Feasibility of elastomeric composites as alternative materials for marine applications –A compendious review on their properties and opportunities

D. Aravind[1, 2], K. Senthilkumar[3, *], N. Rajini[2,*], T. Senthil Muthu Kumar[2], M. Chandrasekar[4], Sikiru O. Ismail[5], Rungsima Yeetsorn[3], Jyotishkumar Parameswaranpillai[7], Suchart Siengchin[3,*]

[1] University Science Instrumentation Centre, Madurai Kamaraj University, Palkalai Nagar, Madurai – 625021, Tamil Nadu, India.

[2] Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil – 626126, Tamil Nadu, India.

[3] Department of Materials and Production Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok, 1518 Wongsawang Road, Bangsue, Bangkok 10800, Thailand.

[4] School of Aeronautical Sciences, Hindustan Institute of Technology & Science, Padur, Kelambakkam, Chennai – 603103, Tamil Nadu, India.

[5] Department of Engineering, Centre for Engineering Research, School of Physics, Engineering and Computer Science, University of Hertfordshire, AL10 9AB, England, UK.

[6] School of Biosciences, Mar Athanasios College for Advanced Studies Tiruvalla (MACFAST), Pathanamthitta, Kerala, India

[*] *Corresponding authors:*

K. Senthilkumar, E-mail: kmsenthilkumar@gmail.com

N. Rajini, Email: rajiniklu@gmail.com

Suchart Siengchin, Email: suchart.s.pe@tggs-bangkok.org

Abstract

The term *elastomer* is a curtailment of two words, which are elastic and polymers. Accordingly, elastomers are polymer materials with elasticity. The significant challenges hindering the development of materials for naval applications, similar to other engineering sectors, include achieving a competitive light elastomeric structure. Marine structures are susceptible to various damage responses due to various loads throughout their service life. Being flexible, elastomer has a low modulus of elasticity, exhibits higher values of failure strain and yield strength. In these regards, elastomers are attractive materials for applications that require elasticity because they offer substantial advantages compared to traditional materials. However, the low fire resistance of these elastomeric materials jeopardizes their use in some critical applications. As a result, elastomeric blends and composites containing flame retardant (FR) additives are commonly used. On the other hand, elastomers possess (i) high strength-to-weight ratio, (ii) excellent impact properties, (iii) low infrared, magnetic, and radar signatures, (iv) excellent durability, and (v) high resilience to extreme loads. Hence, the scope of this study focuses on review and awareness regarding the feasibility of marine applications of elastomers/elastomeric composites, their current scientific and technological drawbacks, and future outlooks or prospects to support several applications in the marine industry.

Keywords: Elastomeric composites, damage modes, mechanisms, properties, opportunities, marine applications.

Nomenclature

3D	three-dimensional
AHP	aluminum hypophosphite
BDP	bis (diphenyl phosphate)
BVID	barely visible impact damage
CB	carbon black
CCT	cone calorimeter test
CNTs	carbon nanotubes
DCP	dicumyl peroxide
EPDM	ethylene-propylene-diene modified
EPR	ethylene propylene rubber
EVA	poly(ethylene-co-vinyl acetate)
FFT	fast Fourier transform
GIC	graphite intercalation compound
GMA	glycidyl methacrylate
GMB	glass micro balloon
HNBR	hydrogenated nitrile butadiene rubber
HSC	high-speed craft
IG	iron-graphene
IMF	intermolecular force
KB	Ketjenblack
LDPE	low-density polyethylene
LOI	limiting oxygen index
MA-g-PP	maleic anhydride grafted polypropylene
MRE	magneto rheological elastomeric
MWCNTs	multi-walled carbon nanotubes
NBR	acrylonitrile/nitrile butadiene rubber
NR	natural rubber
OC	Organoclay
OL	organosolv lignin
PALF	pineapple leaf fiber
pHRR	peak heat release rate
PLA	poly lactide
PMMA	poly methylmethacrylate
PP	poly propylene
pSPR	peak smoke production rate
PTFE	tetrafluoroethylene
PVAc	poly (vinyl acetate)
PZT	lead zirconate titanate
SAM	self-assembled monolayer
SBR	Styrene butadiene
SEBS	styrene–ethylene–butylene–styrene
SEM	scanning electron microscopy
SiC	silicon carbide
SOLAS	safety of life at sea
TG	thermogravimetric
TG-IR	thermo-gravimetric infrared spectroscopy
TMTD	tetramethyl thiuram disulfide
TPE	thermoplastic elastomers
TPU	thermoplastic polyurethane
XRD	x-ray diffraction
ZDMA	zinc dimethacrylate

1. Introduction

Competitive lightweight materials started replacing traditional materials for marine and other related applications such as steel and aluminum because of the increased demand raised by naval architects and marine constructors. The demand for alternative materials in marine applications has been traced to the pursuit of minimizing structural weight. It is proven that even a marginal reduction in structural weight has significant impacts on the energy efficiency. Besides, reduction in the structural weight contributes to an increase in payload and decrease in environmental emissions because it supports better fuel economy [1].

Also, replacing with alternative materials is often necessary for marine applications, as steel contributes to the elevated centre of gravity, and when aluminum is not viable [2]. The use of elastomers establishes real advantages, which include flatness for stealth requirements and improved corrosion resistance. Both these primary requirements are critical to the marine environment to build reliable and durable vessels. It is also essential to consider some difficulties in joining elastomers and metals which dominate marine applications [3]. This is because of the significant differences in mechanical properties between the elastomers and metals [4]. Other properties that have to be taken into account include coefficient of thermal expansion, among others, between the adherents, and the large anisotropy of elastomers.

The elastomeric composites are suitable for marine applications such as (i) on – shore applications which includes construction of marine vessels like fishing vessels, dredgers, speed crafts, structures of cargo vessels, interiors of cargo vessel, accommodation and deck, luxury cruises, special purpose vessels like the ones assisting in laying submarine cables, tug vessels that assist in maneuverability and fighting the accidental fire of larger vessels at the port area, pilot vessels, barges, glands for propelling systems, engine components, pipe line structures, communication systems, navigation systems [5]., etc. and (ii) off – shore applications which includes construction of structures like offshore platforms, berths for mooring vessels, offshore drilling rigs, docks for servicing vessels., etc.

Additional application of elastomers can be traced to large floating structures, elastomeric bearings, tidal and wave energy capturing devices as well as oil rig applications [6], to mention but a few.

2. Marine industry

Discussions on marine sectors are mostly pointed towards the shipping activities. Equitably, there are contributing marine applications that include industries relevant to marine aviation and off-shore. Shipping vessels can be categorically grouped into two: (i)

cargo vessels and (ii) passenger vessels. Cargo transportation through shipping vessels forms the backbone of all import and export activities in all parts of the world because of the huge volume involved. Although sea transport is the cheapest transportation mode available, demand for passenger's vessels is fast declining. This is due to people's choice to opt for quick transportation facilities [6,7].

2.1. Ocean - A challenging environment

The marine environment, which is saline, and the sea density vary differently across the waterscape [9]. Generally, the extreme and aggressive weather conditions prevailing in the ocean make it very rough, thereby creating sudden impact loads on the marine vessels hindering their smooth movement [2]. Therefore, marine structures are susceptible to various damage responses, occurring due to accidental impacts such as collision, grounding of vessels, fire, environmental loads, wear and tear caused by aggressive environments, and many more [9]. The cause of damage to marine structures is highly unpredictable. But their damage responses are widely due to (i) environment loads, (ii) functional loads, which are dead as well as live, and (iii) accidental loads. Hence, marine structures are prone to extreme loads that vary in magnitude and direction [10].

3. Factors influencing structural failures in marine

As marine structures are highly susceptible to severe loads, they could significantly reduce their structural performance or even create instant catastrophic failure. The damage responses are particularly impact and blast-induced. Furthermore, the effects of environmental can induce cyclic fatigue loading on the marine structures. In addition to these, damage responses due to moisture diffusion and humidity can also weaken the structure and induce failure.

3.1. Failure modes of elastomeric composites

Damage modes of composites are quite complex which fails by (i) matrix cracking, (ii) fiber fracture, (iii) interfacial de-bonding (iv) delamination [10][12], (v) pulling-out of fiber, (vi) failures of a compound, which includes kink bands (a case of buckling delamination which refers to kinking of fibers, due to compression), (vii) barely visible impact damage (BVID) and (vii) cone fracture.

The technological advancements aiding the detection of damage responses and computational modeling techniques have promoted accurate predictions of the behaviors of marine composite structures under extreme loads and adverse environments.

4. Pre-requisites for marine applications

In addition to good performance, materials for marine applications should contribute to the integrity and durability of the marine structures, reduce their weights and minimize costs. Some of the prerequisites that apply to maritime sectors are given in Table 1 [12,13].

Table 1. Pre-requisites for materials considered for marine applications.

Pre-requisites	Remarks
Good resistance to impact loads	To hold out against extreme weather conditions and severe environmental loads.
Corrosion resistance	To withstand the saline ocean environment and seawater moisture, being highly corrosive [15].
High non-permeability	To counter the problem of material swelling and prevent damage to materials. For example, prevent delamination.
Fatigue resistance	To prevent fatigue failures occurring due to cyclic loadings.
Wear and tear resistance	To withstand impacts without deformation [16].
Enhanced strength-to-weight ratio	To withstand loading impacts as well as provide a better alternative with good damage tolerance.
Ease of production	To support ease of fabricating complex structures.
Excellent noise and vibrational damping behaviour [17]	To reduce noise and vibration for improved marine performance.
Radar/acoustic transparency	To support navigation without blocking their signaling systems [18].
Fire withstanding capability	A vital convention is defined by the safety of life at sea (SOLAS) [19].

As expected, the materials should have good resistance to impact loads and hold them over a long period. Presently, these materials are of high public scrutiny to preserve marine ecology and adhere to the strict conformity norms set by the governing bodies of the marine field [14]. Taking environment into consideration, there is a need to achieve sustainability in the longer term. This will involve stringently controlled energy expenditures and synthesizing or recycling polymer to prevent rapid depletion of resources [19-21]. Also, considering synthesizing

or recycling, which is not cost-effective, developing new technologies to work towards sustainability and the economy is imperative [22].

5. Elastomers

Elastomers are polymers with the capability to return to their original shapes after deformation when stress is removed. The stress causes the deformity. Rubbers are popular elastomers. These polymers possess high viscosity. On account of having elasticity as well as viscosity, elastomers are said to be viscoelastic. The viscoelastic polymers mainly constitute (i) carbon, (ii) hydrogen, (iii) oxygen, and (iv) silicon in various cases. These are unsaturated or saturated, depending on the existence or non-existence of additional reactions, respectively. The intermolecular forces (IMF) mediate the interaction between atoms and other nearby particles; hence it holds the molecules of elastomers. Nevertheless, the IMF in elastomers is weak [23].

