Chemistry Project

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- Title
- Abstract (150–200 words)
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SECTION 1 — INTRODUCTION (2–3 pages)

Formula One tyres are specialised racing tyres designed for use on a Formula One car. Tyres play a crucial role in the car's performance, affecting grip, handling, and overall speed. Tyres are also a component into racing strategy, depending on factors such as weather or deterioration. Throughout the history of Formula One, tyres have undergone major changes with different manufacturers and specifications used in the sport. Since 2011, tyres have been provided exclusively by Pirelli, an Italian tyre manufacturer. As of the 2025 season, there are 8 separate types of tyres available for use during events.

1.1 What makes F1 tyres special?

Unlike regular tyres, F1 tyres are designed to perform at incredibly high temperatures. During a race, tyre temperatures can soar above 100°C and the compounds are engineered to maintain grip and structural integrity, even under these extreme conditions. Managing tyre temperature is crucial, as overheating can lead to reduced grip, whilst tyres which remain *too low* in temperature can result in poor performance.

While durability is a key consideration for standard road tyres, F1 tyres are built for short bursts of intense use. Most will last only a portion of the race distance before performance starts to degrade. This rapid wear is a trade-off for the exceptional grip they provide. Tyre degradation is closely monitored by teams, as it directly influences pit stop strategy and can affect race outcomes.

"The working range is the window of temperature where the tyres generate the maximum grip," explains Simone Berra, Formula 1 chief engineer at Pirelli. "If the tyres are too cold, the rubber compound can become stiff. If it is too hot, its modulus decreases and the tyres degrade. Both cases lead to lower grip, so to exploit the peak performance of the compound, teams try to keep their tyres within this working range."

1.2 Why tyre chemistry matters

- Rubber is a viscoelastic material, which means when it is stretched, it returns to its original shape but only after a period of time. During this time, energy is lost through heat, which is known as hysteresis. This is why tyre temperature increases during a lap, because the rubber is being worked and therefore its hysteresis generates heat.
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- A good example of this behaviour is blu tack. At first, blu tack is cold and stiff to the touch, but once you start squeezing and stretching it, it gradually gets warmer and stickier.
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- This viscoelastic nature of rubber enables tyres to generate grip via two main ways:
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- **Indentation:** The roughness of the road excites the rubber and as the rubber does not immediately return to its original shape, this leads to asymmetrical deformation and a friction force.
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- **Adhesion:** Rubber molecules bond to the road's surface and as the tyre rolls, these molecules are stretched. The rubber's viscosity resists this deformation, generating a friction force.
- The trade-off between the fast lap times of soft, high-grip compounds and the longevity of hard, low-grip compounds is a primary factor in race strategy and the mandatory use of at least two different compounds during a dry race.

1.3 Purpose of this research

- Understanding tyre compounds at the molecular level
- Linking chemistry to on-track behaviour

SECTION 2 — BASICS OF POLYMER CHEMISTRY (3–4 pages)

2.1 What is a polymer?

A polymer is a large molecule made of repeating subunits called monomers, formed through a process called polymerization. Plastics and elastomers are both types of polymers, but they differ in structure and properties: plastics are generally rigid or semi-rigid with a high stiffness, while elastomers are highly flexible and elastic, capable of stretching and returning to their original shape. This key difference in flexibility comes from the molecular structure, where elastomers have more cross-linking which allows for more movement between chains compared to the more rigid, linear or branched chains of plastics.

2.2 Fundamental properties

 Elasticity: Polymers exhibit elasticity, especially when above their glass transition temperature. This means they can deform under stress and return to their original shape once the stress is removed, a property that is only possible when the polymer chains are mobile enough to rearrange themselves.

 Glass transition temperature: This is the critical temperature range where an amorphous polymer transitions from a hard, brittle, glassy state to a soft, flexible, rubbery state.

- It's a transition, not a sharp phase change like melting.
- Below, molecular mobility is restricted, and the polymer is rigid.
- Above, increased thermal energy allows the polymer chains to move more freely, making the material flexible and elastic.

