use, because of the high setup costs and the unavailability of that technique at the university. Transfer molding is not chosen because of the higher pressure that is needed to transfer the rubber. This increased pressure would increase material costs because stronger materials, or more material must be used to create the mold. This in turn can also make the mold too large for the compression molding machine and decrease the heat transfer from the compression mold to the rubber. Transfer molding could also create more problems if the rubber is too viscous, then it would not flow into the entire cavity correctly. Compression molding is the most simple technique to develop and the only technique which is available on the university. For prototyping compression is the most obvious choice in this case. Three mold concepts are created based on compression molding techniques.

4.2.1 Concept 1

To visualize the concept it must be rotated around the z-axis. The uncured rubber (shown as red in Figure 18) is added in parts, first the bottom part is filled after which element 1, the core of the mold has to be added. Then the rest of the space can be filled with the uncured rubber pieces after which part 2 is placed on top. Element 2 closes the mold and compress the material. The static (right) part of the mold, and element 2 transfers the heat from the Wickert compression machine into the uncured rubber to vulcanize the material. This design is self-aligning so the tire is not be off-centered. It is also relatively easy to manufacture, because it only exists of circular parts. The mold and since the tire is only a few millimeters thick, it is easy to remove it from the core by hand.

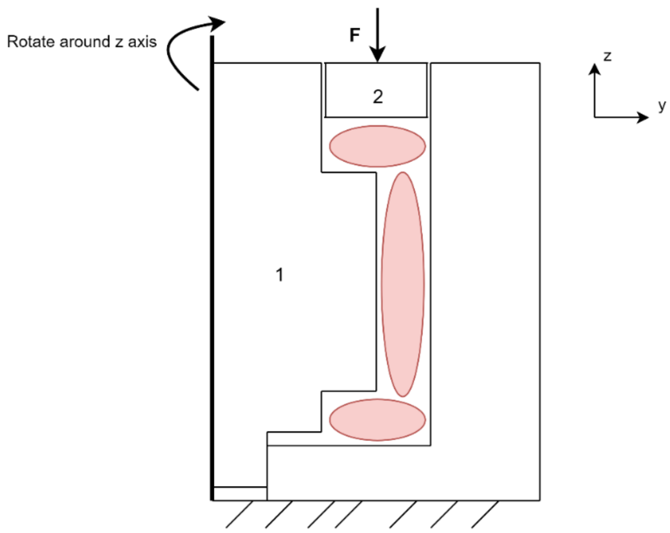

Figure 18: Mold concept 1

4.2.2 Concept 2

Very similar to concept 1, but the core (1) extends less upward. Here a force is only on the core (1). This makes aligning easier and the overall mold less complex. Also, there are less highly precise fits, this decreases the chance of errors and increases production complexity when compared to concept 1.

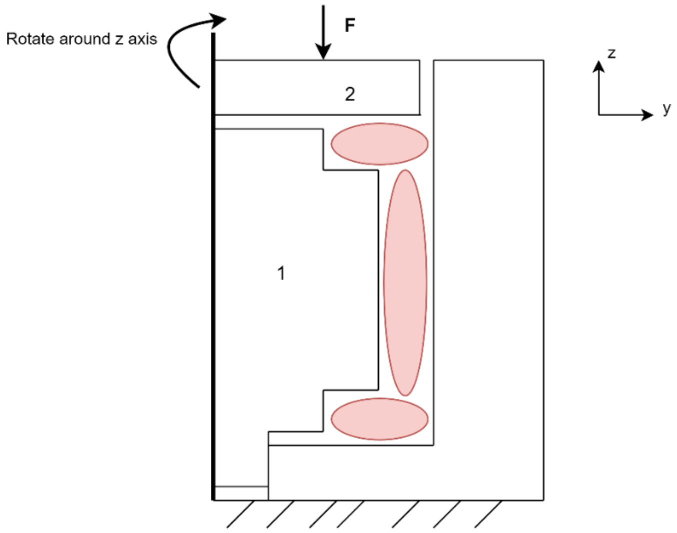

Figure 19: Mold concept 2

4.2.3 Concept 3

Figure 20 shows Concept 3. It is based on a different approach. It consists of a static bottom part, a circular core with guides to make sure the core cannot move in the y or x direction and a top part on which the force is exerted. This design has a smaller footprint so theoretically it can produce more tires while using the same area in the mold compared to concepts 1 and 2. It is, however, harder to manufacture due to the guides and has more parts that must be CNC machined instead of turned on a lathe. The guides give more problems to properly close the mold without material flowing out. Also, aligning in the z direction, is harder and requires more elements in the design. If it is not aligned properly, the top of the tire can have more/less material than the bottom

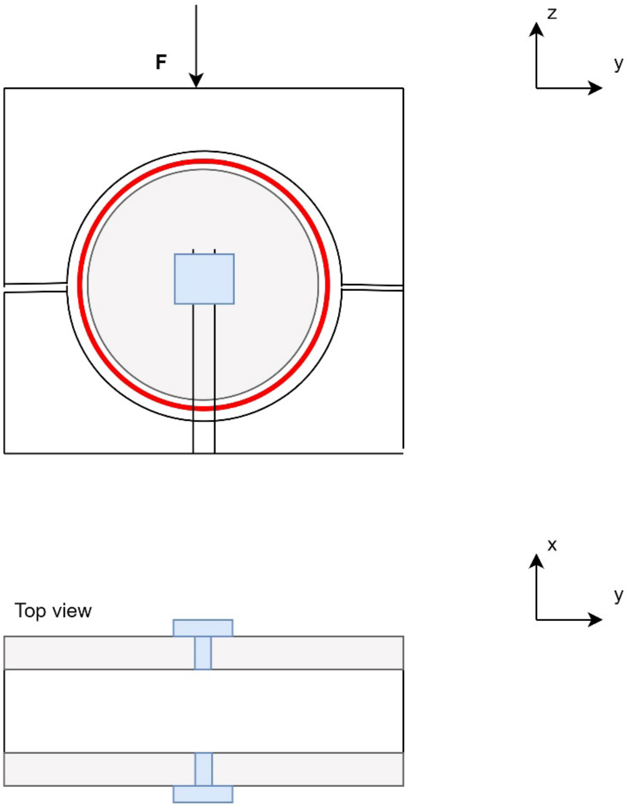

Figure 20: Mold concept 3

4.2.4 Highly detailed concept

Due to simplicity and manufacturability, concept 1 is chosen as basis for further development of the mold. The mold is designed to work in cooperation with the Wickert WLP 1600 vulcanization press. Other molds used in this press are 2D, meaning they have a constant cross section. These molds are mainly used to create test samples. The detailed concept is designed in the same footprint as these molds, 250mm * 250mm. Using this footprint it is possible to create a mold which can produce 4 tires at the same time. This design features three types of elements: The bottom, the top and four times a core. The design is created using Solidworks.

