Review

A Review on Mechanical Properties of Natural Fibre Reinforced Polymer Composites under Various Strain Rates

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Abstract: With the lightning speed of technological evolution, the demand for high performance yet sustainable natural fibres reinforced polymer composites (NFPCs) are rising. Especially a mechanically competent NFPCs under various loading conditions are growing day by day. However, the polymers mechanical properties are strain-rate dependent due to their viscoelastic nature. Especially for natural fibre reinforced polymer composites (NFPCs) which the involvement of filler has caused rather complex failure mechanisms under different strain rates. Moreover, some uneven micro-sized natural fibres such as bagasse, coir and wood were found often resulting in micro-cracks and voids formation in composites. This paper provides an overview of recent research on the mechanical properties of NFPCs under various loading conditions-different form (tensile, compression, bending) and different strain rates. The literature on characterisation techniques toward different strain rates, composite failure behaviours and current challenges are summarised which have led to the notion of future study trend. The strength of NFPCs is generally found grow proportionally with the strain rate up to a certain degree depending on the fibre-matrix stress-transfer efficiency. The failure modes such as embrittlement and fibre-matrix debonding were often encountered at higher strain rates. The natural filler properties, amount, sizes and polymer matrix types are found to be few key factors affecting the performances of composites under various strain rates whereby optimally adjust these factors could maximise the fibre-matrix stress-transfer efficiency and led to performance increases under various loading strain rates.

Keywords: natural filler; polymer composite; various strain rates; mechanical properties

1. Introduction

High-performance requirements and environmental regulations nowadays have risen the demand of industries to utilize green composites materials. It has also become the main driving force of recent research on the development of eco-friendly yet sustainable natural fibre reinforced polymer composites (NFPCs) instead of synthetic one. It is well-known that synthetic fibres reinforced polymer already has out-standing properties and applications. For instance, glass fibre reinforced polymer known for its excellent properties was able to be utilised for sleepers of railway track [1]. Phenolic-based glass fibre polymer composites have good fire-retardant properties to meet the fire requirement of building materials [2]. However, in order to satisfy the eco-friendly aspect, reinforcement using natural fibres may be a better choice as they can be obtained from plants, animals and agriculture wastes. Over the past decade, agriculture waste fibres have been the favourite choices of researchers for its sustainable resources. Example of agriculture waste fibres is oil palm, bagasse, corn,

stalks, coir, bamboo, pineapple, banana and rice husk. These fibres are normally extracted from part of the plant such as stem, leaf, seed or even its fruit [3].

NFPCs are strain rates sensitive due to the viscoelastic nature of their matrix. In simpler terms, NFPCs' mechanical properties are highly dependent on the strain rates [4]. Strain rates mean the rate of change of strain or a measure of deformation per unit second (s^{-1}). Strain rates have a wide application in common civil structures with levels ranging from low to very high rates. For instance, low strain rates ($<0.1 \ s^{-1}$) have application in materials' creep, quasi-static deformation of structures, vehicle impacts, some parts of plane crash and earthquake or wind-induced dynamic motion of high-rise building [5–7]. While for high strain rates ($>0.1 \ s^{-1}$), there are applications such as armour penetration, crashworthiness of materials, blast, hard impacts from plane crash, missile and rockfalls [7,8]. Apart from civil structures, manufacturing processes also involved with strain rates. For instance, material forming, high-speed machining, potential application of superplastic forming and diffusion bonding and automatic control manufacturing system [8,9].

Like any other viscoelastic materials, NFPCs properties such as the stress–strain behaviour, failure mechanism and failure probability are distinctive under different ranges of strain rates. According to the first law of thermodynamics, force or energy applied on viscoelastic material cannot be destroyed but conserved into two different forms, i.e., elastic and viscous parts. Part of applied energy will be stored into materials as internal energy and the other part will be dissipated as heat. While the viscoelastic material will have viscosity change with strain rate, it will cause a different amount of viscous drag and frictional energy loss within the materials [10]. Consequently, it causes the mechanical properties NFPCs to be rather complex under various strain rates and required further studies.