 Molecular mobility: This refers to the ability of the polymer chains to move and slide past each other.

- It is the fundamental property that determines a polymer's mechanical and thermal behavior.
- Changes in temperature directly affect molecular mobility. Low temperatures restrict movement, while higher temperatures increase it.
- The degree of molecular mobility dictates whether a polymer is rigid (like glass) or flexible (like rubber).

2.3 Types of rubbers used in tyres

Natural rubber is used in the tread, sidewalls, and internal layers of the tire, providing elasticity, grip, and resilience to withstand lateral forces and impacts.

Synthetic rubber is also used to manufacture Formula 1 tires. Synthetic rubber includes various different polymers such as styrene-butadiene copolymer, polybutadiene, and bromobutyl, which each have unique properties enhancing different aspects of the tire performance. Styrene-butadiene rubber is derived from petroleum and is produced through a process of polymerization of styrene and butadiene ("Styrene-Butadiene Latex: SB Latex Copolymers: Mallard Creek Polymers"). Styrene-butadiene rubber contributes to a balance between wear resistance and grip. Polybutadiene is particularly important in racing tires as one of its properties is its low heat buildup (Massey). Which when in high speed duress of Formula 1 racing comes in handy. Its synthesization process is similar, a polymerization process involving the monomer butadiene. Bromobutyl rubber is a type of butyl rubber that includes bromine for added stability ("Exxon Bromobutyl"), and is used in the inner lines of tubeless tires because of its exceptional air impermeability.

SECTION 3 — RUBBER BLENDS & FORMULATION (3–4 pages)

3.1 Why tyres use blends instead of one polymer

F1 tires use a blend of synthetic rubbers, carbon black, and other compounds instead of a single polymer to achieve precise control over performance characteristics like grip, durability, and heat resistance. This blend allows engineers to create a range of distinct compounds, from soft tires for maximum grip to hard tires for longevity, each tuned for specific track conditions, a level of control that is impossible with a single material.

SECTION 4 — VULCANIZATION CHEMISTRY (3–4 pages)

4.1 Vulcanization: what it is

In addition to these materials that are used in physical components of a Formula 1 tire there are also materials that are used during its processing and manufacturing. Sulfur is one of these raw materials. Sulfur is a naturally occurring element often recognized for its bright yellow color and distinctive smell when burned. It is found in its elemental form as part of various minerals and also in volcanic emissions. Sulfur is extracted through the Frasch process, in which superheated water and air are injected into underground deposits in order to melt the sulfur, which then surfaces in liquid form. Sulfur is a key ingredient used in the vulcanization process, a chemical reaction between sulfur and rubber polymer that fundamentally changes the properties of that rubber (Martin-Martinez). By adding sulfur, the rubber becomes more cross-linked, enhancing its elasticity, durability, and heat resistance.

It was discovered by Charles Goodyear.

4.2 Chemical process

Vulcanization is a chemical process where sulfur is used to create cross-links between polymer chains in rubber, making it more durable, elastic, and heat-resistant.

SECTION 5 — FILLERS AND REINFORCERS (3 pages)

5.1 Carbon black

Carbon black, a fine black powder derived from the incomplete combustion of heavy petroleum products like coal tar or ethylene cracking tar, is a key material used in tire rubber. It is derived from the process of burning hydrocarbons in a controlled environment in order to produce a high carbon content residue (da Costa Labanca). It serves as a reinforcing filler to enhance tire durability, strength, resistance to abrasion, and thermal conductivity, improving performance and longevity. It also helps distribute heat evenly across the tire, preventing overheating and ensuring consistent grip and handling on the road.

5.2 Silica fillers

Another material used in Formula 1 tires is silica. Silica is a mineral derived mostly from quartz sand. This silicon dioxide is typically extracted through mining and then processed in order to create a fine, pure powder suitable for all types of industrial applications (Mohammad). In tires specifically, silica is incorporated into the rubber compound for the tread. Its inclusion enhances a tire's performance by improving its grip, most notably in wet conditions. Silica also aids in maintaining an optimal tire temperature, enhancing durability and consistency in performance.