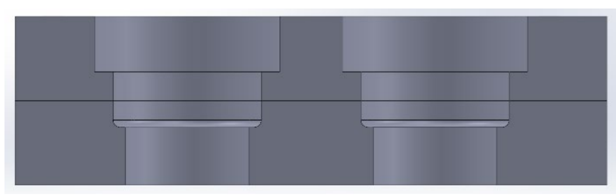

Figure 21: Concept 1 detailed design (cross section)

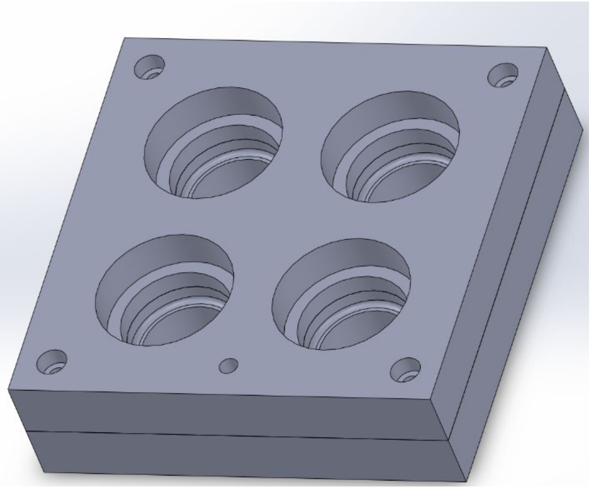

Figure 22: Concept 1 core

Figure 23: Concept 1 detailed design (3D view)

The bottom is made in two parts, because otherwise it could not be created using the CNC machines available for production. These two parts are connected using bolts and nuts. Figure 23 shows a 3D representation of the bottom side of the mold. In the four corners the two parts are connected using bolts and nuts. The smallest hole is used for an alignment pin to make sure that the same corners of the top and bottom part of the mold are on top of each other. This decreases the risk of leakages and, if there are some problems in one of the four mold cavities, it is easier to find a cause for the problem because the same elements are always used together.

In addition, there is a solid core as shown in Figure 22. This makes sure that the material can be easily put in by hand, and removed after vulcanization because the entire core can be pushed out. Also, this core is self-aligning, so the tires are symmetrical and uniform in thickness.

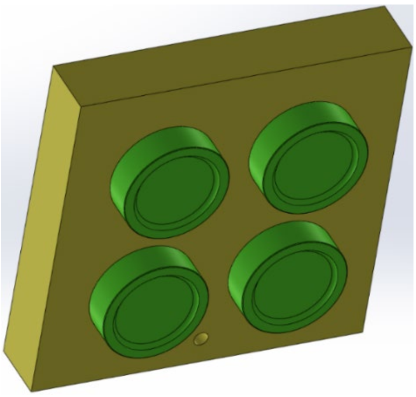

Figure 24: Concept 1 top assembly

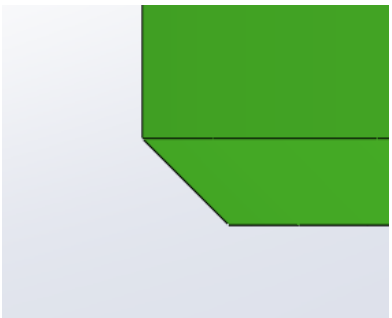

Figure 25: Concept 1 detailed view of chamfer

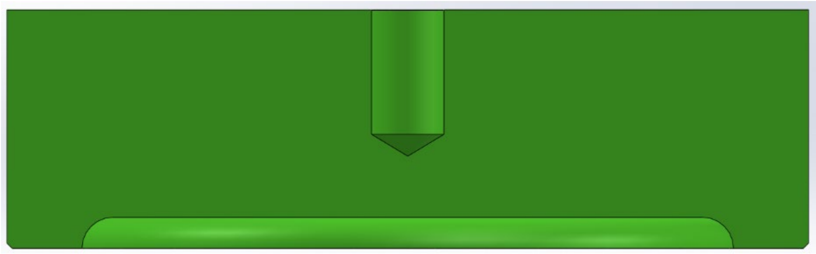

Figure 26: Concept 1 top lid cross section

Finally, there is the top part which delivers the compressional force and closes the mold. This sub assembly consists of two different parts: the base (yellow) and interchangeable lids (green). The lid design is important for the final quality of the product. There is a risk that material can leak out due to a fault in the design or manufacturing. Also, due to the high forces and relatively small contact area, they can deform over time. Therefore, they are made interchangeable so it is easier, cheaper and faster to replace them. The bottom of the lid, which enters and closes the cavity has a chamfer, this makes sure that it fits more easily in the mold bottom. The top of the lid has a threaded hole, this way it is secured to the base (yellow). The detailed assembly of concept 1 can be seen in Figure 27.

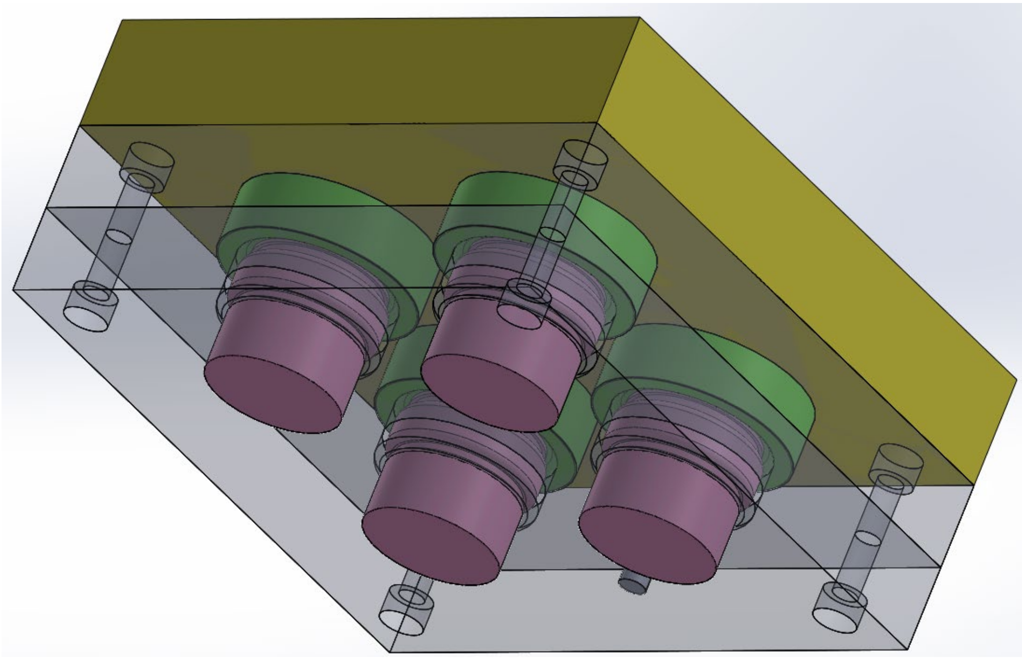

Figure 27: Concept 1 full assembly

4.3 Final mold design

The mold has several functions to fulfill, these functions are listed here. First of all, the mold must withstand the conditions during processing, high pressure of 10 bar and elevated temperatures of 160 °C. The mold must be able to be disassembled with cured rubber in it. The user must be able to fill the mold with the rubber by hand and close it before it is placed in the compression molding machine. Lastly, there must be a relief system, so excess material and air can leave the mold.

Many iterations of this mold have been made before production of the mold started. Because of the moving parts, there are many tight fits which are quite important. Also, the production speed of the tires is not of importance, because this is a proof of concept. To decrease the amount of clearances, the choice has been made to reduce the amount of tires in the mold to one instead of four. If four of those small tolerance fits must be balanced at the same time to close the mold, it is almost impossible to close the mold in real-world use.