These materials possess long polymeric chains with flexibility and mobility of high degrees and are joined as a network structure. This facilitates elastomers to have higher deformation when they are subjected to stress. Their polymeric chains are modified very quickly due to the high mobility of long polymeric chains. This configuration gives solid structure, as the polymeric chains are linked into a network. Hence, the relative flow between them is restricted under stresses that are acting externally. This is the reason for attaining stretchability. When the external forces are removed, the elastomers recover back to their original positions. The network structure is obtained by linking the long polymeric chains together, either physically or chemically by (i) chains adsorbed onto the surface of fine particulate fillers, (ii) formation of small perfect crystals; crystallites, (iii) ionic centers on coalescence and (iv) glassy blocks on coalescence [24].

Moving forward, polymers with high molecular weight form entanglements by an intertwining of molecules. They carry a spacing characteristic of the concerned molecular structure, as presented in Figs 1(a) and (b). Molecular weight between entanglements represents the spacing (M_e). Thus, these polymers exhibit rubber-like behaviour, despite being without any permanent intermolecular bonds [25].
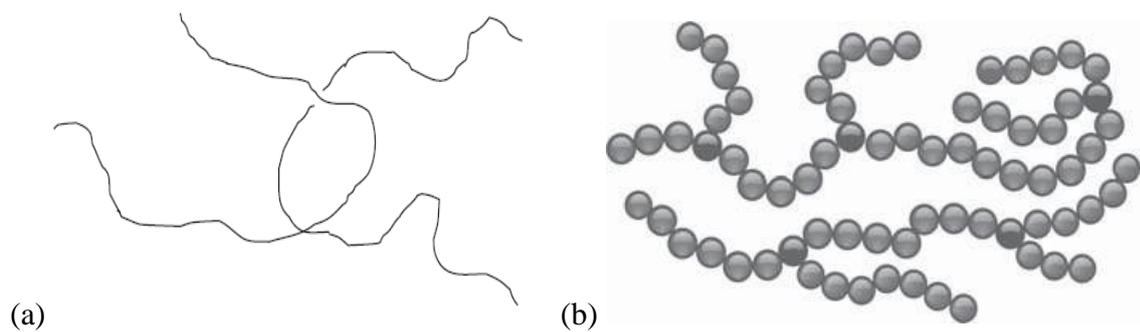
(a)   (b)

Fig. 1. High molecular weight polymer with its molecular entanglements, depicting (a) simple [24] (Reused with permission: License number – 5265920727195) and (b) molecular representations [26] (Reused with permission: License number – 5265921333915).

A more significant number of entanglements are locked permanently in a cross-linked elastomer, as shown in Figs 2(a) and (b). These are considered equal to cross-links at higher degrees, thereby contributing to rubber-like behaviour; its elastic response [27].
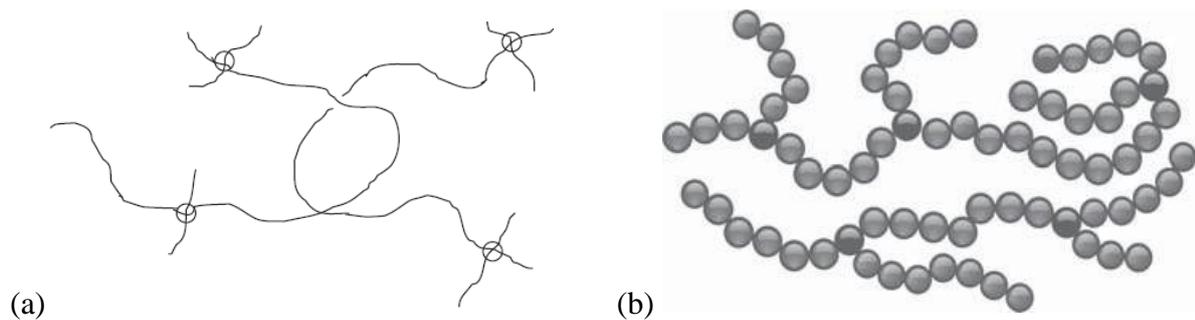

(a)   (b)

Fig. 2. Cross-linked polymer with its entanglements, showing (a) simple [24] (Reused with permission: License number – 5265920727195) and (b) molecular representations [26] (Reused with permission: License number – 5265921333915).

The capacity of long chains on applying stress to reconfigure to its original dimension to distribute the applied stress defines elasticity. It is ensured by the cross-linkages, in particular, that the elastomer returns to its original configuration when the stress is removed. As a result of this extreme flexibility, elastomers can reversibly extend from 5 to 700 percent, depending on the specific material. Without the cross-linkages or with short, uneasily reconfigured chains, the applied stress would result in permanent deformation.

There are specific properties that elastomers possess, which are absent in metals [28]. Table 2 highlights some unique properties of elastomers.

Table 2. Significance of the elastomers

Property	Range	Description
High bulk modulus relative to its modulus of elasticity (Young's modulus)	Bulk modulus (2000–3000 MPa) Young's modulus (0.5–3.0 MPa)	Hard to change its volume when deformation occurs; therefore, they are highly incompressible.
Damping	------	Prevents the amplitude of the vibration.
Large strain deformation	A few hundred percent	Contributes to its elasticity.
Poisson's ratio	Close to 0.5	Almost incompressible.

In order to restrict changes in shape on constraining elastomer, it becomes stiffer [27]. This feature is utilized for designing compression springs. The end applications include bearings of elastomeric bridges and seismic bearings, being examples. Damping that is inherent also plays a vital role in restricting the amplitude of vibration from being exceeded in springs. Vibration isolators and mountings on the engine depend on this inherent damping behaviour of the elastomer. The elastomer is subjected to strain deformation of higher values on exposure to applied stress below its breaking stress without exhibiting failures, denoting more energy stored in it per unit volume [22,27]. This is utilized for elastomeric dock fender systems. The large amount of energy stored is employed for absorbing its large stored energy capacity to absorb shocks caused by the impact that the ships exert.

Additionally, the preference for elastomer is due to the following benefits: (i) less maintenance, (ii) facilitates achievement of varying stiffness different for each condition, otherwise varying characteristics of load-deflection (non-linear), if a precise designing is processed, (iii) tolerance to misalignment up to a specific limit [30], (iv) ease in installation, (v) its ability to inherit hysteresis to dampen resonant vibrations, which could be dangerous [31].

It is essential to mention here that elastomers are highly resistant to alkalis, inorganic acids, and salts, unlike metals. This makes it possible for applications in tanks and pipelines of chemical-carrying shipping vessels, as the elastomers protect metal against corrosive chemicals. Table 3 presents general information on various common elastomeric compounds and general features of most common elastomers.

Table 3. General features of the common elastomers.

Composition	Domain name	Properties	Sensitivity	
			Resistance to	Susceptible to
Isobutylene-isoprene	Butyl	Desirable properties, such as resistivity to weather, good dielectric properties and impermeabiltiy [32]. But they exhibit less resistance to petroleum products.	Oils, alkalis, grease, oxidizing chemicals, ammonia, phosphates and ozone.	Petroleum products, such as fluids, solvents, and lubricants.
Ethylene-propylene-diene modified [33]	EPDM	Excellent resistance to weather, chemicals, ozone, ultraviolet (UV) and aging. But, exhibit less resistance to petroleum-based products.	Oils, alkalis, grease, oxidizing chemicals, ammonia, phosphates, and ozone.	Aliphatic and aromatic hydrocarbons, petroleum products and minerals.
Isoprene, natural	Natural rubber [34]	Good physical properties, but they possess less resistance to petroleum-based products.	Chemicals, organic acids, alcohols, ketones and aldehydes.	Petroleum products, strong acids and ozone.
Chloroprene	Neoprene	Resistance to weather, petroleum products. Possess resilience, abrasion strength and flame-retardancy.	Petroleum products, ozone, refrigerants, Steam and carbon dioxide.	Oxidizing acids, acids, esters, ketones, chlorinated, aromatic and nitro hydrocarbons.
Nitrile-butadiene [35]	Nitrile (Buna-N)	Excellent resistance to petroleum products, tear, heat aging and possess abrasion	Hydraulic fluids, petroleum products and	Ozone [36], ketones, esters, aldehydes, chlorinated and

		strength.	minerals.	nitro hydrocarbons.
Isoprene, synthetic	Poly-isoprene	High resilience and resemblance of natural rubber, but exhibit slightly lower tensile strength.	Aldehydes, moderate chemicals, organic acids, alcohols and ketones.	Ozone, strong acids, hydrocarbons, and petroleum derivatives.
Styrene butadiene [37]	SBR	Effective electrical insulation properties, resistance to alcohol, oxygenated solvents, and mild acids. Exhibit properties similar to natural rubber, but possess superior low-temperature flexibility and heat aging properties.	Aldehydes, moderate chemicals, organic acids, alcohols and ketones.	Ozone, strong acids and most hydrocarbons.
Polysiloxane	Silicone	Excellent temperature properties, vibration damping, fatigue resistance, good elongation capability and dielectric strength. But, possess poor tensile, tear and abrasion resistance. In general, they are odourless and non-toxic.	UV light, moisture, fungus and concentrated sodium hydroxide.	Concentrated acids, alkalines, fuels and steam.

5.1. Elastomeric composites

Most of the mechanical properties of neat polymers are low, and they are incorporated with other materials to succeed in applications [38]. Elastomeric composites can be generally classified into two categories: the thermosets-based and thermoplastics-based elastomeric composites. The former type cannot be melted back, whereas the latter ones can be melted back. It is necessary to point out the differences between thermoplastic and thermosets. The main distinguishing criteria between the two is that the melting point of thermoplastics is typically low, which helps it be remoulded or recycled further quite easily. This involves the application of heat. Conversely, the thermosets are quite the opposite.

The general form of composites consists of two phases: (i) continuous phases and (ii) discontinuous phases incorporated with continuous phases. The continuous phases are called matrices—the discontinuous phases, which are harder and are called reinforcement [39]. The fibers, which constitute the reinforcements and their bonding with the polymer matrix, are responsible for the mechanical behaviour of the composites. Whereas, the resins, , are accountable for load transmission to protect fibers from damage. Additionally, fillers and adhesives are sometimes added to improve the behaviours of composites or reduce the production cost [40].