SECTION 6 — ADDITIVES (2–3 pages)

6.1 Additives.

- Additives such as antioxidants, vulcanizing accelerators, and activators are also used in the manufacturing of Formula 1 tires. Antioxidants, derived from petroleum, work to prevent the degradation of rubber during the mixing process and help protect the tires against sidewall cracking which is usually caused by sunlight and environment exposure. These compounds are usually synthesized through various complex chemical reactions involving petroleum-based products. Vulcanizing accelerators and activators on the other hand, work to improve the elasticity and strength of the rubber. A primary activator used is zinc oxide, which is mined as zinc ore then purified and processed into a fine powder. Zinc oxide is a catalyst, speeding up the reaction between the sulfur and the rubber during vulcanization, which results in a more durable and resilient tire (Kołodziejczak-Radzimska).)

SECTION 7 — HEAT, TEMPERATURE WINDOWS & DEGRADATION (3–4 pages)

7.1 Why temperature matters

Temperature matters in F1 tires because they have a specific "operating window" for peak performance; if the tires are too cold, they lack grip, and if they are too hot, they slide and degrade faster. Teams use tire warmers to bring tires to the correct temperature before a race, as warm tires have softer rubber that conforms to the road, creating more friction and better traction for a perfect start. Maintaining the right temperature during a race is crucial for balancing grip and tire wear, as overheating leads to premature degradation and a loss of performance.

7.2 Degradation

When a tyre does not have enough grip, it slides across the surface of the road. This sliding effect generates temperature which overheats the rubber, causing two types of degradation:

- Thermal degradation
- Wear degradation

Thermal degradation is where the rubber is so hot that its material properties change, and the compound becomes much harder. This means it cannot stick to the surface of the track as much, leading to a smaller contact patch and much less grip.

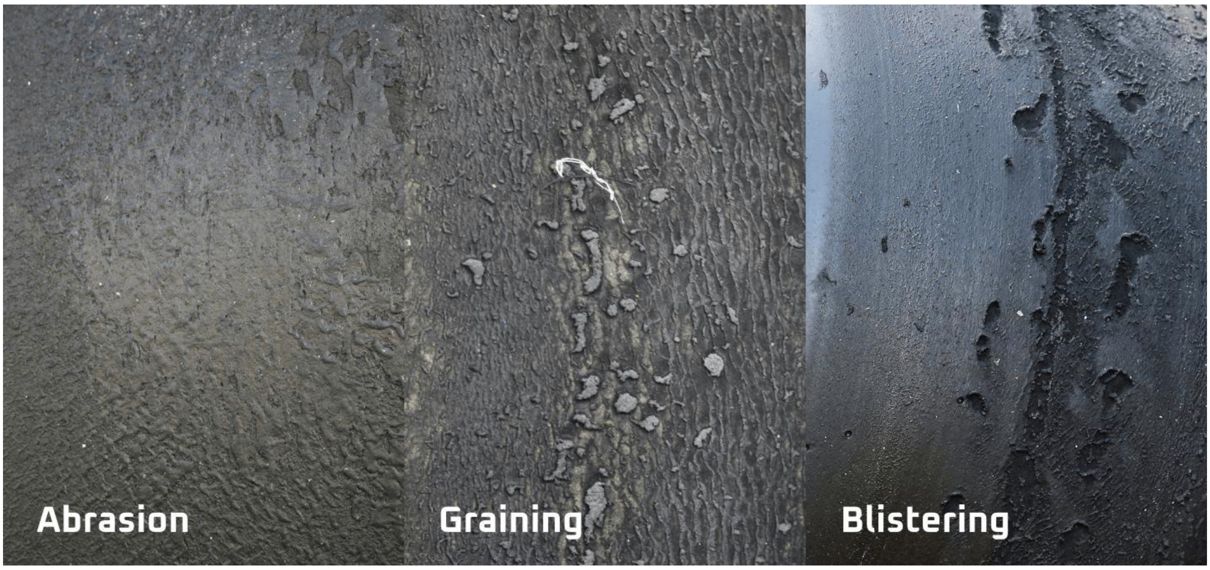
Wear degradation is where the rubber slides across the track, causing pieces of rubber to wear away, resulting in surface damage. With less rubber in contact with the track, less grip is generated.