4.3.1 Material choice

The material choice for the mold parts are of great importance. Aluminium is cheap and easy to machine, but not very strong. Aluminium is therefore used on the parts which have a relatively large area on which the compressional force acts. Because of the very small clearances, there is quite a lot of contact between materials in some areas. With these tight clearances, the oxide layer which is normally on the surface of aluminium can disappear, a new oxide layer cannot form because there is no space for air between the two surfaces of the aluminium parts. With higher pressure and elevated temperatures, it is possible that the aluminium parts fuse together. To tackle this, different metals are used throughout the design.

The second material is brass. Brass is strong, but is relatively soft compared to stainless steel, this makes it easier to manufacture parts from it. Brass also has

The third material that is used is stainless steel, used for the core. Stainless steel is strong and has a high hardness, it also has the lowest linear thermal expansion coefficient, so it used in the core of the mold.

These different materials each have a different thermal expansion coefficients. This is important to know when dealing with clearances. A mold with different parts that is disassembled at room temperature is not guaranteed to disassemble when at elevated temperatures. Since the vulcanization of the rubber takes place at around 160 °C, the difference in thermal expansion between the parts must be taken into account. The values for the linear thermal expansion coefficients (α) are listed in table

This coefficient can be multiplied by the change in temperature in degrees C and then the linear expansion is found.

Table 8: Linear thermal expansion coefficient of the mold materials

Material	α [10^{-6} m/(m °C)]
Brass	18 – 19
Stainless steel	14 – 17
Aluminum	21 - 24

The linear thermal expansion coefficient (CTE) is used in the design to minimize stresses or chances of failure. The material with the lowest CTE is placed in the core, the material with the largest CTE is placed on the outside of the mold. This way the core materials are not expanding more than the material that is surrounding them, making sure very high stresses on these parts are avoided.

4.3.3 Final design

Many iterations of this mold have been made, before production of the mold started. Because of the moving parts, there are many small tolerances which are quite important. Also, the production speed of the tires is not of importance. To decrease the amount of clearances, the choice has been made to reduce the amount of cavities in the mold to one instead of four.

The final design features several different functions compared to the first detailed concept. The top plate, the bottom plate and the top ring are made from aluminum. The large bottom ring (purple) is made from brass, the two smaller rings inside of it are also made from brass. The core is made from stainless steel. Compared to the first detailed design, this is more modular. The core and inner rings can be replaced to create a different tire design. This also makes it easier to replace parts when something is worn out. Small holes with a diameter of 2 mm are used as vent and relief channels. Trapped air and excess material

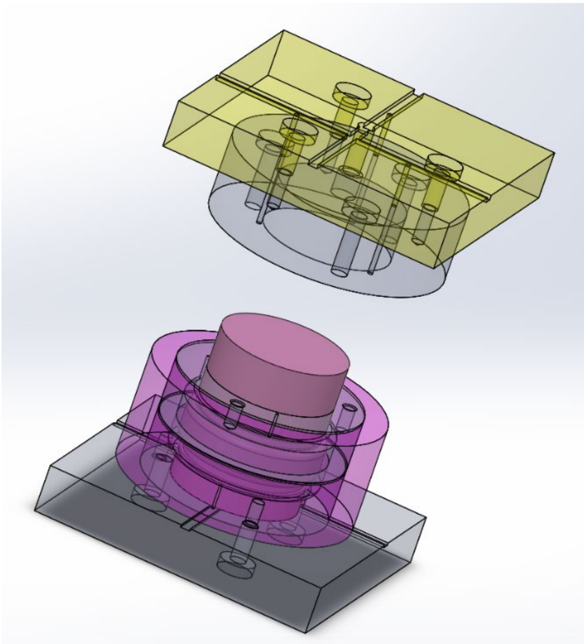

Figure 29: Final CAD model of mold

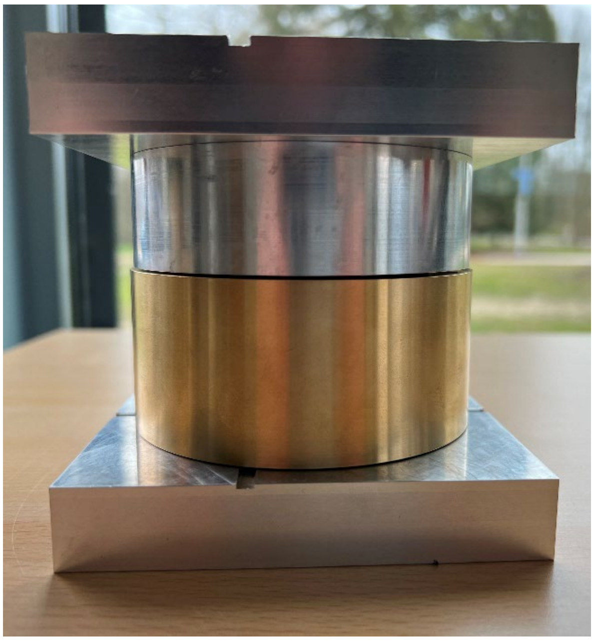

Figure 28: Physical mold

can flow in here and escape the system. These holes are all straight, if rubber ends up in there, it is still possible to remove it.

The tires which are produced with the mold can be seen in Figure 30 . The tire's physical dimensions are as designed. The rubber behaved as predicted in the mold. The excess of material (flash) left the mold in the right places which can be seen in the middle of the tire, and the dots on sidewall of the tire. The flash can easily be removed, but was left on the tire in this case for photographs.

Figure 30: The first produced tire using the mold

4.4 Rim design

To use the designed tire on the RC car, a rim is designed to accommodate for this. Due to the glue-less connection between the tire and the rim, store bought rims could not be used. Also, if a rim breaks in the use, or a different tire design is chosen, it is important to quickly produce a new rim. Therefore 3D printing is used to create the tire, due to the high flexibility because the time between a new CAD model and a produced rim is only a few hours. This production technique also has consequences on the design. The rim is designed with the following features in mind:

The rim must fit a standard 1/10 RC car, the rim must be produced with 3D printing, the tire must be attached to the rim without using glue and it must be possible to put the tire on the rim by hand, without using any tools.

The rim is designed with several features in mind which are present in one final concept made using Solidworks. The rim design started as a copy of an existing rim for an RC car, but slightly altered: some curvatures and overhangs were removed to make sure it would be possible to produce using 3D printing. A second design is also created which features a snap-on tire. This means that the tire can be attached to the rim without using glue.

One of the design features is the slope which is added. This slope ensures that the user can slide the tire more easily over the rim. This is done without compromising the surface area between the rim and the tire.