Based on the literature, there are two simple rheological models, e.g., Maxwell models and Kelvin Voigt models that commonly used to describe viscoelastic behaviour. Both models used spring and dashpot to represent the elastic and viscous component respectively. Their arrangements are shown in Figure 1. Maxwell model is commonly used for modelling stress relaxation where strain as a controlled variable to observe stress response. However, the Maxwell model is weak in describing creep behaviour where stress as a controlled variable for the strain response in which the Kelvin–Voigt model is more suitable [11].
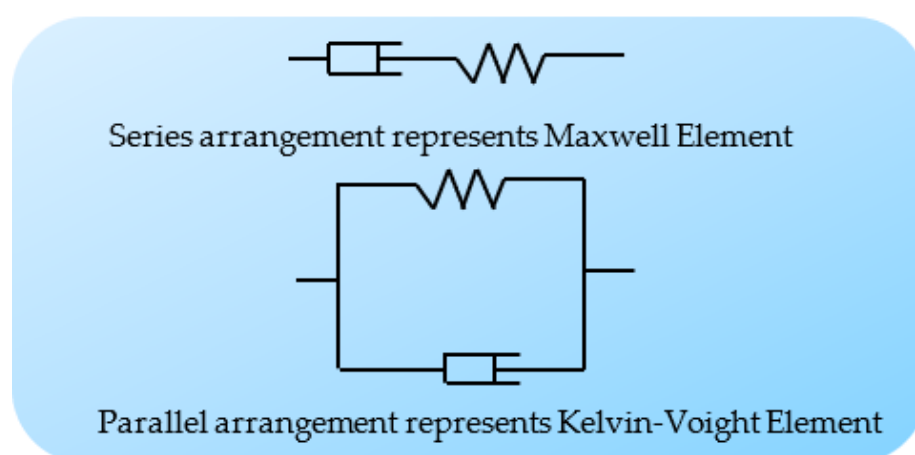

Figure 1. Simple rheological models of viscoelastic behaviour.

Most of the studies towards the effects of strain rates in the past have been focused on synthetic fibre polymer composites [12]. While the behaviour of NFPCs under various strain rates has only been investigated recently. For instance, Kumar and Bhowmik [13] studied coir particle interaction in epoxy composites under low tensile strain rates of 1 to 3 mm/min. The crack initiation and propagation in the tensile test were found extremely affected by the strain rate variation. Silva et al. [14] found the cork powder reinforced epoxy bending stress and strain are also sensitive under a wide range of strain rates. Furthermore, Xiang et al. [15] found the hemp fibre reinforced epoxy is compressive strain rates sensitive.

The peak stress and energy absorption under high compressive strain rate were different from those of quasistatic test. Although it is quite a recent area of research, there are already numerous works of literature established on the strain rate sensitivity of NFPCs, their limitations and factors affecting it, but limited relevant review articles are available. Some significant insight has been achieved in this field. For instance, many studies often found embrittlement and fillers debonding as the primary issues in most of the NFPCs under higher strain rates loading. Nonetheless, there are still many other critical issues that need to be addressed to produce a mechanically competent NFPCs under diverse loading conditions in order for them to be utilized in high performance industries such as automotive and aerospace. Hence, this article aims to provide a summary for current studies of NFPCs under various strain rates conditions, the challenges remain and also discuss the possible future research directions.

2. Strain Rates Characterisation

Conventional research toward NFPCs mechanical properties was conducted under constant quasistatic condition. However, researchers over the past decade have started to focus on strain rates effect toward NFPCs. Table 1 shows a wide strain rates regime that has been studied and their respective experimental techniques. It can be any form of strain rates including tension, compression, bending and impact depend on the equipment listed.

Table 1. Summary of strain rate corresponding experimental technique.