There are several mechanisms of wear degradation that we see in Formula 1:

Abrasion: As the tyre slides across the track, small portions of rubber are worn away from the surface, leaving a uniform pattern of ridges and spots. This is often referred to as ‘normal’ wear.

Graining: A more extreme version of abrasion, where rubber shears away from the surface and rolls into small grains, similar to dragging an eraser across paper. This leaves a pattern of wavy ridges on the surface which from a distance, appears as a dark band on the tyre.

Blistering: The rubber overheats and essentially boils, producing bubbles that then explode, removing chunks of rubber from the surface. This is rare with the current Formula 1 compounds, but can sometimes be seen in the centre or on the outer edges of a tyre.



7.4 Heat cycles

- What happens to rubber after cooling-heating cycles
- Why used tyres are slower than new ones

SECTION 8 — TIRE CONSTRUCTION & MATERIAL LAYERS (3–4 pages)

8.1 Tread

The core of every Formula 1 tyre lies in its rubber compounds, which are tailored to offer optimal performance under varying conditions. These compounds are a mix of synthetic rubber, carbon black and chemical additives, designed to achieve a perfect balance of grip, durability, and heat resistance. For F1, the rubber compounds are fine-tuned into different categories: soft, medium, and hard for dry conditions, as well as intermediate and wet compounds for unpredictable weather.

8.2 Carcass

Tires require strength and durability, which is why kevlar and carbon threads are crucial. Kevlar is a synthetic aromatic polyamide polymer with exceptional strength and resistance to heat, ideal for reinforcing tire sidewalls. It is produced through a process that starts with the polymerization of aniline and terephthaloyl chloride, resulting in poly-para-phenylene terephthalamide. This polymer is then made into fibers using a solution spinning process (Algahtani). Carbon fibers, derived from polyacrylonitrile or

PAN, are used for structural integrity. PAN is treated to oxidation and carbonization at extremely high temperatures to form tightly interlocked carbon chains ("How Is Carbon Fiber Made?") of fibers. In Formula 1 tires, both kevlar and carbon fibers are used in belts and carcass layers to maintain shape and structure under extreme conditions.

8.3 Steel beads

Steel beads are vitally important to its structural integrity. Steel is an alloy that is primarily composed of iron and carbon, along with small amounts of other elements that enhance its properties. These other elements usually include manganese, chromium, vanadium, and tungsten. It is produced by smelting iron ore in a blast furnace, removing its impurities and adding carbon. The process starts with mining the iron ore, and then melting it at high temperatures to separate the iron from the ore. The iron is even further processed in a basic oxygen furnace where it is combined with carbon and the other elements to create steel (Luecke). The tire bead is a part of the tire that sits on the wheel (Silvestro). The steel beads ensure a tight fit between a tire and its rim, ensuring its structural integrity is able to handle the forces and speeds of Formula 1 racing.

8.4 Interaction between layers

In the manufacturing process of tires, all of the raw materials are processed to create the final product. First the natural and synthetic rubbers, along with the other additives and sulfur and accelerants, are mixed in a process known as compounding. Once the rubber compound is made, it is fed into an extruder where it is formed into long continuous strips of rubber known as gum rubber. The strips are then sliced and shaped into the tire's tread, sidewalls, and inner liners through calendaring and molding processes ("How a Tire Is Made"). Then other materials are incorporated to enhance the structural integrity and performance of the tire. Steel beads are placed between the tread's layers of rubber to maintain the shape of the tire. The fibers are used in the tire's carcass, sidewalls, and bead areas. The layers are bonded together through a combination of heat, pressure, and adhesives.

