Study of Various Materials for Automobile Bumper: A Review

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Abstract
India leads the world in annual road fatalities (230,000), despite being a top-ten car market. This discrepancy highlights the urgent need for stricter vehicle safety regulations. While concerns regarding an 8-15% increase in car prices due to stricter standards exist, the potential for global car exports and significant lives saved outweighs these costs. This review analyses the critical role car bumpers play in mitigating accident severity. By absorbing impact energy and protecting occupants and vehicles, bumpers directly address a crucial gap in current Indian automotive safety. Implementing stringent safety regulations, including robust bumper testing programs, can significantly reduce road fatalities and injuries, aligning India's car safety standards with global best practices and fostering a safer transportation ecosystem.
Keywords: *Bumper Material; Car Bumper; Mechanical properties, Mechanical Testing.*

1. Introduction
Daily accidents, despite perceived driver control, lead to staggering fatalities (10,000+) and injuries (hundreds of thousands to millions) annually. To address this, car safety improvements are crucial, with the automotive bumper system playing a key role in preventing or minimizing collision damage.[1]. Car bumpers act as shields, absorbing impact to protect vital car parts (hood, trunk, etc.) and safety features (lights). They're designed to be lightweight for passenger safety, but standards vary by country.[2]

2. Advanced Technology for Passenger Safety
Low-speed crashes pose a challenge in automotive bumper design. Studies show that increased bumper thickness improves energy absorption in such collisions [1, 3]. While research highlights the metal bumper beam's role in energy absorption, further exploration of real-world implications, applicability in the car industry, and manufacturing/cost considerations is needed. The bumper beam's importance to vehicle safety has attracted numerous researchers [4]. A recent study proposes a new design balancing pedestrian safety with low-speed crash protection. By optimizing key parameters, both pedestrian safety and low-speed impact performance are significantly improved [5]. Essentially, the bumper acts as an adaptable shield, adjusting to impact severity and enhancing pedestrian safety while absorbing energy in minor collisions [6]

3. Functionality of Bumper
Car bumper design plays a critical role in vehicle safety, particularly during prevalent low-speed collisions [7, 8]. Kannan et al. employed FEA simulations to analyze the impact performance of three front bumpers (ABS material) on expensive cars. Their findings suggest that optimized bumper design significantly influences stress, deformation, and strain during collisions, highlighting the importance of meticulous design for improved safety [7]. Chandrakant and Ajit addressed the challenge of misaligned bumpers causing damage in low-speed impacts. Their research, adhering to IIHS guidelines, demonstrated that aligning the front metal bumper with appropriate stiffness reduces damage by 1.3 times, emphasizing the importance of proper alignment. Additionally, they identified crucial factors for effective crash energy management, including crush initiators, bumper thickness, shape,

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and profile [9]. These studies underscore the necessity for further research on optimizing bumper design to enhance energy absorption, improve alignment, and ultimately, bolster vehicle and occupant safety in low-speed collisions.

4. Various Bumper Materials

Car bumpers balance safety and aesthetics, playing a crucial role in absorbing impact energy while contributing to vehicle styling. Modern automakers strive to optimize weight in bumpers without compromising safety. Here are some common bumper materials, each offering unique advantages and drawbacks:

4.1. Steel car bumpers

Steel bumpers offer superior impact protection due to their ability to absorb and disperse energy. They are also generally easier and cheaper to repair compared to other materials. Additionally, their lower cost makes them a budget-friendly option for many car owners [14]. However, weight remains a concern. While research by Zeng et al. explores high-yield strength steel for lighter bumpers, large-scale adoption hasn't materialized [10]. High-strength steel options like TRIP steel allow for thinner, lighter sheets while maintaining strength [11]. Further research like Grajcar et al exploration of medium-manganese steel is ongoing. The quest for lighter, yet robust, steel bumpers continue [12]. Mechanical Properties of different steel grade are shown in Figure 1 and Table 1. Steel bumpers, though tough and budget-friendly, are heavy (impacting fuel and handling), prone to rust, and limited in design options. Disposal can harm the environment too. Consider these factors (car type, usage, budget, and environmental impact) before choosing steel [15].