The elastomers, which are primarily thermosets, require curing. The curing process may be thermal, chemical and/or radiation treatments. During curing, the existing polymer chains, which are long, are converted into cross-linked covalent bonds. This makes the polymer stronger, and it can withstand high temperatures once hardened. Some elastomers are thermoplastic, melting to a liquid state when heated and turning brittle when cooled sufficiently. Here the existing polymer chains become cross-linked by weaker bonds.

5.2. Combinations of elastomeric composites

The composites of elastomers can be widely branched out based on three categories, namely: (i) matrices, (ii) reinforcements, and (iii) additives, as shown in Fig. 3. These elastomers are combined with various ingredients such as fibers, fillers, among others, to form composites. This is done to achieve desirable properties, such as mechanical, chemical, and wear resistance.
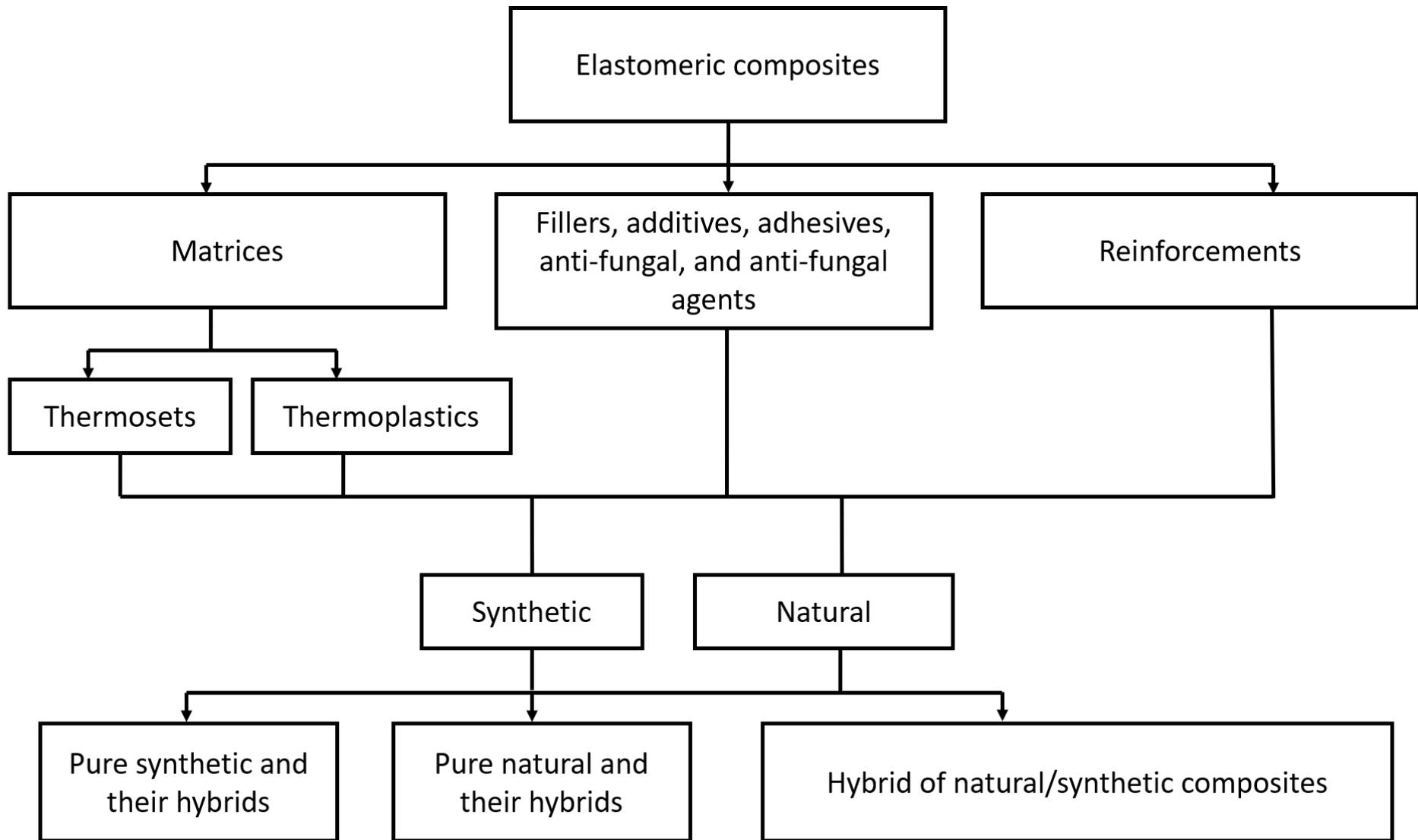
Fig. 3. Combinations of elastomeric composite systems.

6. Factors influencing applications of elastomeric composites in the marine sector

Some of the significant factors that influence the application of elastomeric composites in the marine industry are shown in Fig. 4.
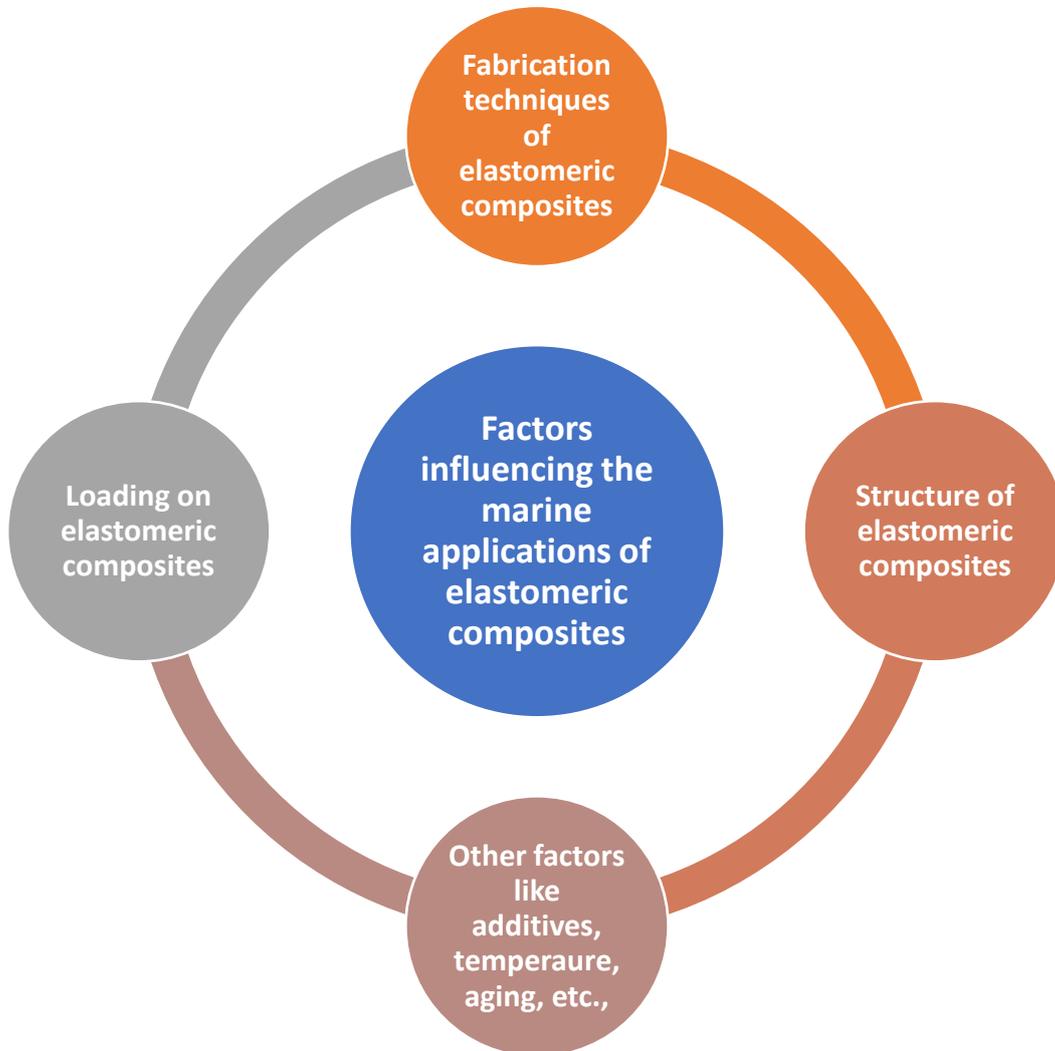
Fig. 4. Factors influencing the marine applications of elastomeric composites.

6.1. Fabrication techniques

The development of elastomeric composites, which are expected to possess mechanical and thermal properties for application-oriented performance, is a significant trend in studies involving the materials science of the modern world. The fabrication process of elastomeric composites involves two equally consequential stages, namely: (i) synthesis of elastomers and (ii) fabrication of elastomeric composites [41].

Moreover, the synthesis of elastomers, which form the elemental structure starts with polymerization, where monomers, in general, are converted into polymers (Fig. 5). Then, the

polymerized form is subjected to mastication to make the elastomer softer through shredding. For synthetic elastomers, the mastication is bypassed. The process of mastication is followed by blending and processing. The elastomers are vulcanized during the process or on completion of the process. Vulcanization helps to enhance the elasticity and dimensional stability of elastomers [42], hence making it feasible for applications like lenses, windows, housings, impellers and parts requiring high impact resistance.
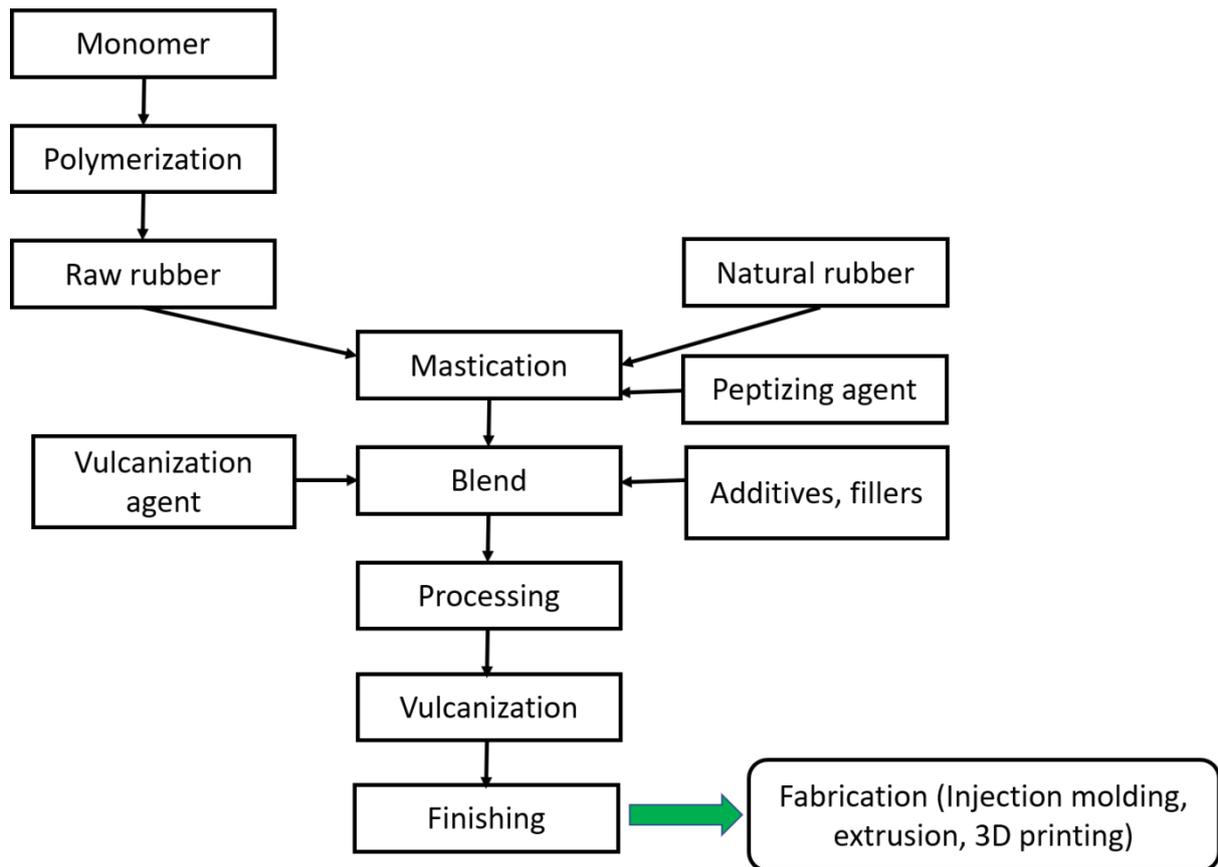