SECTION 9 — F1 COMPOUND BEHAVIOUR (2–3 pages)

9.1 Soft, Medium, Hard compounds

Currently, Pirelli supply five slick tyre compounds for Formula 1: C1, C2, C3, C4 and C5 as well as wets and intermediates. The C1 is the hardest compound and then each compound is slightly softer until the C5, which is the softest.

Both hard and soft compounds can be designed to work at any working range. In

Formula 1, Pirelli match soft compounds with lower working range temperatures and hard compounds with high working range temperatures.

Softer compounds are more flexible and so the rubber stretches and compresses more which generates heat. This ability to warm up faster enables soft compounds to produce grip more easily, making them more suited to a low temperature working range. Otherwise, the heat generated by a soft compound combined with a high temperature working range would cause the rubber to overheat and degrade.

Harder compounds on the other hand are much stiffer and therefore generate minimal heat on their own. Instead, they rely on high-speed corners and rough track surfaces to excite the rubber. This can lead to much higher temperatures in the rubber and therefore are more suited to a working range at high temperature.

"Soft compounds are easier to warm up and to reach their optimum temperature, so are better suited to cool conditions and smooth tracks with less high-speed corners, where it is typically difficult to get enough energy into the tyres," highlights Eric Blandin, deputy technical director at Aston Martin Aramco F1 Team. "Whereas hard compounds are more robust and so can generate grip at tracks with high surface temperatures and roughness, without overheating or damaging the surface of the tyre."

9.2 Wet & Intermediate tyres

F1 intermediate and wet weather tyres use specialized, **soft rubber compounds** with tread patterns to generate grip in wet conditions. Their primary function is to avoid aquaplaning by displacing water from the track surface, a stark contrast to the slick (smooth) dry weather tyres.

Intermediate Tyres (Green)

- **Conditions:** Used for a damp or lightly wet track with no standing water, or on a drying surface.
- **Compound Behavior:** The compound is designed to have a wide working range, allowing it to function across a broad crossover window between slick and full wet conditions. It is softer than dry weather compounds but slightly less soft than the full wets. The tread blocks are designed to flex and generate heat to maintain optimal temperature in cool, wet conditions.
- **Water Displacement:** A single intermediate tyre can disperse around 35-40 litres of water per second at high speeds (around 300 kph).
- **On Dry Track:** They overheat quickly on a dry track, which causes rapid degradation (blistering and graining) and a significant loss of grip, making them

much slower than slick tyres. Drivers may weave to find wet patches on a drying track to cool the tyres.

Wet Tyres (Blue)

- **Conditions:** Designed for heavy rain and standing water on the track surface.
- **Compound Behavior:** These use an extremely soft compound, even softer than the softest slick tyre, to generate grip and heat in colder, very wet conditions. The soft rubber allows the tyre surface to micro-deform and bond with the track surface more effectively through the water film.
- **Water Displacement:** They feature deep tread patterns and a specific profile to offer maximum resistance to aquaplaning and are capable of dispersing large quantities of water (up to 85 litres per second per tyre at 300 kph).
- **On Dry Track:** The soft compound and tread pattern cause them to overheat extremely rapidly on a dry surface, literally melting the rubber off the tyre within a few laps. This makes them unusable on a dry track for anything more than a single lap.

9.3 Strategy implications

- The undercut and overcut are strategic gambles centered on the timing of a pit stop relative to a rival car, leveraging the difference in speed between fresh and worn tyres.
- Undercut: This is when a trailing driver pits before the car they are battling. The goal is to use the superior grip and speed of the fresh tyres to put in a few very fast laps (an "out-lap" and subsequent laps) and build enough of a time advantage so that when the leading car eventually pits, it emerges from the pit lane behind the car that pitted earlier. The undercut is effective on circuits with high tyre degradation.
- Overcut: This is the opposite strategy, where a driver stays out on track longer than their rival who has already pitted. This is used when the older tyres are still performing well, or when the new tyres on the rival's car are slow to get up to optimal temperature. The driver staying out on track aims to use the "clean air" (undisturbed airflow, allowing for better aerodynamic performance) and good pace on their current tyres to build a gap, so that after their own later pit stop, they still emerge ahead. The overcut is rare but can be particularly effective on circuits where tyre wear is minimal or the pit loss time is large, such as Monaco.