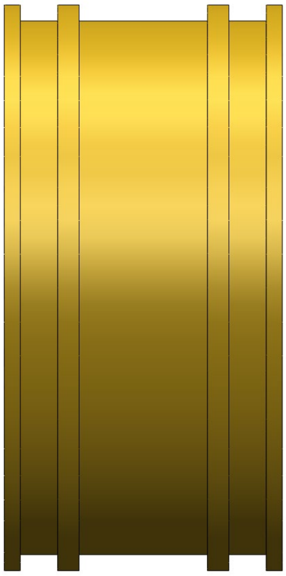

Figure 33: Regular rim

Figure 31: Regular rim (3D view)

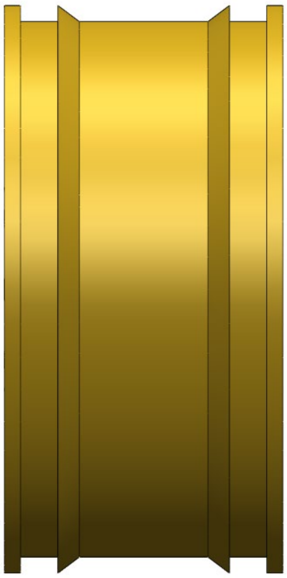

Figure 32: Rim with slope feature

A second design feature has to do with the production technique. By losing wheel spokes, the design is more robust and is more easily produced using 3D printing. The flat surface is used as baseplate while 3D printing. The final rim design can be seen in Figure 34 and Figure 35.

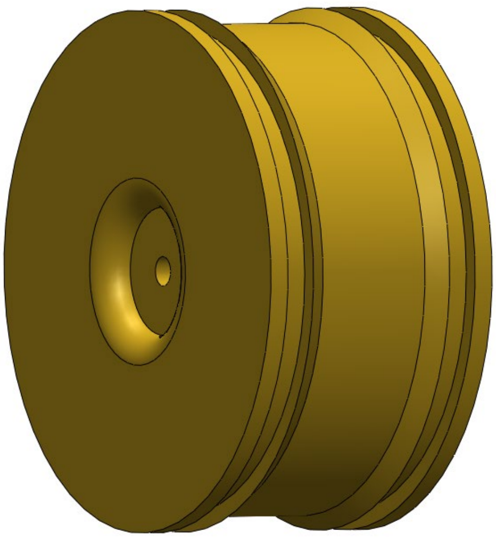

Figure 34: Final rim design (front)

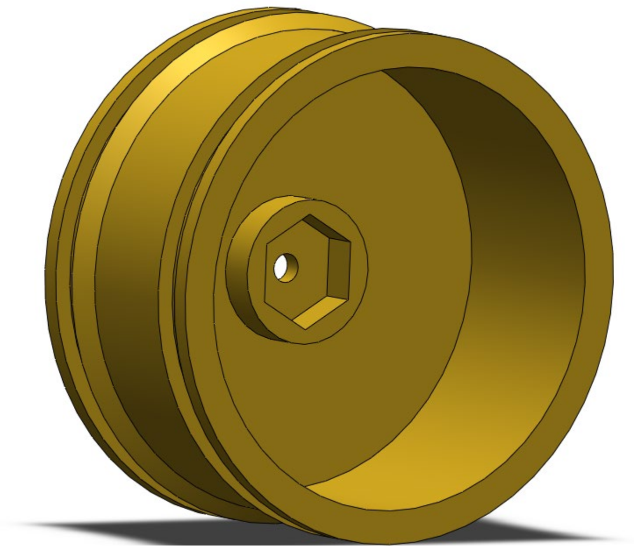

Figure 35: Final rim design (back)

The rim is produced using a 3D printing technique. There are several additive manufacturing (AM) techniques available at the Rapid Prototyping lab of the University of Twente. The first prototype of the rim is made using Fused Deposition Modeling (FDM), this rapid prototyping technique uses a continuous filament of in this case polylactic acid (PLA). The first prototype can be seen in Figure 37 and Figure 36.

Figure 37: Side view of first prototype

Figure 36: Overview of first prototype

After testing the connection between the rim and tire some problems with the dimensions are found. The part of the tire that connects to the rim did not fit perfectly. This could be due to 3D printing defects, or rubber expanding. Some changes to the design of the rim have been made. The rim is altered, because it is easier to print a new rim than to create a new mold for the rubber. To make sure the rubber fit correctly in the insert, the width of the insert was increased from 1.5 to 2 mm. To increase the adhesion of the rubber to the rim, the diameter of the rim was also increased by 2 mm.

After these alterations the tire did not slide over the rim and fit snug. After five iterations the design is accepted as final.

4.5 In-rubber properties

The most important in-rubber properties of the proposed compounds are tested. The results are reviewed in this section.

4.5.1 Mooney viscosity

The Mooney viscosity is valuable information for the production. It indicates the flow behavior of the material during processing. The test is performed for 4 minutes with a temperature of 100 °C and a preheating time of 1 minute. All tests are performed according to ISO 289 (35). The results are listed below in Table 9.

Table 9: Mooney viscosity of rubber compounds

Formulation	15-N330	35-N330	55-N330	15-N660	35-N660	55-N660
MU (NR)	23.4	28.6	40.5	25.3	29.6	37.1
MU (BR)	x	48.3	68.4	x	45.1	57.9
MU (HIIR)	x	61.6	79.8	x	60.8	69.5

It is anticipated that the lowest viscosity will be the easiest to produce, because it flows better into the cavities of the mold. The results reflect that the grip compounds probably will be the easiest to form in the mold because of the lower viscosity. Even with the highest filler loadings, it still has a lower viscosity than the wear and reference compounds with lower filler loadings. The viscosity results are also as expected, with a direct relationship between filler load and viscosity: increasing the filler load increases the viscosity. The same relationship is found between the filler surface area and the viscosity

4.5.2 Curing behavior

The way each compound cures is valuable information for the production. By testing the cure behavior, the cure time (t_{c90}) is determined. This determines how long the mold is in the compression molding machine. Other valuable information like the scorch time can also be derived. 'Scorch' is a premature vulcanization in which a product is partially vulcanized before being in its final form and ready for vulcanization. A very short scorch time could result in a rubber that vulcanizes before the rubber has flowed into the entire cavity. The cure graph of the reference compounds can be seen in Figure 38.

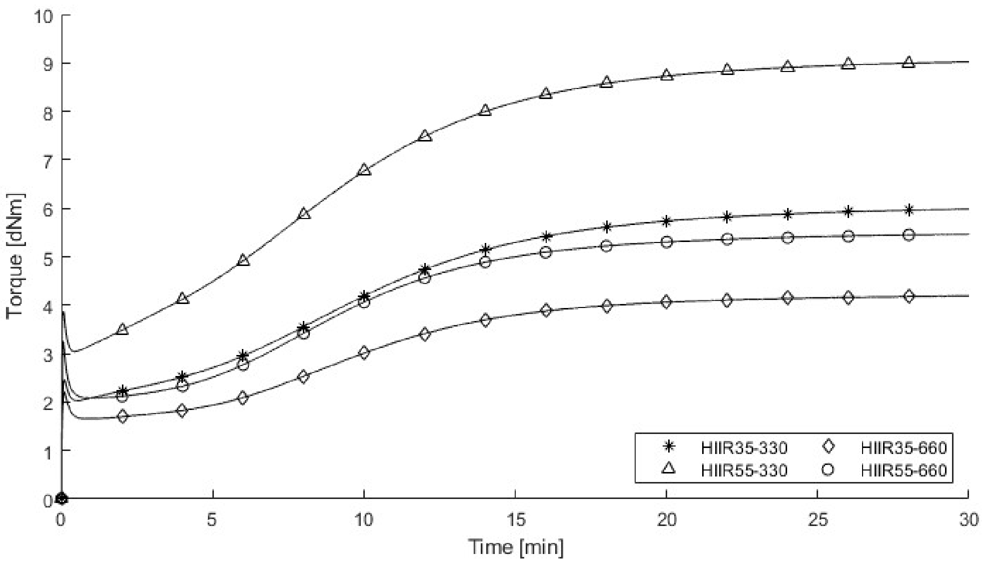

Figure 38: Cure graph of reference compounds

The vulcanization rate of these compounds are much slower than those of the grip and wear compounds. This indicates that the curing is not efficient, because curing takes a long time. This might be due to the fact that the reference compounds based on chlorobutyl rubber have less accelerator and less sulfur which can be seen in the compound formulation in Table 2. For sulfur vulcanization, double bonds are needed. Chlorobutyl rubber is a copolymer of isobutyle and isoprene. Isoprene does not have double bonds, therefore the reaction is slower and less efficient.