Fig. 5. Fabrication process of elastomeric composites.

Fabrication of elastomeric composites can be done with several techniques. Some of the widely used methods are melt blending, injection moulding, compression moulding, extrusion, solution mixing, hot compression, and three-dimensional (3D) printing. Despite of all these available techniques, it is necessary to find an optimum method for fabrication. Hence, the fabrication of elastomers is not restricted to a specific method. It could be an individual process or combination of operations at various levels according to the expectations and requirements for marine applications.

Furthermore, Chukov et al. [30] used a new approach involving carbonization of elastomeric compounds at low temperatures. The compounds contained carbon fillers that were highly filled, silicon carbide (SiC) that were dispersed, and nitrile butadiene rubber (NBR) as a matrix. The team reported that the composites possessed high tensile and flexural strengths at certain levels of impact toughness that are acceptable, leading to the possibility of producing complex shapes with less machining. All such phenomenon will make elastomeric composites attractive for propulsion shaft, fuel pipes, pipes of the cooling system including freshwater pipe, seawater pipe, and oil pipe, lubricating systems, shaft generator coupling, to name a few even in engine room applications. Other applications include mast and superstructures of ferries. It is to be noted that elastomeric composites usage has become vital in ducts and pipelines laid for oil transfer between refineries and mother vessels. Linhares et al. [43] formulated nitrile rubber with 45% acrylonitrile to assess vulcanization systems involved and their influence on the resistance of NBR to biodiesel. They also studied its sulphur-based curing systems and their influence. They summarized the followings as the contributing factors for the resistance of NBR to biodiesel: (i) composition of NBR with similar cross-link densities, and its cross-link, (ii) vulcanization system played a vital role in mechanical resistance, (iii) choice of the accelerator and (iv) tetramethyl thiuram disulfide (TMTD); low TMTD produced voids on the fractured surface. Croom et al. [44] injected a mixture of Sylgard glass micro balloon (GMB) specimens into a cylindrical syringe, and it was cured and accelerated at room temperature. The Sylgard GMB specimens were obtained using two-part Sylgard184 silicone elastomer (Dow Corning) mixed with A16 glass micro balloons (3M) in the presence of a curing agent. The mixture was injected into a cylindrical syringe and cured at room temperature with an accelerator. They reported that the major cause for the collapse of GMB depended on: (i) decreased spacing between particles and (ii) non-linearity of the orientation of the nearest neighboring particles.

Besides, Mahesh et al. [45] fabricated flexible green composite laminates, using compression molding with the applied temperature of 138 ºC and pressure of 25 kg/cm^2. The laminates were then cured. The fabricated composites were compounds of nature woven jute fabric of density of 1450 kg/m^3 and areal density of 350 g/m^2, as reinforcement and flexible rubber ('B' stage cured prepegs), as a matrix with various stacking sequences. It was reported that additional layers of rubber and jute increased energy absorption and ballistic limit with a decrease in residual velocity, leading to increased resistance to damage which will make it suitable for applications in high-speed craft and structures requiring resistance to ballistic loads [46]

A computational 3D reconstruction of the composite specimen with an efficient polydisperse convex particle packing algorithm was done by Dehnavi et al. [47]. A fast Fourier transform (FFT) homogenization method developed was able to predict effective thermal properties of this complex specimen with low volume fractions.

6.2. Structure of elastomers

In general, the properties of any blends of polymer, such as an elastomeric composite, are dependent on the: (i) mode of dispersion of the polymers and (ii) interaction between different phases; the harder discontinuous and continuous phases, namely reinforcements and matrices, respectively and (iii) properties of their parent polymers.

Xu et al. [48] demonstrated an approach to improve the stability between polypropylene (PP) and acrylonitrile-butadiene rubber (NBR) with maleic anhydride grafted polypropylene (MA-g-PP) as a compatibilizer. This was carried out in the presence of zinc dimethacrylate (ZDMA). It was observed that ZDMA contributed to interfacial bonding. The MA-g-PP incorporation contributed to the enhanced mechanical properties of the blends due to the polarity change of the PP phase when melting mixed. The better mechanical performance, light weight nature and its high stiffness will make elastomeric composites applicable for hull structures over the traditional metals. Besides, an improvement in the viscosity of the product was also observed. He et al. [49] studied and introduced isolation film, which consisted of micropores on the composite surface to restrict the flow between regions. This helped form an elastomeric microfluidic valve naturally, and the valve facilitated avoiding wrinkles and evacuating bubbles. Thereby, it contributed to: (i) improve the quality of surface and (ii) manufacture composites of uniform thickness, reducing the need for external hardware.

In addition, Ohk et al. [50] reported that the de-wetting of thermally annealed polymethylmethacrylate (PMMA) films by varying and measuring the surface energies of underlying self-assembled monolayers (SAM) supported by the silicon substrate. It was observed that the effects of interface increased with the increase in surface energies, which indicated stability. The eco-composites, also known as green composites, can be elastomeric. The composition of an eco-composite may be with either natural reinforcements or with a natural matrix. It can also be natural reinforcement and an eco-friendly matrix, such as natural rubber matrices and natural fiber reinforcements. Bio-composites provide numerous benefits, such as (i) cost-effectiveness, (ii) desirable dimensional stability, (iii) thermal stability, (iv) low coefficient of friction and (v) low density [48,52]. The structure of these materials makes them the highly sought materials as it lowers thermal conductivity and are

thermally stable which are required for marine applications. Example being life boats and utility boats which needs longevity and low maintenance [53]. In eco-composites, the adhesion between fiber and matrix is responsible for incorporating reinforcement and matrix [34]. This decides the characteristics of the composites, such as mechanical, rheological, and dynamic mechanical properties, due to the transfer of stress between matrix and fiber. Though this is not clear, it is believed to happen through shearing at the fiber and matrix interface.

Also, Ismail et al. [54] explored an elastomeric composite, an active dense array stamp consisting of 16 stamps that were individual with a lead zirconate titanate (PZT) actuator and a strain gauge sensor, each for controlling the process and improving throughput while enabling at the local. Also, the stamp was of a scalable design with a multiplexed interconnection scheme to ensure a small footprint with actuation, characterization sensing, and closed-loop feedback control. This kind of latest printing involved micro-transfer and is a fast-developing technology for manufacturing 3D integrated heterogeneous micro-systems.

6.3. Loading

The structural performance of marine structures is significantly reduced as they are highly vulnerable to extreme loads. Besides, environmental loads, along with the moisture content of seawater and humidity, cause damage. Thermoplastic composites have been the most desired composite material for marine applications, especially applications beneath the water surface. Though there are options for these, there have been questions raised over its tensile, compressive behaviour [55], and water sensitivity. An experiment was conducted on polyamides that were less expensive to study their mechanical properties when immersed in sea water [56]. A reduction in the performance of laminates was observed.

The damage responses could be due to impact loading [57], impulsive loading [58], environmental effects, blast-induced, and fatigue due to cyclic loading. [60]. Also, elastomeric composites for marine applications are subjected to static and fluctuating loads, mainly due to the inception of cracks that keep on propagating. Hence, both hydrostatic and hydrokinetic pressures contribute significantly to the mechanical behaviours of elastomeric composites and their failures. Nasirzadeh et al. [61] investigated the behaviour of composite sandwich structures on the application of varying high-velocity impact loads at different foam densities. It was observed that: (i) very high ballistic velocity performance and energy absorptions were obtained for high-density foam core of 48 kg/m^3, (ii) phenomenon of projectile yawing, side-impact, and higher energy absorption were recorded for optimized core with foam density

and (iii) low ballistic velocity performance and energy absorptions were obtained for low-density foam core, below 40 kg/m^3. Perillo and Jørgensen [62] used a numerically and independently developed model with simple and measured data of material and evaluated the effects of impact on composites and was successful in predicting the impact and compression due to impact.

Moreover, a study was conducted to analyze coupled effect of thermal and cyclic mechanical loadings on the viscoelastic response of nitrile rubber filled with carbon black [63]. The results obtained were as follows: (i) there was an increase in storage modulus and cycle numbers. This was due to an increase in cross-links. The temperature was also influenced in amplifying this, and (ii) the cyclic mechanical loading played an essential role in increasing the temperature responsible for the above increase in storage modulus. Fiber-reinforced elastomeric composites have extended application in numerous civil as well as military, marine structures. Besides exposure to loads and moisture, they are subjected to UV radiations predominantly in these applications. The UV radiations could cause mechanical degradation and compromise the structural integrity of elastomeric composites. An investigation was performed on vinyl ester composites to study the cumulative effect of moisture, especially cyclic loads and UV radiation [64]. This was carried out with a focus to enhance the reliability of the marine composites over a long period. It was reported that moisture and UV interacted synergistically to cause damage due to accelerated fatigue. Altunsaray et al. [65] investigated fatigue behaviors of fiber-reinforced plastics, composites incorporated with E-glass non-crimp reinforcements that were hand-laid, and polyester resin. The results showed that both thickness and direction of the material did not significantly impact their fatigue behaviors. Besides, the magnetic field also played a vital role in marine applications [66]. Schrödner et al. [67] fabricated composites from various thermoplastic elastomers and powder of carbonyl iron by melt blending, using a twin-screw extruder. By tensile testing, magnetic and mechanical characterization was carried out both in the presence and absence of a magnetic field. A significant increase in Young's modulus, as the magnetic field strength was reported.