Track Abrasiveness: Rougher track surfaces, like the one at Silverstone, cause tyres to wear out faster, necessitating harder, more durable compounds (e.g., C1, C2, C3) to last a reasonable stint. Smoother circuits, such as Monaco, allow for softer compounds (e.g., C3, C4, C5) that offer more grip and speed without excessive degradation.

Cornering Forces & Speeds: High-speed circuits with many demanding corners (e.g., Spa, Suzuka) put more energy and stress through the tyres, requiring tougher compounds to withstand the forces and prevent failure.

Track and Air Temperatures: Tyres are designed to operate within a specific temperature range. Different compounds are chosen based on the expected ambient and track temperatures to ensure they can reach and maintain optimal performance without overheating (which causes rapid wear) or running too cold (which results in a lack of grip).

Track Layout: The number of straights, hard braking zones, and types of corners (high-speed vs. low-speed) all factor into how tyres are stressed and thus which compounds will offer the best compromise of speed and longevity.

SECTION 10 — TESTING METHODS (2–3 pages)

- **10.1 How are the tyres Tested?**

  F1 tires are tested through a combination of laboratory simulations and real-world on-track testing. Manufacturers use specialized machines to replicate racing conditions, such as a "flat track" that can simulate a full race on a virtual circuit to test durability and performance. In parallel, F1 teams use their cars in official test days, running with prototype tires and providing crucial feedback on aspects like grip and wear, which helps manufacturers like Pirelli develop and fine-tune compounds and constructions for safety and performance.

SECTION 11 -- Tire Manufacturing Process

- **11.1 Ingredient mixing**
- **11.2 Extrusion**
- **11.3 Layer assembly**
- **11.4 Vulcanization**
- **11.5 Quality inspection**

12.1 Why F1 tyres degrade quickly

For a racecar to achieve fast lap times, its tyres need to generate an extreme amount of grip so that it can accelerate, brake and corner quickly. Therefore, the

tyre compounds used in motorsport are much softer than the compounds used in road tyres.

Soft compounds warm up faster, increasing the ‘stickiness’ of the rubber which maximises the contact patch area, leading to higher grip. However, the punishing longitudinal and lateral loads, combined with the constant sliding that race tyres are subjected to, leads to accelerated wear and degradation.

Road cars travel at slower speeds and consequently demand much less grip from the tyres. This means that road tyres can be made from harder compounds that operate at cooler temperatures and don’t wear as much. In fact, a typical road car tyre can last up to 40,000 miles (64,000 km) whereas the longest stint on a Formula 1 tyre last season was 188 miles (302.5 km).

12.2 Why compounds differ

From ultra-soft to hard, each offering different levels of grip and wear. Softer compounds provide more grip but wear out quickly, making them ideal for short stints where speed is paramount. Harder compounds are more durable but offer less traction, making them better suited for longer runs. Teams strategically choose compounds based on track conditions and race strategy, aiming to balance performance and longevity.

12.3 How molecular structure shapes racing strategy

One of the most fascinating aspects of Formula 1 is how teams select tyres for different track conditions. Each race weekend, teams are given a choice of several compounds, from soft to hard, and they must decide which tyres to use based on the circuit’s characteristics, weather, and how the tyres performed in practice sessions. For wet or mixed conditions, teams rely on special rain or intermediate tyres, which are designed with grooves to disperse water and provide grip on slippery surfaces.

This careful selection process is often a determining factor in race strategy. A well-timed tyre change can be the key to outpacing competitors, while a poor choice can lead to lost time or even accidents.

SECTION 12 — CONCLUSION (1 page)

Summarize key learnings.

SECTION 13 — REFERENCES (2 pages)

Compile reliable sources:

- Polymer chemistry textbooks
- Rubber technology papers
- Materials science references
- Basic Pirelli/F1 public data
- Academic articles on vulcanization and fillers