The cure graph for the grip compounds, based on NR, can be found in Figure 39.

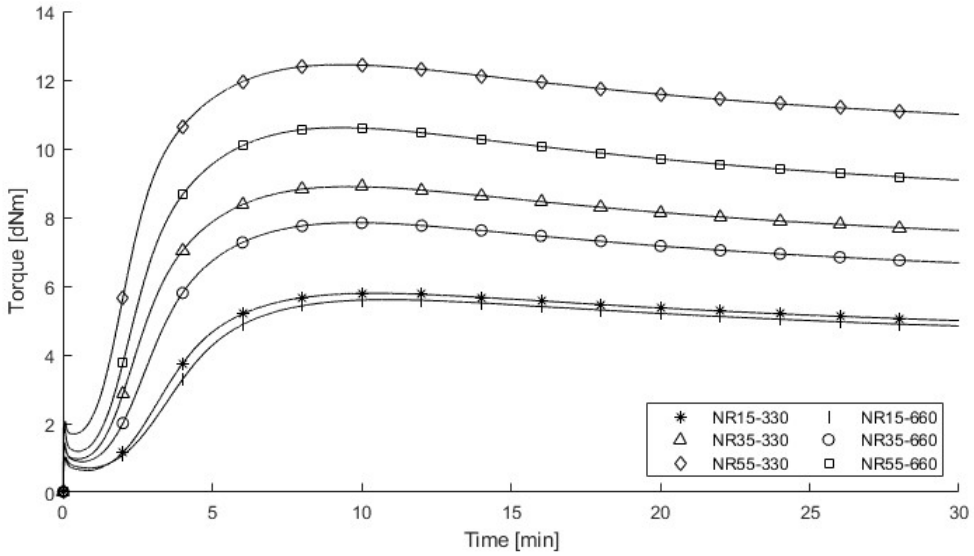

Figure 39: Cure graph of grip compounds

The results shown in Figure 39 are in line with expectations: increasing the filler load increases the final torque. The cure graph of the wear compounds can be seen in Figure 40.

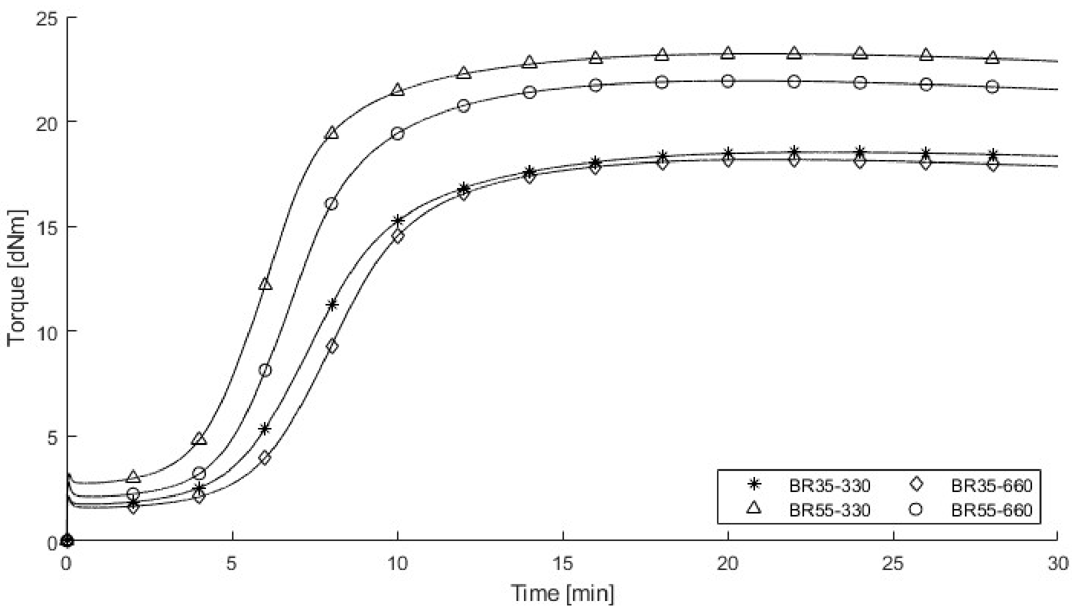

Figure 40: Cure graph of wear compounds

Increasing the filler loading will decrease the curing time, this could be due to the fact that with more filler, there is relatively less polymer to cure. What also is in line with expectations is that the final torque is higher for compounds with a higher filler load. This is due to filler-filler interactions. The optimum cure times for all the compounds are summarized in Table 10. Note that there are no results for 15 PHR of carbon black in the wear (BR) and reference (HIIR) compounds, this is because these compounds were not created. As stated earlier, these compounds are not created because the processibility with 15 PHR of carbon black would be too hard. The most important information from these graphs is that all the compounds reach a plateau when curing. This means that curing works well.

Table 10: Optimum cure times for rubber compounds

Formulation	15-N330	35-N330	55-N330	15-N660	35-N660	55-N660
t_{c90} [min] (NR)	7	6	5	7	6	6
t_{c90} [min] (BR)	x	13	10	x	12	11
t_{c90} [min] (HIIR)	x	18	17	x	17	17

4.5.3 Tensile strength

The tensile test results from the reference compounds can be seen in Figure 41. Each compound has been tested 5 times for statistical relevance. In the stress-strain plots the median of each of these compounds is shown.