Table 1 Mechanical Properties of Different Steel Grades [10], [11]

Steel Grade	Mechanical Properties			
	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (Brinell, HB)
Mild Steel	400-550	250-410	20-25	120-180
High-Strength Low-Alloy (HSLA) Steel	450-700	300-550	14-30	140-220
Dual-Phase Steel	500-800	300-550	10-20	160-220
Advanced High-Strength Steel (AHSS)	700-1500	450-1200	2-15	200-400

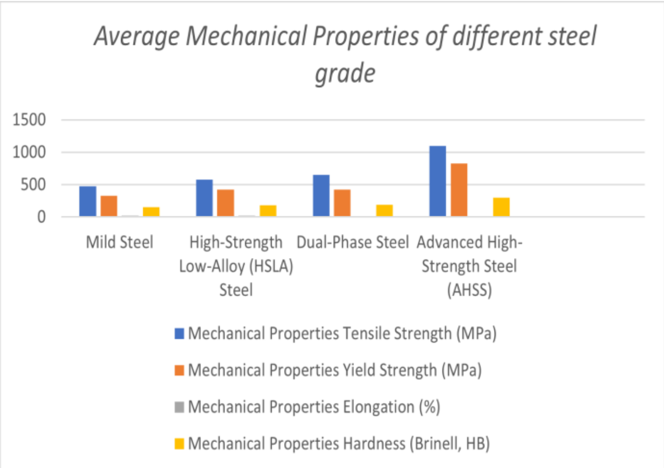

Figure 1 Average Mechanical Properties of different steel grade

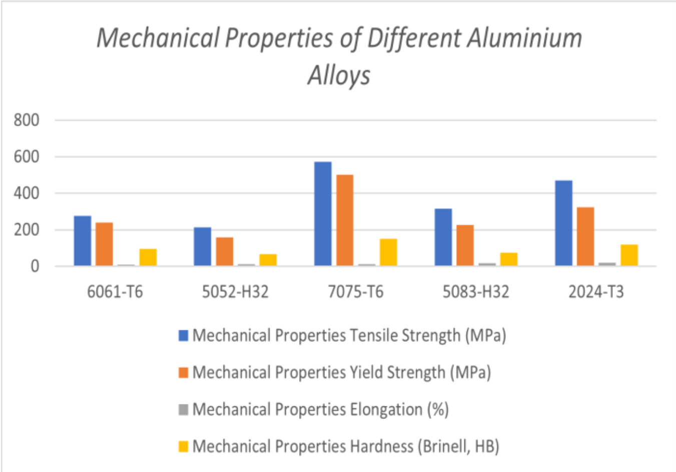

Figure 2 (Avg. Mechanical Properties of Different Aluminum Alloys [18], [19])

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4.2. Aluminium car bumpers

Aluminum car bumpers are gaining popularity due to their light weight (improved fuel efficiency and handling) and corrosion resistance (extended lifespan and reduced maintenance) compared to steel [13]. Aluminum car bumpers, despite being lighter than steel, offer comparable impact protection due to their high strength-to-weight ratio. This weight reduction enhancing both aesthetics and fuel efficiency. Additionally, aluminum's full recyclability makes it an environmentally friendly option with a reduced carbon footprint [17]. Aluminum bumpers are more expensive and harder to repair than steel ones due to higher material and manufacturing costs [16]. Aluminum bumpers, though lighter, are more brittle (cracking risk) and prone to galvanic corrosion with steel. They might also be less available for repairs, leading to delays and higher costs [19]. While aluminum bumpers offer weight and corrosion advantages, their higher costs and complex repairs necessitate careful consideration of vehicle design, performance needs, and budget before implementation [20]. Mechanical Properties of Different Aluminum Alloys [18], [19] are shown in Figure. 2 and Table 2.

4.3. Plastic Car Bumpers

Plastic car bumpers, typically made from lightweight materials like polypropylene or polycarbonate, are popular for their contribution to improved fuel efficiency, handling, and performance also it potentially reduces damage and injury risk in low-speed impacts.[23]. Plastic bumpers boast corrosion resistance (longer lifespan, less maintenance), lower production cost compared to metal, and are lightweight for potential performance benefits [24]. Plastic bumpers are more susceptible to damage and raise environmental concerns.[25]. Plastic bumpers are more prone to damage and expensive/difficult to repair compared to metal, potentially requiring full replacements.[21].[24], [25], [26] They also face potential heat damage and may have lower perceived quality compared to metals [27]. Mechanical properties of Thermosetting Plastics [28][29] are shown in Figure 3 and Table 3.