6.4. Other factors

Other factors influencing elastomeric composites for marine applications are subsequently elucidated.

6.4.1. Additives

Generally, the elastomeric composites consist of elastomer, fiber, and additives. Some of the known additives are fillers and vulcanization agents. The additives help to improve the properties of elastomeric composites and their processability [68].

Pittayavinai et al. [69] demonstrated the stress-strain behavior of short pineapple leaf fiber (PALF) reinforced with natural rubber (NR) and manipulated by changing the cross-link density (sulfur) and the amount of carbon black (CB) primary filler. It was reported that in the stress-strain curve, PALF was responsible for deficient strain region, sulfur and carbon black for moderate and high strain regions, respectively. Shankar et al. [68] added conductive and dielectric fillers, namely Ketjenblack 300 J (KB) and Dicumyl peroxide (DCP), respectively, to elastomers of solid silicone rubber with a hardness level of shore A 40 and fabricated using compression molding. They intended to alter their mechanical behaviors by improving the permittivity of the elastomeric composites. The experiment achieved the highest values of Young's modulus, density, and shore levels: A hardness of 25.2 MPa, 1210 kg/m³, and 86, respectively. The investigation reported that the above-mentioned factors could be manipulated to achieve desirable mechanical properties [70].

Also, Posada et al. [71] studied shielding properties of rubber composite materials in terms of structures and electromagnetic characteristics of NBR rubber filled with magnetite (Fe_3O_4). The elastomeric composites were separately fabricated with ore magnetite and synthetic magnetite at various ratios, using a rubber mill. Carbon black was also added to (i) improve the mechanical properties, (ii) increase the dielectric permittivity, and (iii) decrease the resistance to electricity. The ratio of carbon black remained the same in all the samples of the elastomeric composites. The study summarized that the: (i) source of magnetite, (ii) its ratio in the matrix, and (iii) thickness of elastomeric composites were responsible for the electromagnetic behaviour of the elastomeric composites [71].

Additionally, Samal et al. [72] worked on magneto rheological elastomeric (MRE) composite in which iron was distributed as filler. In this work, an improvement in the engineering strength of MRE composite was obtained by varying magnetic field intensity. The magneto-mechanical behaviour of the composite mainly depended on the bending angle and correlation bending onset with magnetic and elastic properties of the composite [67].

6.4.2. Operating Temperature

The operating temperature of elastomeric composites also affects their elasticity. Composites of elastomers that are cooled to obtain a crystalline phase are expected to have chains with less mobility. Consequently, they exhibit less elasticity than elastomeric

composites obtained at higher temperatures. The temperature involved here is greater than the glass transition temperature of the elastomer. Furthermore, the elastomers are relatively soft at ambient temperatures with Young's modulus of about 3 MPa, and they are highly deformable. For example, elastomers including hydrogenated nitrile butadiene rubber (HNBR) have less stability dimensionally with changes in temperature, which can lead to contraction thermally. This can lead to leakages due to incongruity between the metal surface and elastomeric sealing components.

Akulichev et al. [35] examined the effect of the addition of alloy particles (MnCoGe) to HNBR elastomer to form an elastomeric composite. The fabrication involved the fusion of solvent casting technique and shear mixing using a twin-roll mill. This combined process was followed by compression moulding. The addition of alloy particles was to thwart the thermal contraction during cooling. A positive effect on the thermal expansion was reported due to the addition of filler for an extended range of temperature from -20 to 40°C. Guo et al. [73] investigated into the influence of sintering temperature on the ceramic residue of polysiloxane-based elastomeric composite that was converted into ceramics. These hard ceramics were fabricated to act as insulation and protect the internal copper core against high-temperature exposure. Moreover, the sintering temperature served as an idle factor to monitor the emergence of protecting layers. The study reported an increase in flexural and impact strengths of the residue, weight loss, and linear shrinkage when an increase in the sintering temperature was monitored from 700 to 1100 °C. Also, the following phenomena were observed in the ceramic residue, as the sintering temperature was increased: (i) an analysis using scanning electron microscopy (SEM) depicted conversion of residue from two phases to an invariable matrix, and (ii) X-ray diffraction (XRD) analysis exhibited formation of quartz crystal at 800°C and $MgSiO_3$ crystal at 1000 °C, both contributed significantly to the mechanical strength of the ceramic composite residue.

In addition, Guo et al. [74] studied the effect of the glass frit with a low softening temperature of 480°C on polysiloxane elastomer-based ceramic. The glass frit that acted as a fluxing agent was vital in ascertaining the microstructure of the elastomeric composite. The ceramic residue was observed using a digital camera. The analysis was carried out using SEM and XRD. The reported results showed an increase in flexural and impact strengths of the residue, weight loss, and linear shrinkage when an increase in the glass frit content was monitored from 0 to 30 phr. Similar to the previous study, the following phenomena were evident in the ceramic residue, as the glass grit content was increased: (i) an analysis using SEM showed conversion of residue from two phases (sea-island) to an invariable matrix, and

(ii) XRD analysis exhibited formation of quartz and $MgSiO_3$ crystals, because of eutectic reaction that occurred between mica and glass frit. Both of these contributed significantly to the mechanical strength of the ceramic composite residue.

Abdelwahab et al. [75] engineered a bio-based and sustainable composite using polylactide (PLA) and organosolv lignin (OL). The multifunctional composite was fabricated using reactive extrusion in poly vinyl acetate (PVAc) and glycidyl methacrylate (GMA), which resulted in a successful, sustainable, and bio-based elastomeric composite. The existence of PVAc and GMA enhanced the interfacial. A generation of single glass transition temperature was also significant. The work reported that: (i) pre-treating of lignin chemically, using organic solvent OL proved to be commendable as OL with lower glass transition temperature and a high number of functional groups enhanced the miscibility and compatibility with polar polymers thermogravimetric analysis (TGA), (ii) OL enhanced the thermal stability of the composite and (iii) elastomeric composite exhibited excellent elongation at break and improved impact strength. The toughened elastomeric composite could replace commercially available thermoplastic elastomers, such as petroleum-based EPDM elastomers.

6.4.3. Aging

All composites have their various life spans, which depend on the environment and nature of the surrounding where they are applied. Hence, materials selection depends on their intended applications, natures, and environments. The life span of a composite is a function of its aging process, which is associated with degradation. The degradation may be of different forms. For example, corrosion in metals occurs as rusting due to oxidation in the presence of moisture. In elastomers, the term degradation is preferred. Degradation of elastomeric composites may be due to a wide range of factors, which include: (i) oxidation, (ii) ozone cracking, (iii) flex cracking, (iv) liquid absorption, and (v) heat aging. Besides, the degradation of elastomeric composites also depends on mechanically imposed strains and could also be due to trace metals. Other agencies, such as solvents in petroleum industries, crude oils, fuels, hot and water, also influence the life spans of elastomeric products. Thus, the degradation of elastomeric composites is a complex phenomenon, unlike metals. Hence, elastomeric composites are resistant to weather-related problems such as corrosion, discoloration, and abrasions which makes it suitable for handrails against the slippage in wet conditions.

Siriruk et al. [76] studied the effect of seawater confinement on cyclic fatigue characteristics of elastomeric composites. The composites were fabricated using carbon fiber and vinyl ester

and subjected to one side confinement. It was observed that: (i) yield failure under fatigue was more prominent when the composites were immersed in seawater than in air, (ii) the failure could be attributed to water absorption into the matrix and fiber-matrix interface due to diffusion and capillary actions and (iii) the inability of water to ingress during compressive loading created pores, leading to failure. Kruželák et al. [36] studied thermo-oxidative and ozone stability of elastomeric composites, using oven aging and thermogravimetric analysis. The elastomeric composites constituted ferrite and ferrite with carbon black on natural and butadiene rubber. The reports summarized that though the ferrite separately or in combination with black carbon influenced the elastomeric composites in many ways, including their ozone stability, their thermo-oxidative stabilities were not influenced. Hatamleh et al. [77] conducted a study on clinical significance and investigated into impacts of human and environmental conditions on some of the mechanical properties: tensile strength, modulus, elongation, tear strength, and hardness of maxillofacial silicone elastomeric composite. The experiment was performed under accelerated daylight aging with mixed storage of simulated sebum. Daylight aging was the regime where the clinical elastomeric composites degraded to the maximum. Statistically, the results showed a significant degradation, but the effect would be less prominent for real-time applications due to less sebum concentration and daylight exposure.

7. Importance of flammability

The fire resistivity nature of composites materials for marine applications is one of the major considerations that define the suitability of the materials. Hence, the norms and protocols for selecting marine materials have been very stringent. Additionally, the regulations have strictly restricted the applications of materials if the defined norms for non-combustion are not met correctly, which could ultimately deter the flag state registry of the ships and restrict its entry into a water body governed by other countries or international water bodies. This could not be protected even though the vessel might carry a flag state legally obtained somewhere. Currently, the international maritime organization-regulated high-speed craft (IMO-HSC) code has encouraged including composites as part of fire restricting materials for applications, such as lining compartments and even for bulkheads. This is subjected to conditions of successful and satisfactory performance in fire tests. Amidst these, during huge fires, its stability and withstanding ability will be questioned. The flammability of elastomers is a serious concern that limits their marine applications since fire safety is paramount [78]. It is also a formidable challenge to produce flame-retarding elastomeric composites without compromising their mechanical performances[70,79].

Araby et al. [80] fabricated an elastomeric composite using a low-cost graphite intercalation compound (GIC). The GIC acted as a multifunctional additive, and the melt compounding technique carried out the fabrication. An actual fire condition was presented by cone calorimeter. The GIC was added to enhance both the flame retarding property and the mechanical performance. The study results established improvements in tensile strength by 230%, Young's modulus by 100%, elongation at the break by 220%, and tear strength by 200%. More importantly, there was an improvement in fire performance index and reductions in average heat release rate at peak and the rate of loss in mass. These were all aided by: (i) chemical reaction that endothermically occurred as the GIC expanded and (ii) a layer of char formed over the elastomeric composite, which protected the underneath layers. Wu et al. [81] achieved a uniform dispersion of carbon nanotubes (CNTs) in stretched filament form with the styrene–ethylene–butylene–styrene (SEBS). The SEBS was coated with bisphenol-A bis-diphenyl phosphate (BDP) in liquid form and a flame retardant that is free of halogen. It was observed that the material system possessed enhanced mechanical and flame resistance properties.