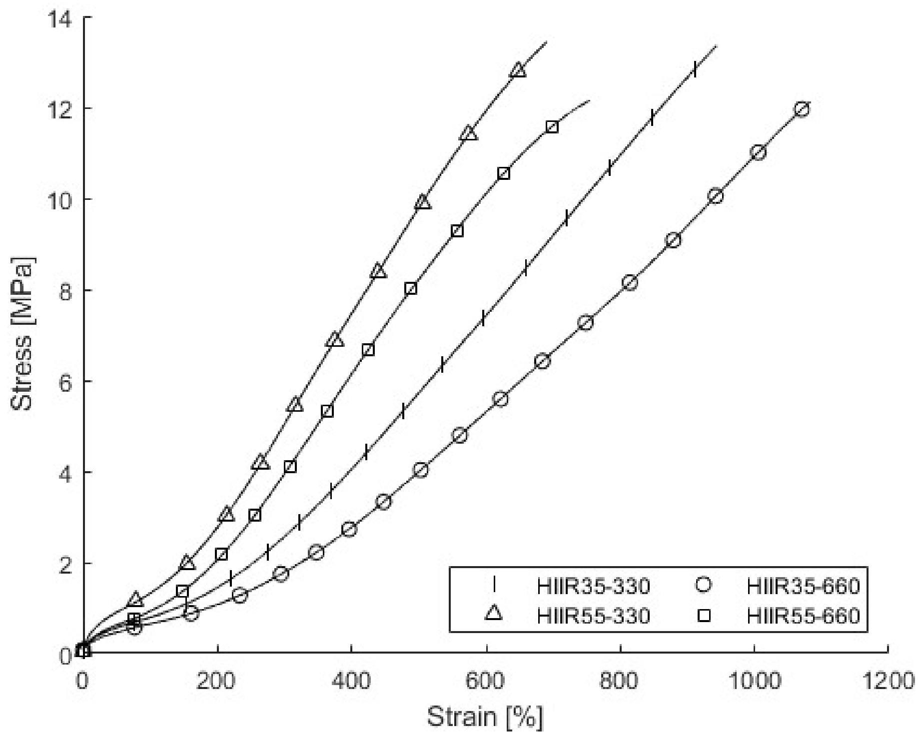

Figure 41: Stress-strain plot of reference compounds

Increasing the filler load increases the maximum tensile stress, but decreases the elongation at break. The same can be observed when comparing carbon black N330 to N660, where N330 is the more reinforcing filler. When comparing the reference compounds to grip compounds in Figure 43, it can be seen that the tensile strength is lower. The reference compounds, however, generally show a higher elongation at break than the wear compounds Figure 42 and similar elongations as the grip compounds.

In the results from the tensile tests of the wear compounds can be seen. It is generally known that a filler (carbon black in this case) will increas the tensile strength compared to unreinforced compounds. This also shows in the results.

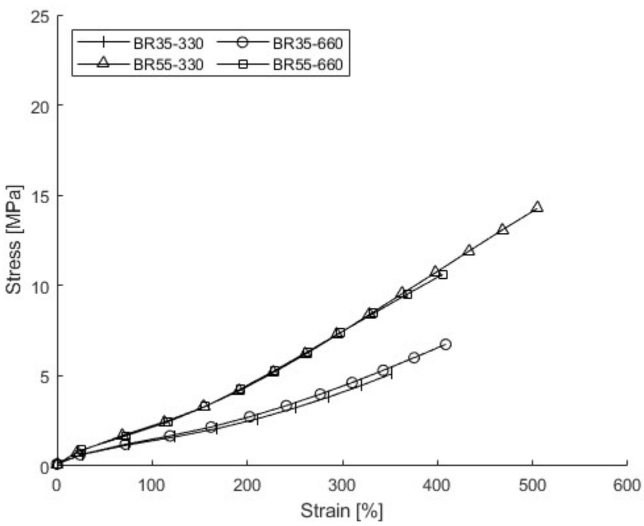

Figure 42: Stress-strain plot of wear compounds

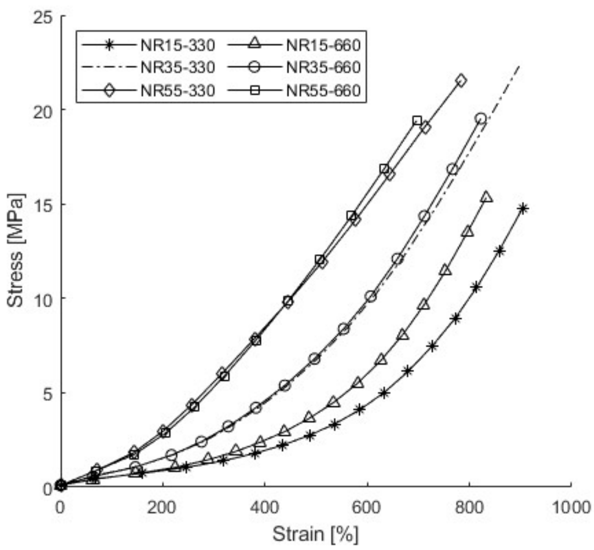

Figure 43: Stress-strain plot of grip compounds

Lower filler loadings show lower tensile strength. When comparing Figure 43 with Figure 41 and Figure 42 it is clear that the grip compounds generally have a higher tensile strength. This was expected since the grip compounds are based on natural rubber as compared to BR and HIIR. Natural rubber has a very high tensile strength. This is due to its higher molecular weight and strain induced crystallization.

Something that cannot be seen in Figure 43 is the fact that during some tensile tests, the specimens slipped from the clamps at high loads. This happened with some grip compounds, because these are based on NR, which generally has a very high tensile strength. That combined with a low filler load, means that a very high elongation at break was possible. It was tried to fix this issue using sandpaper and other adhesives to make sure the specimens stayed in the clamps, but it still happened in some instances.

The tensile properties of all the samples is summarized in Table 11.

Table 11: Tensile properties of rubber compounds

Formulation	15-N330	35-N330	55-N330	15-N660	35-N660	55-N660
Elongation at break [%] (NR)	953	950	815	843	824	765
Elongation at break [%] (BR)	x	373	517	x	410	394
Elongation at break [%](HIIR)	x	912	674	x	1077	730
Max. tensile strength [MPa] (NR)	14.8	22.3	21.5	15.3	19.5	19.4
Max. tensile strength [MPa] (BR)	x	5.1	14.3	x	6.7	10.6
Max. tensile strength [MPa] (HIIR)	x	13.3	13.4	x	12.0	12.2

The elongation at break of the compounds, is generally inversely proportional to the filler load, this is as expected. One result differs from this assumption and that is the BR compound with 55 PHR of carbon black N330.

4.5.4 Hardness

The Shore A hardness of the compounds is summed up in the following tables. The hardness test is performed 3 times, for 3 seconds, the average value is given.

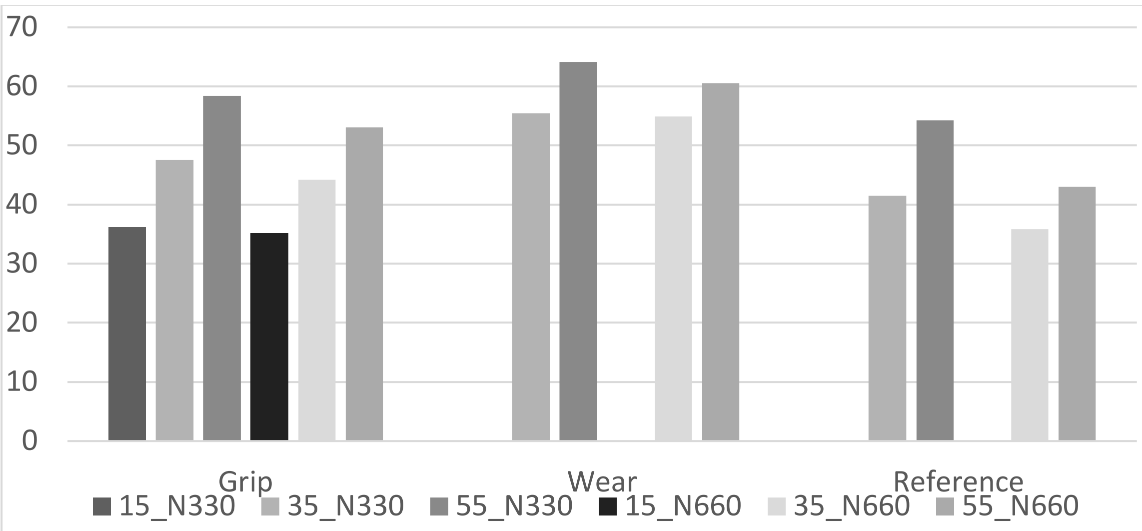

Figure 44: Shore A hardness of rubber compounds

The hardness values of all the compounds are as expected. Increasing the amount of filler increases the hardness. Increasing the surface area grade, increases the hardness slightly as can be seen in Figure 44. So, the compounds with N330 carbon black have a slightly higher hardness overall than the compounds with N660 carbon black.