Table 2 Mechanical Properties of Different Aluminum Alloys [18], [19]

Aluminum Alloy	Mechanical Properties			
	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Hardness (Brinell, HB)
6061-T6	276	240	8	95
5052-H32	214	159	12	68
7075-T6	572	503	11	150
5083-H32	317	228	16	75
2024-T3	470	325	20	120

Table 3 Mechanical Properties of Thermosetting Plastics [28][29]

	Mechanical Properties			
Plastic Type	Tensile Strength (MPa)	Impact Resistance (Joules)	Flexibility (Flexural Modulus, GPa)	Heat Resistance (Temperature Range, °C)
Polypropylene	25-40	300-800	1.5-2.5	-10 to 120
Polyvinyl Chloride (PVC)	40-60	20-100	1.5-3.0 (Flexible) / 3.0-6.0 (Rigid)	0 to 60
Polycarbonate	60-70	800-1200	2.5-3.0	-40 to 120
Acrylonitrile Butadiene Styrene (ABS)	40-50	160-300	2.0-2.5	-20 to 80

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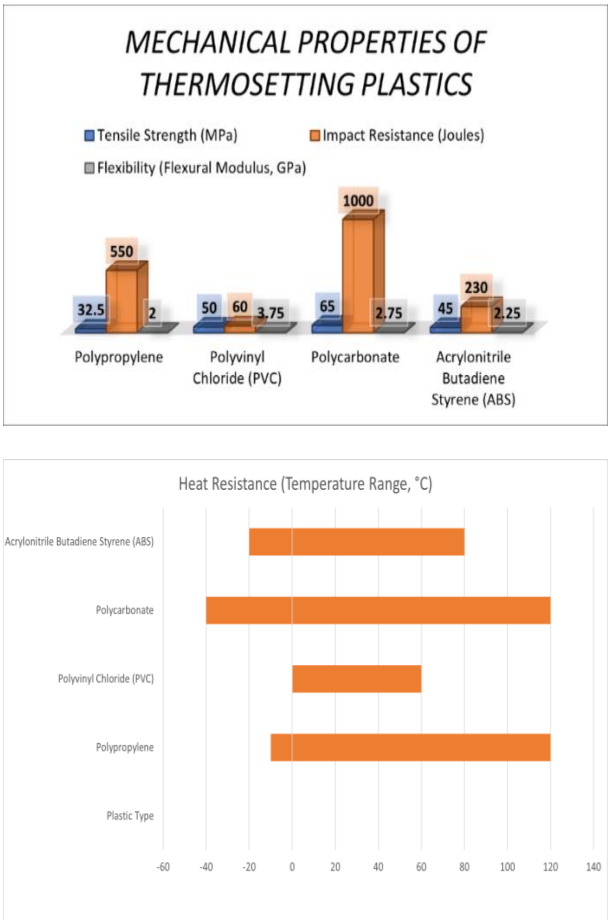

Figure 3 **(Average Mechanical Properties of Thermosetting Plastics [28][29])**

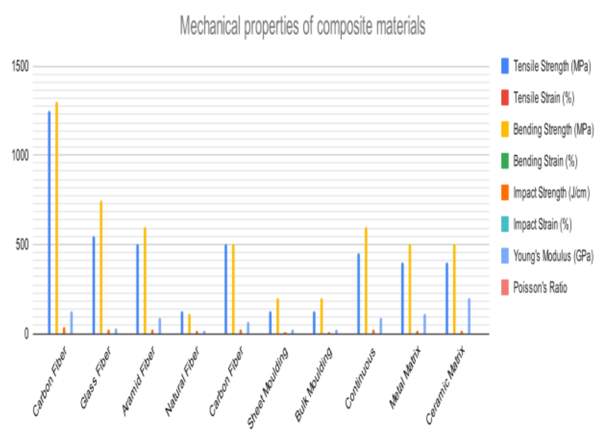

Figure 4 **Average Mechanical properties of composite materials.[32], [33], [34], [35], [36], [37], [38])**