More also, Chen et al. [82] studied flame resistance behaviour as well as smoke suppression properties of thermoplastic polyurethane (TPU)-based elastomeric composite with iron-graphene (IG) and aluminum hypophosphite (AHP). Smoke suppression property is a vital parameter in retarding the spreading of flame. In the TPU-based elastomeric composite, the AHP acted mainly as flame retardant, whereas iron-graphene (IG) acted as a synergistic agent. The fabrication involved preparation of TPU/IG using a solution-blending method, followed by preparation TPU/AHP/IG composites through the melt-blending method. The flame resistive nature of TPU-based elastomeric composites was analyzed, using: (i) limiting oxygen index (LOI), (ii) UL 94 test, (iii) cone calorimeter test (CCT), (iv) SEM, (vi) thermogravimetric (TG) analysis and (vii) thermo-gravimetric/Fourier transform infrared spectroscopy (TG-IR). The results of rigorous tests projected a remarkable flame retardant nature through their data. At 0.25 weight percentage (wt.%) of IG and 9.75 wt.% of AHP, the elastomeric composite reached UL 94 V-0 rating, and the LOI increased by 31.5 of volume percentage (vol.%), peak heat release rate (pHRR) value decreased by 90%, and peak smoke production rate (pSPR) value decreased by 72%, among others. Also, the SEM images depicted a lamellar form with more residues of char. The TG-IR data confirmed the release of carbon dioxide (CO_2) and water (H_2O) due to the addition of AHP and IG. Besides, there was also a reduction in the release of harmful gases.

The extensively conducted studies demonstrated that some additives provided both flame resistivity and reinforcement to elastomeric composites to improve their mechanical properties. These advantages help in extensive applications in industries, and therefore the scope of their applications is also broadened. More importantly, these can be achieved at a reduced cost [83].

8. Elastomers for marine applications – A justification

Given the advances in materials, design process, and production procedure, it is now possible to produce high strength, lightweight, and cost-effective composite structures that could compete and outperform their metal counterparts. Unlike metals, the density of a composite can be easily controlled through structural arrangements. Besides, it increases structural buoyancy. Moreover, other secondary features, including greater material strength, flexibility, environmental resistance, damage tolerance as well as reductions in weight, size, and cost, can also be appreciated [5,84]. Conventionally, the preferred geometrical arrangement of fiber reinforcement for marine applications has been woven fabric, often combined with chopped strand mat layers. The selection of such currently available materials is quite advanced for fast vessels, such as surface effect ship and hydrofoils, both surface piercing and fully submerged types. In these applications, weight savings are critical and structural optimization is essential. Composite materials and structures for marine applications offer many advantages over traditionally preferred engineering materials. Some of the prominent benefits include lightweight and corrosion resistance. Composite materials also show excellent behaviors under extreme and cyclic fatigue loading, which lead to a significant reduction in maintenance costs. Table 4 presents some advantages of elastomeric composites in marine applications.

Table 4. Specific advantages of elastomeric composites in marine applications.

Property of composite	Specific advantages to marine applications
Corrosion resistance	Makes it durable and reduces the cost involved towards maintenance, anti-corrosive paints, and anti-corrosive treatments.
Lightweight	Increases the revenue generation, due to increase in payload, facilitates high speed, and improves depth.
Monolithic, seamless construction	Enables achievement of complex shapes easily, as it gets draped over smoothly.

Accurate finish	Material wastage is minimized; reduces the need for secondary machining.
Aesthetical look	Expenses towards painting and polishing are reduced.
Tailorability of design criteria	Expected performance efficiency could be achieved.
Non-magnetic	Signature and galvanic corrosion are reduced.
Non-magnetic	Radar cross-sections are reduced, which improves its function.
Inherent damping	Radiated noise level reduction.
Radar/acoustic transparency	Radar/sonar performance improvement.
Low thermal conductivity	Enhanced fire containment.
Multiple sources	Facilitates easy procurement of raw materials.
cascading effect	The performance of one component can replace or eliminate other system components through its performance.

Applications of elastomeric composites for marine applications have become wider since their inception in the 1950s, including applications in laminated glass plastics, reinforced plastic piping, and glass-fiber-reinforced plastics. Though their applications were limited to small vessels such as fiber boats, lifeboats, and small fishing vessels, but started expanding to large structures, including hulls, superstructures, submarine vessels, and offshore platforms throughout the period [85]. This defines the suitability of elastomeric composites in marine applications.

9. Elastomeric nanocomposites

The issue of an uncontrollable energy crisis has increased the demand for minimal usage or optimization of available resources. This has become the order of the day. Nanocomposites have become one of the drivers of optimization of resources as well as to better performances. Besides, they are also competitive in cost. Recently, an integral contribution of material engineering includes the fabrication of elastomeric nanocomposites. Improvement of mechanical properties and vital strengthened elastomeric composites could be achieved by adding nano-materials into the elastomeric mix [86–92].

Jurczuk and Galeski [86] investigated thermoplastic elastomer fabricated with poly tetrafluoroethylene (PTFE) nanofibers and thermoplastic elastomer/low-density polyethylene

(TPE/LDPE). It was observed that the nanofibers influenced the strain hardening coefficient. Razavi-Nouri et al. [93] fabricated thermoplastic elastomeric nanocomposites with NBR and poly (ethylene-co-vinyl acetate (EVA) by varying weight ratios of NBR at 20, 40 and 60% along with 5% by weight of organoclay (OC). The composites were fabricated using a mixer. An observation on the morphology, thermal stability, mechanical properties, and rheology of the different blends of composites depicted that there was a significant improvement in Young's modulus and yield stress, whereas there was a decrease in the elongation and stress at the break in relation to the unfilled materials. Wu et al. [94] reported significant improvement in thermal conductivity of elastomers produced with styrene-butadiene rubber boron incorporated with nitride nanosheets and coated with polyrhodanine. It was reported that the orientation of nanosheets improved their thermal conductivity. Furthermore, studies have reported multi-walled carbon nanotubes (MWCNTs) with impressive dielectric, electromagnetic, morphological and microstructural characteristics [95–97].

10. Other applications of elastomeric composites

Wide applications of elastomers involve rubbers, which could be natural and/or synthetic. The rubber is widely used for the production of tires and tubes. The other applications of elastomers are hoses, friction belts, gloves, balloons, bands, erasers, matting components, corrosion protective composite coating, oilfield implementations, auxetic fabrics, adhesive materials, and sometimes for intermuscular electrode applications [98–100]. Rubber fibers are considered a valuable element in the textile sector. Ethylene propylene rubber (EPR) is handy in applications as an insulator for high voltage cables. Polyurethanes find their applications in high-resilience requirements, foam sealing, seats, flexible gaskets, carpet underlay, spandex fibers, and electrical potting.

Thus, the flexible and soft elastomers are of great use in various engineering applications, namely earthquake bearing, seismic bearings, and bridge bearings. Indeed, elastomers have played a vital role in several applications involving engineering and other uses for more than a century.

11. Recycling – A mandate for future

Composite materials have become the choice of naval architects and engineers for marine applications, considering the following vital marine requirements: mechanical properties, energy efficiency, economic competitiveness, ease of construction, fire performance nature, and greater life expectancy. Despite all these, there are limitations in their recyclability and

sustainability, which have attracted great concern [101]. Recycling has become an essential practice since the reusability of materials minimizes new productions and the energy involved. This is facilitated as the synthesis of newer materials gets bypassed, contributing to sustainability [83]. The current legislations for waste management and environmental protection are inclined towards the safe recycling of materials without any adverse environmental impacts. The same has been demanded by marine governing bodies and their regulatory departments over the years. These legislations will become more demanding in the future. Presently, the recycling of composite materials is limited to energy recovery from waste, whereas the recovery of fibers is difficult even to a limited extent. The reasons being difficulties in technological and economic viabilities [102]. Exclusive studies over the years have highlighted three main technologies for recycling: (i) mechanical processes, (ii) chemical treatment, and (iii) thermal processes. To survive in the shipping industry dominated by environmental legislations, it has become necessary for the material fabricators to ensure suitable recycling techniques to manage elastomeric composite wastes through energy recovery.

12. Hybridization technique – A proffered solution

An exciting choice for marine applications of elastomeric composites is their hybrid structures, obtained by incorporating two or more types of fibers of different properties. The hybridization may be synthetic fibers with natural fibers or purely natural or purely synthetic compounds. Hybridization of composites enables benefiting from the inherent advantageous properties of an individual component. This could be an efficient method to improve the mechanical properties, strength-to-weight ratio, corrosion resistance, fire retardancy behaviors, impermeability, protection against fungus, resistance to aqueous delamination or degradation. Thus, the concept of hybridization could act as a solution to achieve stringent requirements of the marine environments. Also, the hybrid system is an established engineering concept to obtain superior material properties and structural performances. Thus, hybridization could offer a flexible solution in materials selection, design, development, and optimization for specific marine applications.

13. Concluding remarks

A comprehensive feasibility study on elastomeric composites as alternative materials for marine applications has been conducted and reported, comprising a compendious review of

their properties and opportunities. Cargo transportation through shipping vessels forms the backbone of all import and export activities in all parts of the world because of the huge volume involved. Although navigation is the cheapest mode of transportation available, but demand for passenger vessels is fast declining. This is due to people's choice to opt for quick transportation facilities.

The need to replace most traditional ship/naval structures, such as steel and aluminum, with elastomeric composites has been attributed to the higher structural weight or strength-to-weight ratio, cost, lower reliability, durability, corrosion resistance, among other mechanical properties of the conventional naval components. This substitution is necessary, considering the peculiarity and challenging environment of oceans. Therefore, marine structures must meet some prerequisites and standards, as discussed. The elastomers and their nano/composites were introduced mainly due to their general features, various unique properties, sensitivities, and benefits/applications have been extensively discussed.

In addition, several factors that influence applications, structural failures, and failure modes of elastomeric composites in marine sector have been identified and well elucidated. To prevent unpredictable damage or failure of marine structures due to extreme and aggressive weather and working environments, it is very important to consider fabrication technique, structure, loading, additive, temperature, aging, flammability, among other factors, before elastomeric composites are used in the marine industry.