The hardness values of the wear compounds are also as expected. The difference between grades of carbon black however, shows less of a pattern than the grip compounds. With the BR compounds filled with 35 PHR of carbon black, there is almost no difference in hardness whereas with 55 PHR of carbon black there is a noticeable difference in hardness. Overall, the hardness of the BR compounds is higher than that of the NR compounds, which is wanted, because a higher hardness could indicate a higher durability and a lower hardness could indicate a higher grip.

Most importantly, all of the produced compounds have a Shore A hardness of over 32. This means that all of them could be used in professional RC racing according to the Dutch organization for RC cars (36).

4.5.5 Rebound

The resilience of the rubber compounds is measured and yielded the following results. It is measured at room temperature (20 °C) and 60 °C. Each test was performed and standard deviation is also shown in the table.

Table 12: Rebound resilience of rubber compounds

Formulation	15-N330	35-N330	55-N330	15-N660	35-N660	55-N660
Rebound 20 °C [%] (NR)	71.0 ± 0.4	61.2 ± 0.4	48.5 ± 0.8	72.8 ± 0.5	68.6 ± 0.2	59.9 ± 0.5
Rebound 60 °C [%] (NR)	78.6 ± 0.3	69.6 ± 0.5	58.8 ± 0.5	81.1 ± 0.4	77.5 ± 0.1	71.6 ± 0.7
Rebound 20 °C [%] (BR)	x	79.2 ± 0.1	69.3 ± 0.2	x	84.5 ± 0.3	78.3 ± 0.2
Rebound 60 °C [%] (BR)	x	80.2 ± 0.1	74.1 ± 0.1	x	85.1 ± 0.2	82.1 ± 0.1
Rebound 20 °C [%] (HIIR)	x	12.1 ± 0.4	10.9 ± 0.3	x	12.1 ± 0.5	11.4 ± 0.5
Rebound 60 °C [%] (HIIR)	x	35.6 ± 1	30.2 ± 0.8	x	37.4 ± 1.3	35.2 ± 1.1

It can be seen that the rebound resilience is inversely proportional to the filler load. This is as expected. Rebound resilience is also inversely proportional to the surface area of the filler.

The resilience of the wear compounds are similar to that of the grip compounds. What is interesting however, is that with the lower filler loadings (35 PHR) the difference between room temperature and 60 °C is negligible. With higher filler loadings it is more noticeable, but still small. Especially compared to the grip compounds.

The results from the reference compounds show some interesting results. First of all, the results are much lower than those of the grip and wear compounds. Such a low resilience could indicate higher grip. The difference between the tests performed at room temperature and those at 60 °C are also substantial. The results at room temperature are generally a factor 3 lower than those performed at 60 °C.

This could also explain why the standard deviation in the test results for the reference compounds is higher than those of the grip and wear compounds. Since temperature plays such a large role in the resilience of the reference compounds, a small change in temperature can influence the results greatly. Each sample is hit 15 times. Each time a sample is hit, it absorbs a portion of the kinetic energy as heat. This eventually increases the temperature of the sample. This is was also seen in the test results, during the room temperature tests, the resilience increased with each test, which could be explained by the rise in temperature.

The other way around could be possible for the results at 60 °C. The sample is placed in the apparatus directly from the oven, but by the time test is over, it is approximately 1 minute later. The sample cools down in the meantime. This was also seen in the test results, the resilience of the sample decreased during the test, indicating that the sample

It can be seen from Table 12 that the rebound resilience is inversely proportional to the filler load. This is as expected. It is known from literature, that more filler leads to lower rebound resilience (37).

4.5.6 Abrasion

The results from the abrasion tests are summarized in Table 13.

Table 13: Abrasion resistance of rubber compounds

Formulation	15-N330	35-N330	55-N330	15-N660	35-N660	55-N660
ΔV**rel** [mm^3] **(NR)**	x	x	151.9	x	x	155.9
ΔV**rel** [mm^3] **(BR)**	x	39.6	30.4	x	63.7	49.3

Performing the tests on the wear compounds did not give any problems. The results are also as expected. They lose much less material than the standard test compounds which loses between 180-220 mg of material each run according to ISO 4649. The compounds focused on wear reduction have a much better abrasion resistance, which can be seen in Table 13. Also, there is an inverse relationship between the filler loading, filler type and abrasion resistance. This is also which is expected from literature.

The results for the grip compounds proved to be more challenging. Because the grip compounds focused on increasing grip, the abrasion tests were difficult to perform due to the high grip. The friction between the abrading surface and the rubber was too high for the lower filler loadings (15 and 35 PHR). Due to this high grip, the rubber sample started bouncing on the abrading surface when performing the test. Therefore only the results from the high filler loadings (55 PHR) are shown. The abrasion is much higher for the grip compounds than the wear compounds, which was as expected as well.

There are no results in Table 13 from the reference compounds based on HIIR, because with the available test setup, it was not possible to accurately measure the abrasion resistance. The reference compound is quite soft, has a lot of grip and an expected low abrasion resistance. When performing the tests the test sample would be completely abraded, and the contact area would not be horizontal, because the material really 'bites' into the abrasion paper. What could be seen from the tests, however, is that the abrasion resistance of the reference compounds probably is the lowest from all compounds.

4.5.7 Theoretical performance

All the aforementioned tests are done to give an idea of the rubber's practical performance. This sub-chapter is used to give a quick summary on the in-rubber properties and their expected performance.

The first part is the Mooney viscosity. The Mooney viscosity indicates the viscosity during processing. Increasing filler load increases the viscosity, and the differences between different polymers is also clear. The compound with the lowest viscosity is used in the first production tests, because this material will flow the easiest.

From the hardness results it can be seen that the wear compounds generally have the highest hardness. It is expected that the wear compounds therefore experience a lower wear than the rest of the compounds.

The resilience is directly related to the hysteresis of the compound. The lower the resilience, the more energy is dissipated. A lower resilience increases the rate at which the tires heat up, so more grip is reached earlier. It is expected a lower resilience indicates a higher grip potential. The reference compounds have the lowest resilience, and the wear compounds the highest resilience.

The expectation is that the wear compounds, suffer the least from abrasion. The wear compounds show a much lower abrasion than the grip compounds. It is expected that the reference compounds abrade even more, because it is not possible to test them correctly due to their high abrasion and grip.

In general it is expected the compound groups perform the best in their specialization. This is an assumption based on the in-rubber properties and must be checked with different tests to validate.

4.5.8 Production and assembly

After the mold was produced, it is tested by using it to produce tires from a rubber. This way the ease-of-use of the mold can be tested, but also the quality of the produced tires. Therefore this chapter is divided into two parts: The use of the mold and the quality of the tires.