4.4. Composite materials

Composites exceeds the strength and durability of steel or aluminum, lightweight for improved performance, flexible design possibilities, corrosion resistant, noise-reducing, and improve ride comfort [30]. Despite their superior strength, lightweight design, and design flexibility, composite bumpers are expensive to make and repair, potentially brittle, and susceptible to sun damage and environmental concerns.[31]. Mechanical properties of composite materials.[32], [33], [34], [35], [36], [37], [38]) are shown in Figure 4 and Table 4. Commonly used materials for car bumpers fall under the category of composites. Glass Fiber Car Bumpers:[40] Fiberglass bumpers are popular for customization among enthusiasts due to their lightweight construction (improved fuel efficiency and handling) and mouldability for unique designs. This material boasts a high strength-to-weight ratio for protection despite being lightweight. Minor repairs are simple (sanding, filling, repainting) while significant damage might require patching or replacement [39]. Despite lightweight construction (better fuel efficiency, and handling) and customizable designs, fiberglass bumpers are brittle (limiting high-speed protection) and can be expensive due to the need for quality materials and skilled installation. However, they offer low-speed impact protection and are easier to repair compared to some materials. Their availability might be limited, requiring customization for specific vehicles[22].[41] Fiberglass bumpers offer corrosion resistance (longer lifespan, less maintenance) and improved serviceability after impacts due to faster pressure wave transmission. However, their lightweight construction might limit high-speed protection and they can be expensive and have limited availability for certain vehicles.[42]. Mechanical Properties of GFRP Material[43], [44], [45], [46] are shown in Figure 5 and Table 5.

Carbon Fiber Car Bumpers: Carbon fibre bumpers are the pinnacle of lightweight performance. Their exceptional strength-to-weight ratio makes them significantly lighter than steel or aluminum, improving acceleration, handling, and fuel efficiency.

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Table 4 Mechanical Properties of Different Composite Materials.[32], [33], [34], [35], [36], [37], [38]

Composite Material	Reinforcement	Matrix	Tensile Strength (MPa)	Tensile Strain (%)	Bending Strength (MPa)	Bending Strain (%)	Impact Strength (J.cm^{-1})	Impact Strain (%)	Young's Modulus (GPa)	Poisson's Ratio
Carbon Fiber Reinforced Polymer	Carbon Fiber	Epoxy Resin	500 -2000	0.5 - 2	800 - 1800	1 - 2.5	20 - 60	0.5 - 1.5	100 - 150	0.2 - 0.4
Glass Fiber Reinforced Polymer	Glass Fiber	Polyester Resin	300 - 800	1-3	500 - 1000	1-3	10-40	0.5 - 2	20 - 40	0.2 - 0.3
Aramid Fiber fiber-reinforced polymers	Aramid Fiber	Epoxy Resin	300 - 700	1-3	400 - 800	1 - 2.5	10-40	0.5 - 2	60 - 120	0.3 - 0.4
Natural Fiber Reinforced Polymer	Natural Fiber	Biodegradable Polymer	50 - 200	1-5	70 - 150	1-3	5-20	1-3	5-20	0.3 - 0.4
Carbon Fiber Reinforced Thermoplastics	Carbon Fiber	Thermoplastic Polymer	200 - 800	0.5 - 2	300 - 700	1 - 2.5	10-40	0.5 - 1.5	40 - 100	0.2 - 0.4
Sheet Moulding Compound	Glass Fiber or Carbon Fiber	Thermoset Resin	50 - 200	1-3	100 - 300	1-3	5-15	0.5 - 2	15 - 30	0.3 - 0.4
Bulk Moulding Compound (BMC)	Glass Fiber or Carbon Fiber	Thermoset Resin	50 - 200	1-3	100 - 300	1-3	5-15	0.5 - 2	15 - 30	0.3 - 0.4
Continuous Fiber-Reinforced Metal Matrix Composite	Continuous Fiber	Metal Matrix (Aluminium)	300 - 600	0.5 - 1.5	400 - 800	0.5 - 1.5	10-30	0.2 - 0.5	60 - 120	0.3 - 0.4
Metal Matrix Composite (MMC)	Various Metals	Metal Matrix (Aluminium)	200 - 600	0.5 - 1.5	300 - 700	0.5 - 1.5	5-30	0.2 - 0.5	70 - 150	0.2 - 0.3
Ceramic Matrix Composite (CMC)	Ceramic Fiber	Ceramic Matrix	200 - 600	0.5 - 1.5	300 - 700	0.5 - 1.5	5-30	0.2 - 0.5	100 - 300	0.2 - 0.3

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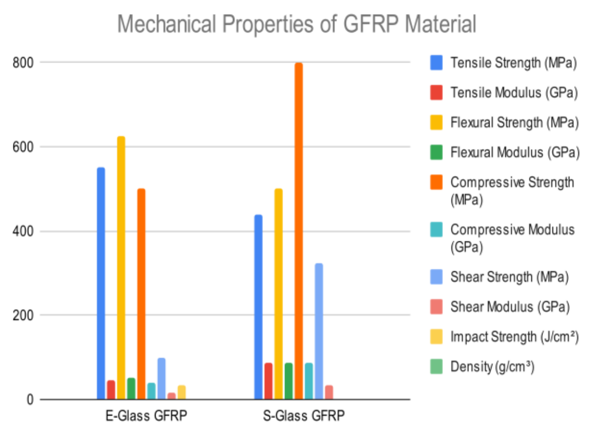