The current legislations for waste management and environmental protection are inclined towards the safe recycling of materials without any adverse environmental impacts. The same has been demanded by marine governing bodies and their regulatory departments over the years. These legislations will become more demanding in the future. Hence, to survive in the shipping industry dominated by environmental legislations, it has become necessary for the elastomeric material designers and manufacturers to ensure suitable recycling techniques to manage elastomeric nano/composite wastes through energy recovery.

Lastly, the composites industry is thriving. It has very bright and promising future outlooks and prospects, as improved elastomeric nano/composites are required for wide and specific marine applications. Therefore, the quest to further enhance their properties and performances should be a continuous task through several optimizing simulations and/or experimentation-based techniques, such as hybridization, treatments, and manufacturing processes, to mention but a few.

Acknowledgements

Conflicts of Interest

None declared.

References

1. Crupi V, Epasto G, Guglielmino E. Comparison of aluminium sandwiches for lightweight ship structures: honeycomb vs. foam. *Mar Struct* 2013; 30: 74–96.

2. Stewart R. Better boat building—trend to closed-mould processingcontinues. *Reinf Plast* 2011; 55: 30–36.

3. Cerracchio P, Gherlone M, Di Sciuva M, et al. A novel approach for displacement and stress monitoring of sandwich structures based on the inverse Finite Element Method. *Compos Struct* 2015; 127: 69–76.

4. Neşer G. Polymer based composites in marine use: History and future trends. *Procedia Eng* 2017; 194: 19–24.

5. Roland CM. Naval applications of elastomers. *Rubber Chem Technol* 2004; 77: 542–551.

6. Vardhan DH, Ramesh A, Reddy BCM. A review on materials used for marine propellers. *Mater Today Proc* 2019; 18: 4482–4490.

7. Cho H, Lee J. Does transportation size matter for competitiveness in the logistics industry? The cases of maritime and air transportation. *Asian J Shipp Logist* 2020; 1–10.

8. Kalgora B, Christian TM. The Financial and Economic Crisis, Its Impacts on the Shipping Industry, Lessons to Learn: The Container-Ships Market Analysis. *Open J Soc Sci* 2016; 04: 38–44.

9. Garcia-Espinel JD, Castro-Fresno D, Parbole Gayo P, et al. Effects of sea water environment on glass fiber reinforced plastic materials used for marine civil engineering constructions. *Mater Des* 2015; 66: 46–50.

10. Yang N, Das PK, Blake JIR, et al. The application of reliability methods in the design of tophat stiffened composite panels under in-plane loading. *Mar Struct* 2013; 32: 68–83.

11. Tran P, Kandula SS V., Geubelle PH, et al. Hybrid spectral/finite element analysis of dynamic delamination of patterned thin films. *Eng Fract Mech* 2008; 75: 4217–4233.

12. Petrucci R, Santulli C, Puglia D, et al. Impact and post-impact damage characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion. *Compos Part B Eng* 2015; 69: 507–515.

13. Sutherland LS. A review of impact testing on marine composite materials: Part I – Marine impacts on marine composites. *Compos Struct* 2018; 188: 197–208.

14. Chen X, Yan N. A brief overview of renewable plastics. *Mater Today Sustain* 2020; 7: 100031.

15. Xie Y, Jiang J (Jimmy), Islam MA. Elastomers and plastics for resisting erosion attack of abrasive/erosive slurries. *Wear* 2019; 426–427: 612–619.

16. Bayraktar E, Bessri K, Bathias C. Deformation behaviour of elastomeric matrix composites under static loading conditions. *Eng Fract Mech* 2008; 75: 2695–2706.

17. Kumbhar SB, Chavan SP, Gawade SS. Adaptive tuned vibration absorber based on magnetorheological elastomer-shape memory alloy composite. *Mech Syst Signal Process* 2018; 100: 208–223.

18. Factors affecting perceptual motor processes Physiology , anthropometry and biomechanics. 1977; 1977.

19. Mcgeorge D, Höyning B-. Fire Safety of Naval Vessels made of Composite Materials : Fire Safety Philosophies , Ongoing Research and State-of-the-Art Passive Fire Protection. *Fire Saf Surviv* 2002; 23–26.

20. Stein RS. Environmental aspects of polymer science and engineering. *J Plast Film Sheeting* 2015; 31: 355–362.

21. Zhu J-B, Watson EM, Tang J, et al. A synthetic polymer system with repeatable chemical recyclability. *Science (80-)* 2018; 360: 398–403.

22. Arndt NT, Fontboté L, Hedenquist JW, et al. Future global mineral resources. *Geochemical Perspect* 2017; 6: 1–184.

23. Samsuri A. <Samsuri - Degradation of Natural Rubber and Synthetis Elastomers.pdf>.

24. Mattes V. 1 Introduction. *Types of Reduplication* 2014; 1: 1–4.

25. Shanks RA, Kong I. *General Purpose Elastomers: Structure, Chemistry, Physics and Performance*. 2013. Epub ahead of print 2013. DOI: 10.1007/978-3-642-20925-3_2.

26. Saldıvar E, Vivaldo E. *Handbook of Polymer Synthesis, Characterization, and Processing / Wiley*, https://www.wiley.com/en-ec/Handbook+of+Polymer+Synthesis,+Characterization,+and+Processing-p-9780470630327 (2013).

27. Shi G, Wang W, Lu H, et al. Study of crosslink structure and dynamic mechanical properties of magnetorheological elastomer: Effect of vulcanization system. *J Intell Mater Syst Struct* 2019; 30: 1189–1199.

28. Lu Y, Liu L, Tian M, et al. Study on mechanical properties of elastomers reinforced by zinc dimethacrylate. *Eur Polym J* 2005; 41: 589–598.

29. Crookes RG, Wu H, Martin SJ, et al. Bio-inspired platelet reinforced elastomeric-ceramic composites for impact and high strain rate applications. *Compos Sci Technol* 2019; 184: 107857.

30. Chukov DI, Stepashkin AA, Salimon AI, et al. Highly filled elastomeric matrix composites: Structure and property evolution at low temperature carbonization. *Mater*

Des 2018; 156: 22–31.

31. Yang Z, Peng H, Wang W, et al. Crystallization behavior of poly(ε-caprolactone)/layered double hydroxide nanocomposites. *J Appl Polym Sci* 2010; 116: 2658–2667.

32. 1%2E3543028.pdf.

33. Martuscelli E. Structure and properties of polypropylene-elastomer blends. *Polypropyl Struct blends Compos* 1995; 1: 95–140.

34. Smitthipong W, Suethao S, Shah D, et al. Interesting green elastomeric composites: Silk textile reinforced natural rubber. *Polym Test* 2016; 55: 17–24.

35. Akulichev AG, Alcock B, Protasov A, et al. HNBR elastomer composite with zero thermal contraction over a range of temperatures. *Compos Commun* 2019; 15: 76–79.

36. Kruželák J, Hudec I, Dosoudil R. Influence of thermo-oxidative and ozone ageing on the properties of elastomeric magnetic composites. *Polym Degrad Stab* 2012; 97: 921–928.

37. Sun Y, He J, Zhong B, et al. A synthesized multifunctional rubber additive and its improvements on the curing and antioxidative properties of styrene-butadiene rubber/silica composites. *Polym Degrad Stab* 2019; 170: 108999.

38. Tang Z, Zhang C, Wei Q, et al. Remarkably improving performance of carbon black-filled rubber composites by incorporating MoS2 nanoplatelets. *Compos Sci Technol* 2016; 132: 93–100.

39. Mallick PK. *Fiber-reinforced composites: materials, manufacturing, and design*. CRC press, 2007.

40. Yoon B, Kim JY, Hong U, et al. Dynamic viscoelasticity of silica-filled styrene-butadiene rubber/polybutadiene rubber (SBR/BR) elastomer composites. *Compos Part B Eng* 2020; 187: 107865.

41. Kuperman V. L Exical P Rocessing of M Orphologically. 2008; 16: 631–653.

42. Zaimova D, Bayraktar E, Miskioglu I. Design and manufacturing of new elastomeric composites: Mechanical properties, chemical and physical analysis. *Compos Part B Eng* 2016; 105: 203–210.

43. Linhares FN, Corrêa HL, Khalil CN, et al. Study of the compatibility of nitrile rubber with Brazilian biodiesel. *Energy* 2013; 49: 102–106.

44. Croom BP, Jin H, Mills B, et al. Damage mechanisms in elastomeric foam composites: Multiscale X-ray computed tomography and finite element analyses. *Compos Sci Technol* 2019; 169: 195–202.

45. Mahesh V, Joladarashi S, Kulkarni SM. Damage mechanics and energy absorption capabilities of natural fiber reinforced elastomeric based bio composite for sacrificial

structural applications. *Def Technol*. Epub ahead of print 2020. DOI: 10.1016/j.dt.2020.02.013.

46. Dhandapani A, Krishnasamy S, Muthukumar C, et al. Plastics in Marine Engineering. *Ref Modul Mater Sci Mater Eng* 2020; 1–12.

47. Nosouhi Dehnavi F, Safdari M, Abrinia K, et al. Numerical study of the conductive liquid metal elastomeric composites. *Mater Today Commun* 2020; 23: 100878.

48. Xu C, Cao X, Jiang X, et al. Preparation, structure and properties of dynamically vulcanized polypropylene/acrylonitrile butadiene rubber/zinc dimethacrylate ternary blend composites containing maleic anhydride grafted polypropylene. *Polym Test* 2013; 32: 507–515.

49. He Y, Li Y, Ju K, et al. Elastomeric microfluidic valve for active resin flow control within composite structure. *Compos Struct* 2020; 254: 112844.

50. Ohk CW, Koo M, Lee BJ, et al. Slip behavior in polymethylmethacrylate films in dependence of self-assembled monolayer wettability. *Polymer (Guildf)* 2014; 55: 6935–6939.

51. Nair AB, Joseph R. *Eco-friendly bio-composites using natural rubber (NR) matrices and natural fiber reinforcements*. 2014. Epub ahead of print 2014. DOI: 10.1533/9780857096913.2.249.

52. Liang S-L, Cook WD, Thouas GA, et al. The mechanical characteristics and in vitro biocompatibility of poly (glycerol sebacate)-Bioglass® elastomeric composites. *Biomaterials* 2010; 31: 8516–8529.

53. Mandlekar N, Joshi M, Butola BS. A review on specialty elastomers based potential inflatable structures and applications. *Adv Ind Eng Polym Res* 2022; 5: 33–45.

54. Ismail N, Ferreira PM. Active elastomeric composite dense array stamp for micro-transfer printing. *Procedia Manuf* 2020; 48: 64–70.