The mold is used inside a Wickert compression molding machine. First, a new program is made to accommodate the different mold size. Other parameters like the speed of closing and pressure are changed to decrease the chance of breaking the mold in the first try. If these settings seem insufficient, they can be increased in a later stage.

The amount of rubber which is needed to fill the volume is calculated using its theoretical density from the rubber compound and the theoretical volume of the tire from CAD model. The compression mold was pre-heated to 160 °C and the rubber processed through the two-roll-mill for a few rounds to make it softer and easier to handle. The rubber is cut into small strips to make it fit inside the mold, this can be seen in Figure 46. After curing it can be seen in Figure 45 that the relief channels work as designed.

Figure 46: Mold and rubber before curing

Figure 45: Rubber from relief channel

The amount of material that flows out of the relief channel is more than expected, so either the volume of the mold, or the density of the rubber was not correct. It is most likely that difference between the theoretical density and actual density of the rubber is the cause. Because rubber mixing and weighing is done by hand, the chance of errors is more likely than the mold being different from the CAD model. The tire was also measured and the dimensions of the tire were as designed. The tire was weighed at 17.3 grams after flash removal. Having a little more material is wanted, so with this particular compound, 18.3 grams is used in future rubber molding.

Although the tire produced was quite good, using the mold is not easy. Because of the tight tolerances, it is hard to fit the parts in each other which makes filling the mold with the rubber difficult. After the rubber is cured, it is difficult to open the mold, at room temperature or elevated temperatures. A hydraulic press is used to push the mold open. Once the mold is open, removing the tire is easy.

After the rim's dimensions were changed, the tire fit the rim good. The connection between the tire and rim is good and the tire did not slip around the rim when force is applied by hand.

Chapter 5

Conclusions

In this study the design and production of tires for radio-controlled (RC) cars was researched. A new rim and tire design is proposed, which eliminates the need to glue tires to rims. Rims are designed which can be produced easily with additive manufacturing, and fit standardized RC racing cars. Different tire compounds, focused on different aspects of racing are proposed, produced and characterized. Finally, a mold is designed and produced to create vulcanized tires from the proposed compounds.

The mold produced high quality tires with the grip compound (NR15 N330), other compounds were not tested. The mold fulfilled the desired functions, but was difficult to open after vulcanization. After iterating the rim design, the tire fit good. The tire did not slip around the rim and generally showed a good connection between rim and tire.

5.1 Research summary

In this study, many aspects of the production of RC tires were examined. These could be divided in three key concepts: Tire and rim design, compound design and mold design.

5.1.1 Tire and rim design

During the literature research and experience with an actual RC racing car, it was found that the tires are mostly glued to the rim. When testing different compounds, it is easier if the tires can be quickly interchanged on the rim. Therefore a design that accommodates a glue-less connection between tire and rim is proposed. This connection relies on the friction between the tire and rim. This frictional force is enlarged by designing the tire with a slightly smaller diameter than the rims, due to the tensile strength of the tire, it would clamp itself tightly around the rim.

The tire design is also kept as simple as possible and with its production technique (compression molding) kept in mind. This way the possibility of production defects was minimized.

5.1.2 Compound design

Three different groups of compounds are created. The first group of compounds is the ‘grip’ compounds, so focused on maximizing the grip. These compounds are based on natural rubber (NR). The second group is the ‘wear’ compounds, so focused on wear minimization. These compounds are based on polybutadiene rubber (BR). The third group of compounds is the reference group. A simplified version of a compounds designed for RC cars found in literature. These compounds are based on chlorobutyl rubber (HIIR) and are called ‘reference’ compounds.

To have several options with different hardness values and viscosity, the compounds have different filler loads and surface grades of carbon black. Each compound (14 in total) is then characterized, this gives a good overview on how different polymers, fillers and filler loadings can alter the mechanical properties of the rubber.

5.1.3 Mold design

Once the tire design was established, the mold to vulcanize the rubber in the compression molding machine is created. Due to the fact that only a compression molding machine was available at the University of Twente, three concepts using this production technique were created. One concept was chosen and a detailed version of it modelled using Solidworks. Several revisions were made in consultation with people with a lot of experience in machining. Minimizing the amount of tight clearances the rubber should not flow out of the mold and make the production of the mold as simple is possible. Different metals were used to minimize the risk of parts fusing together under high pressure and temperature. Air holes are in the necessary locations to help trapped air escape, and let excess rubber flow out. Finally, the design was made more modular, to easily create different tire designs if necessary. This also makes it more convenient to replace certain parts if they are worn out.

5.2 Recommendations and outlook

5.2.1 Mold redesign

To increase the durability of the mold, using a different material is recommended. Using only stainless steel for example would greatly improve the durability of the mold. In this research, the types of molding techniques was limited, only compression molding was available. It might be beneficial for quality, speed or costs to use a different forming technique for the rubber.

The use of the mold is difficult, due to the rubber’s natural stickiness, it is hard to open the mold after vulcanization. In future research it is recommended to take this into account.

5.2.2 Compounds

There are many things in the compound formulation which have not yet been reviewed. Since the main scope of the research is not to develop new compounds for a tire, but a proof of concept for a mold, the compounds which were developed are relatively simple. To produce an even better tire, the following points of interest are recommended.

Silica and silane

A Carbon black (CB) filler was used in the aforementioned compounds. A silica silane system is in some ways better than a CB filler. Especially in tire technology, silica silane systems can increase the overall performance of the tire. Silica filled compounds generally have a lower rolling resistance and higher wet grip, with a similar wear resistance. However, silica silane compounds bring other challenges, especially in raw material costs, mixing and processing. The reaction of the coupling agent with the filler is mostly achieved during compounding. As a result it is necessary to control the mixing process very carefully For a higher performing tire, it is recommended to use a silica silane filler, possibly in combination with carbon black.

Resin

Another area for future compounds which can be studied is the use of resins in the compound. The relationship between different performance factors for tires: Rolling resistance and (wet) skid resistance is researched in the following study (38). It was found that an addition of low amounts of resins has the potential to enhance skid resistance and also reduce the rolling resistance of silica-reinforced tires. To further increase the performance of the tire compound, the addition of resins can be considered.

Polymer blends

In this study compounds with just one polymer are created. One part of rubber compounding is not treated in this research: polymer blends. Since the final material properties are greatly dependent on the type of polymer which is used in the compound. If one would like to combine certain properties of different polymers, it is possible to use polymer blends. Blending of different polymers is an effective method to achieve required properties. Not all polymers are great matches to blend together. An SSBR/BR blend can often be found in passenger car tires.

5.2.3 Rim design

Improvement can still be reached in the design of the rim. It can be optimized to be lighter, so less material is required, which also increases the performance of the car. Using a different material can also have the same effect. With a different design and more tests, the connection between the rim and tire can also be improved.

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BIOGRAPHY

Almer Lagerweij is a student Msc Mechanical Engineering at the University of Twente. After his bachelor’s in Mechanical Engineering he continued the Master’s degree with a specialization in high tech systems and materials (HTSM).

UNIVERSITY OF TWENTE
Drienerlolaan 5
7522 NB Enschede

P.O.Box 217
7500 AE Enschede

P +31 (0)53 489 9111

info@utwente.nl
www.utwente.nl