Figure 5 (Average Mechanical Properties of GFRP Material [43], [44], [45], [46])

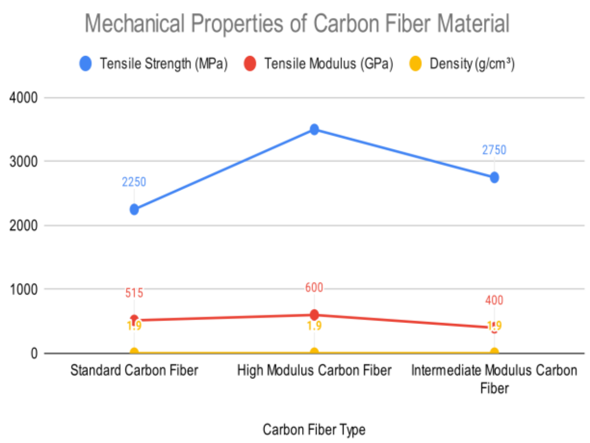

Figure 6 (Average Mechanical Properties of Carbon Fiber Material [54], [55], [56])

Despite being lightweight, carbon fiber offers superior impact protection and increased bumper stiffness for even force distribution during collisions [47].[48] [49] Their high cost and brittleness requiring specialized repairs limit accessibility. Additionally, they boast corrosion resistance and allow for intricate, customizable designs [50][51], [52]. Additionally, finding replacements can be challenging. While they offer superior performance and aesthetics, these come at a price, making them ideal for those prioritizing performance and looks with a budget to match [53]. Mechanical Properties of Carbon Fiber Material [54], [55], [56] are shown in Figure 6 and Table 5.

Table 5 Mechanical Properties of Carbon Fiber Material [54], [55], [56])

Carbon Fiber Type	Mechanical Properties		
	Tensile Strength (MPa)	***Tensile Modulus (GPa)***	***Density (g.cm⁻³)***
Standard Carbon Fiber	1500 - 3000	230 - 800	1.7 - 2.1
High Modulus Carbon Fiber	2000 - 5000	300 - 900	1.7 - 2.1
Intermediate Modulus Carbon Fiber	1500 - 4000	200 - 600	1.7 - 2.1

4.5. Rubber Car Bumpers

Rubber car bumpers are less common but offer excellent shock absorption [57]. Rubber bumpers excel in impact absorption and deform upon collision [55]. Impact absorption is through energy dissipation and deformation upon impact, minimizing damage and shape recovery[56].Beyond superior impact absorption, rubber bumpers offer a smoother ride, weather resistance (sunlight, rain, snow, temperature fluctuations), and cost-effectiveness compared to steel or aluminum [60].While rubber bumpers are effective at absorbing impacts in low-speed collisions, they may not provide sufficient protection in high-speed crashes [58].Rubber is softer than materials like steel or plastic, so it may not withstand significant impacts without sustaining damage. These bumpers may not have the same aesthetic appeal as bumpers made from other materials [62]. They can appear utilitarian or less visually appealing, which may not be desirable for some vehicle owners, they may wear out or degrade over time with repeated impacts or exposure to environmental factors [63]. Rubber bumpers can become brittle and crack over time, reducing their effectiveness. Additionally, their weight can negatively impact fuel efficiency and handling, especially in smaller vehicles.[64] While offering superior impact absorption, smooth ride, weather resistance, and affordability, rubber bumpers can age, crack, and be heavy (reduced fuel efficiency and handling). Additionally, their production and disposal raise environmental concerns [62].

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Mechanical Properties of Different Rubber Material [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71]) are shown in Fig 7 and Table 7 and Figure 7.