55. Bull PH, Edgren F. Compressive strength after impact of CFRP-foam core sandwich panels in marine applications. *Compos Part B Eng* 2004; 35: 535–541.

56. Arhant M, Le Gac PY, Le Gall M, et al. Effect of sea water and humidity on the tensile and compressive properties of carbon-polyamide 6 laminates. *Compos Part A Appl Sci Manuf* 2016; 91: 250–261.

57. Krollmann J, Schreyer T, Veidt M, et al. Impact and post-impact properties of hybrid-matrix laminates based on carbon fiber-reinforced epoxy and elastomer subjected to low-velocity impacts. *Compos Struct* 2019; 208: 535–545.

58. Ghazlan A, Ngo TD, Tran P. Three-dimensional Voronoi model of a nacre-mimetic

composite structure under impulsive loading. *Compos Struct* 2016; 153: 278–296.

59. Tran P, Ghazlan A, Nguyen TP, et al. *Experimental and theoretical damage assessment in advanced marine composites*. Elsevier Ltd. Epub ahead of print 2019. DOI: 10.1016/b978-0-08-102264-1.00003-0.

60. Sutherland LS. A review of impact testing on marine composite materials: Part II – Impact event and material parameters. *Compos Struct* 2018; 188: 503–511.

61. Nasirzadeh R, Sabet AR. Study of foam density variations in composite sandwich panels under high velocity impact loading. *Int J Impact Eng* 2014; 63: 129–139.

62. Perillo G, Jørgensen JK. Numerical/Experimental Study of the Impact and Compression after Impact on GFRP Composite for Wind/Marine Applications. *Procedia Eng* 2016; 167: 129–137.

63. Garnier P, Le Cam JB, Grédiac M, et al. On the evolution of the viscoelastic properties and its microstructural/chemical origin in filled NBR subjected to coupled thermal and mechanical loads. *Polym Degrad Stab* 2013; 98: 2102–2110.

64. Afshar A, Alkhader M, Korach CS, et al. Synergistic effects of fatigue and marine environments on carbon fiber vinyl-ester composites. *J Eng Mater Technol Trans ASME* 2015; 137: 1–8.

65. Altunsaray E, Neser G, Erbil C, et al. Umweltbedingtes Dauerfestigkeitsverhalten knitterfreier, E-glasfaserverstärkter Polyester-Verbundwerkstoffe für maritime Anwendungen. *Materwiss Werksttech* 2012; 43: 1053–1058.

66. Stanier DC, Ciambella J, Rahatekar SS. Fabrication and characterisation of short fibre reinforced elastomer composites for bending and twisting magnetic actuation. *Compos Part A Appl Sci Manuf* 2016; 91: 168–176.

67. Schrödner M, Pflug G. Magnetomechanical properties of composites and fibers made from thermoplastic elastomers (TPE) and carbonyl iron powder (CIP). *J Magn Magn Mater* 2018; 454: 258–263.

68. Shankar BSM, Mathias KA, Kulkarni SM. Influence of filler and processing parameters on the mechanical properties of dielectric elastomer composites. *Mater Today Proc* 2020; 27: 221–226.

69. Pittayavinai P, Thanawan S, Amornsakchai T. Manipulation of mechanical properties of short pineapple leaf fiber reinforced natural rubber composites through variations in cross-link density and carbon black loading. *Polym Test* 2016; 54: 84–89.

70. Marzec A, Szadkowski B, Rogowski J, et al. Novel eco-friendly hybrid pigment with improved stability as a multifunctional additive for elastomer composites with reduced

flammability and pH sensing properties. *Dye Pigment*; 186. Epub ahead of print 2021. DOI: 10.1016/j.dyepig.2020.108965.

71. Garzón Posada AO, Landínez Téllez DA, Roa-Rojas J, et al. Electromagnetic shielding response of magnetite elastomeric composites: Source and filler content dependence. *J Mater Res Technol* 2020; 9: 10597–10607.

72. Samal S, Vlach J, Kavan P. Improved mechanical properties of magneto rheological elastomeric composite with isotropic iron filler distribution. *Cienc e Tecnol dos Mater* 2016; 28: 155–161.

73. Guo J, Zhang Y, Li H, et al. Effect of the sintering temperature on the microstructure, properties and formation mechanism of ceramic materials obtained from polysiloxane elastomer-based ceramizable composites. *J Alloys Compd* 2016; 678: 499–505.

74. Guo J, Gao W, Wang Y, et al. Effect of glass frit with low softening temperature on the properties, microstructure and formation mechanism of polysiloxane elastomer-based ceramizable composites. *Polym Degrad Stab* 2017; 136: 71–79.

75. Abdelwahab MA, Jacob S, Misra M, et al. Super-tough sustainable biobased composites from polylactide bioplastic and lignin for bio-elastomer application. *Polymer (Guildf)* 2021; 212: 123153.

76. Siriruk A, Penumadu D. Degradation in fatigue behavior of carbon fiber-vinyl ester based composites due to sea environment. *Compos Part B Eng* 2014; 61: 94–98.

77. Hatamleh MM, Polyzois GL, Silikas N, et al. Effect of extraoral aging conditions on mechanical properties of maxillofacial silicone elastomer. *J Prosthodont* 2011; 20: 439–446.

78. Gu J, Liang C, Zhao X, et al. Highly thermally conductive flame-retardant epoxy nanocomposites with reduced ignitability and excellent electrical conductivities. *Compos Sci Technol* 2017; 139: 83–89.

79. Araby S, Li J, Shi G, et al. Graphene for flame-retarding elastomeric composite foams having strong interface. *Compos Part A Appl Sci Manuf* 2017; 101: 254–264.

80. Araby S, Wang CH, Wu H, et al. Development of flame-retarding elastomeric composites with high mechanical performance. *Compos Part A Appl Sci Manuf* 2018; 109: 257–266.

81. Wu Z, Wang H, Tian X, et al. Mechanical and flame-retardant properties of styrene-ethylene-butylene-styrene/carbon nanotube composites containing bisphenol A bis(diphenyl phosphate). *Compos Sci Technol* 2013; 82: 8–14.

82. Chen X, Ma C, Jiao C. Enhancement of flame-retardant performance of thermoplastic

polyurethane with the incorporation of aluminum hypophosphite and iron-graphene. *Polym Degrad Stab* 2016; 129: 275–285.

83. Ren X, Cornish K. *Waste Conversion Into Sustainable and Reinforcing Fillers for Rubber Composites*. Elsevier Ltd. Epub ahead of print 2020. DOI: 10.1016/b978-0-12-803581-8.10547-8.

84. Manuel A, Rosa LA. High Performance Elastomers in Navy Cables. Epub ahead of print 2016. DOI: 10.13140/RG.2.2.18734.31045.

85. Ionov A V., Buvailo LE, Volkova M V., et al. Elastomer materials in ship vibration and noise protection means. *Russ J Gen Chem* 2010; 80: 2122–2133.

86. Jurczuk K, Galeski A. Thermoplastic elastomers reinforced with poly(tetrafluoroethylene) nanofibers. *Eur Polym J* 2016; 80: 58–69.

87. Xu W, Zhang B, Xu B, et al. The flame retardancy and smoke suppression effect of heptaheptamolybdate modified reduced graphene oxide/layered double hydroxide hybrids on polyurethane elastomer. *Compos Part A Appl Sci Manuf* 2016; 91: 30–40.

88. Zhang C, Tang Z, Guo B. High-performance rubber/boehmite nanoplatelets composites by judicious in situ interfacial design. *Compos Sci Technol* 2017; 146: 191–197.

89. Thuong NT, Dung TA, Yusof NH, et al. Controlling the size of silica nanoparticles in filler nanomatrix structure of natural rubber. *Polymer (Guildf)* 2020; 195: 122444.

90. Yuan B, Fan A, Yang M, et al. *The effects of graphene on the flammability and fire behavior of intumescent flame retardant polypropylene composites at different flame scenarios*. Elsevier Ltd. Epub ahead of print 2017. DOI: 10.1016/j.polymdegradstab.2017.06.015.

91. Mokhireva KA, Svistkov AL, Solod'ko VN, et al. Experimental analysis of the effect of carbon nanoparticles with different geometry on the appearance of anisotropy of mechanical properties in elastomeric composites. *Polym Test* 2017; 59: 46–54.

92. Zhou X, Zhang Q, Wang R, et al. Preparation and performance of bio-based carboxylic elastomer/halloysite nanotubes nanocomposites with strong interfacial interaction. *Compos Part A Appl Sci Manuf* 2017; 102: 253–262.

93. Razavi-Nouri M, Karami M. Effect of rubber content on morphology and thermal and rheological behaviors of acrylonitrile-butadiene rubber/poly(ethylene-co-vinyl acetate)/organoclay nanocomposites. *Polymer (Guildf)* 2014; 55: 6940–6947.

94. Wu X, Yang Z, Kuang W, et al. Coating polyrhodanine onto boron nitride nanosheets for thermally conductive elastomer composites. *Compos Part A Appl Sci Manuf* 2017; 94: 77–85.

95. Abraham J, Arif P M, Xavier P, et al. Investigation into dielectric behaviour and electromagnetic interference shielding effectiveness of conducting styrene butadiene rubber composites containing ionic liquid modified MWCNT. *Polymer (Guildf)* 2017; 112: 102–115.

96. Liebscher M, Tzounis L, Pötschke P, et al. Influence of the viscosity ratio in PC/SAN blends filled with MWCNTs on the morphological, electrical, and melt rheological properties. *Polymer (Guildf)* 2013; 54: 6801–6808.

97. Sharika T, Abraham J, Arif P M, et al. Excellent electromagnetic shield derived from MWCNT reinforced NR/PP blend nanocomposites with tailored microstructural properties. *Compos Part B Eng* 2019; 173: 106798.

98. Riaz U, Nwaoha C, Ashraf SM. Recent advances in corrosion protective composite coatings based on conducting polymers and natural resource derived polymers. *Prog Org Coatings* 2014; 77: 743–756.

99. Dolog R, Ventura D, Khabashesku V, et al. Nano-enhanced elastomers for oilfield applications. *Proc Annu Offshore Technol Conf* 2017; 1: 583–593.

100. Kwietniewski M, Miedzińska D. Review of elastomeric materials for application to composites reinforced by auxetics fabrics. *Procedia Struct Integr* 2019; 17: 154–161.

101. Mohajerani A, Burnett L, Smith J V., et al. Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. *Resour Conserv Recycl* 2020; 155: 104679.

102. Medina NF, Garcia R, Hajirasouliha I, et al. Composites with recycled rubber aggregates: Properties and opportunities in construction. *Constr Build Mater* 2018; 188: 884–897.