Table 6 mechanical properties of GFRP material

GFRP Type	Glass fiber Mechanical Properties									
	Tensile Strength (MPa)	*Tensile Modulus (GPa)*	*Flexural Strength (MPa)*	*Flexural Modulus (GPa)*	*Compressive Strength (MPa)*	*Compressive Modulus (GPa)*	*Shear Strength (MPa)*	*Shear Modulus (GPa)*	*Impact Strength (J.cm^{-2})*	*Density (g.cm^{-3})*
E-Glass GFRP	200 - 900	10-80	250 - 1000	15 - 90	200 - 800	10-70	50 - 150	05-30	10-60	1.5 - 2.0
S-Glass GFRP	400 - 480	85 - 90	480 - 520	86 - 90	700 - 900	85 - 90	300 - 350	33 - 35	Na	2.5 - 2.6

Table 7 Mechanical properties of different rubber materials [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71]

Rubber Material	Mechanical Properties			
	Tensile Strength (MPa)	**Elongation at Break (%)**	**Hardness (Shore A)**	**Abrasion Resistance (mm³)**
Natural Rubber	15 - 25	500 - 800	40 - 90	100 - 500
SBR (Styrene Butadiene Rubber)	15 - 30	300 - 500	40 - 90	150 - 600
EPDM (Ethylene Propylene Diene Monomer)	10-20	100 - 600	40 - 90	100 - 400
Nitrile Rubber	14 - 30	200 - 600	50 - 100	150 - 500
Neoprene (Polychloroprene)	20 - 30	100 - 500	40 - 90	100 – 600

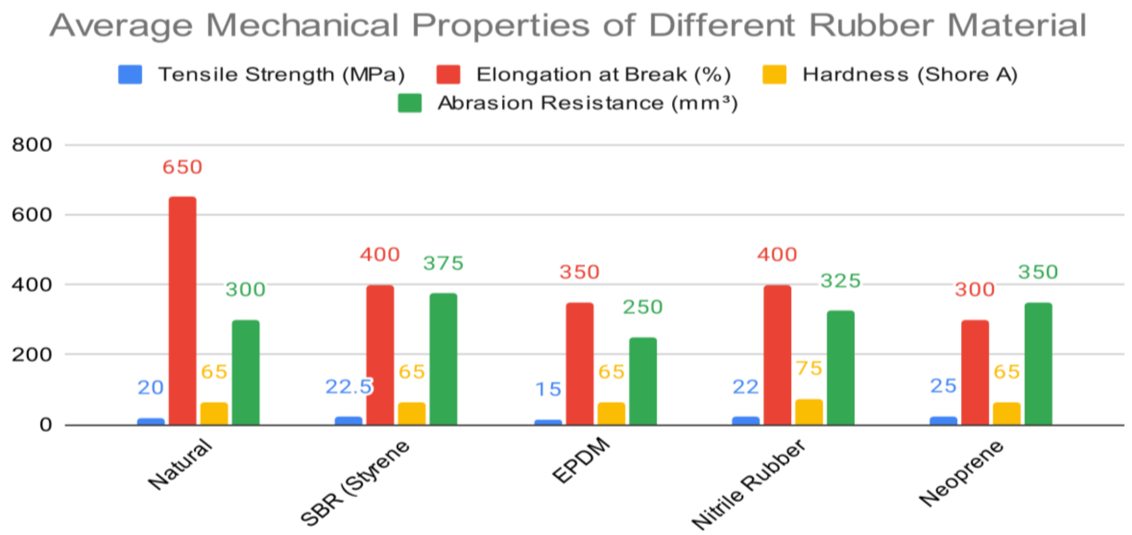

Figure 7 (Average Mechanical Properties of Different Rubber Material [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71])

Conclusion

Choosing the right car bumper material requires careful analysis of technical properties. Steel and aluminium offer good impact protection, while composites excel in high-performance applications. Rubber excels in low-speed impacts but may not suffice at high speeds. Lighter materials (aluminium, composites, plastics) improve fuel efficiency and handling. For durability, aluminium and composites resist corrosion naturally, unlike steel. While generally corrosion-resistant, plastics and rubber can degrade over time. Steel and aluminium are less brittle than most composites (except high-strength steel). Rubber is prone to cracking with age. Steel is the most cost-effective material, followed by aluminium and plastic. Composites and rubber, especially complex designs, are more expensive. Repairing steel and aluminium is generally cheaper than composites and rubber, which often require specialized techniques. Design flexibility is highest with composites, followed by plastics. Steel and aluminium offer limited design options. Aesthetics are subjective, but some materials like rubber may be seen as less appealing. A life-cycle environmental impact assessment is crucial for all materials. Ultimately, the optimal car bumper material depends on the vehicle's needs and priorities, balancing performance (impact, weight), durability (corrosion, brittleness), cost (material, repair), aesthetics (design, appeal), and environmental impact – all based on technical specifications.

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