Strain Rate Regime	Experimental Technique
Low rate $\dot{\varepsilon} < 0.1s^{-1}$	Conventional mechanical universal tester Electronic universal testing machine
Medium rate $0.1s^{-1} \leq \dot{\varepsilon} \leq 200s^{-1}$	Mechanical tester with ultra-capacity Split Hopkinson pressure bar (SHPB) Drop weight Servo-hydraulic testing machine
High rate $200s^{-1} \leq \dot{\varepsilon} \leq 10^5s^{-1}$	Split Hopkinson pressure bar (SHPB) Taylor rod impact
Very high rate $\dot{\varepsilon} > 10^5s^{-1}$	Flyer plate impact

Conventional mechanical tester for example for screw-type universal testing machines are routinely used to characterise the stress–strain behaviour of materials under strain rate of 0.1 s^{-1} and below. A specifically designed high-capacity servo-hydraulic driven, high-speed control and data-acquisition instrument can achieve higher strain rates under compression testing due to ease of positioning. However, such specialised equipment is extremely expensive and required caution on ensuring the accuracy of measured parameters are not affected by the dynamics of the structure itself under higher strain rate test [16].

As for higher strain rate setup, i.e., 200 s^{-1} and above, Hopkinson pressure bar is a common choice among the researchers. However, there are still reported gaps for fibre material testing at high strain rates which is difficult to close using existing measurement setups including high-capacity servo-hydraulic driven testing machines and Hopkinson pressure bar. A novel test method by using a rotary drive machine also face challenges in coupling force, reliable clamping specimen and high-speed data acquisition issues above the strain rate of 267 s^{-1} [17]. While for the flyer plate impact technique, commonly a gas gun plate impact is used in shock dynamic laboratory. Although it is capable of precisely controlled impacts with velocity up to 1.5 mm/μs, it is mainly used for impact test and much higher cost equipment [18].

3. NFPCs under Different Forms of Strain Rates

NFPCs mechanical properties highly depend on strain rate due to their viscoelastic and viscoplastic behaviour [19]. Pure viscoelastic behaviour usually occurs within a small amount of strain. While the viscoplastic inelastic strain only accumulates when it reaches a certain amount depending on the material [20]. A study also proved these viscous behaviours such as energy losses or hysteresis cycle occur under cyclic load above certain stress level on polymer composites [21]. This phenomenon occurs due to the time-dependent behaviours, such as the stress relaxation and creep phenomena [22]. NFPCs under a different type of strain rates could also exhibit diverse mechanical properties and failure mechanism. Tensile, compressive and flexural strain rates behaviour have been commonly investigated based on the current literature.

3.1. Tensile Strain Rate

Tensile strain rate is one of the strain rates types that have been studied by numerous researchers in recent decades toward NFPCs. For instance, a recent study on pure HDPE (High-Density Polyethylene) and hemp-HDPE composites found that the young modulus and tensile strength increase as the strain rate increase due to strain hardening effect [23]. This result indicated that short hemp fibre reinforced composite mechanical behaviours was dominated by the matrix. The normalised tensile stress–strain behaviours of polymer under extreme cases based on studies are represented in Figure 2. Increase the strain rate experience by the polymer could lead to increasing strength but brittle behaviour due to shorter stress relaxation time [11]. However, the amount of stress and strain increase or decrease are very dependent on the reinforcement. Another study found that the flax fibre reinforced epoxy shows a significant increment of tensile strength under high strain rate loading although it did not show much variation at low strain rate [24]. In addition, different types of natural fibres reinforcement, i.e., banana, bamboo and flax fibre reinforced composites were found having different amounts of tensile strength increment as the strain rate increases. Flax/polyester composites were found to exhibit the highest tensile strength compared to banana/polyester composites and bamboo/polyester composites. It could be due to the highest tensile strength of flax fibre than the banana and bamboo fibre [25]. Which indicates the composite strain rate sensitivity is reliant on the type and form of natural fibre reinforcement.
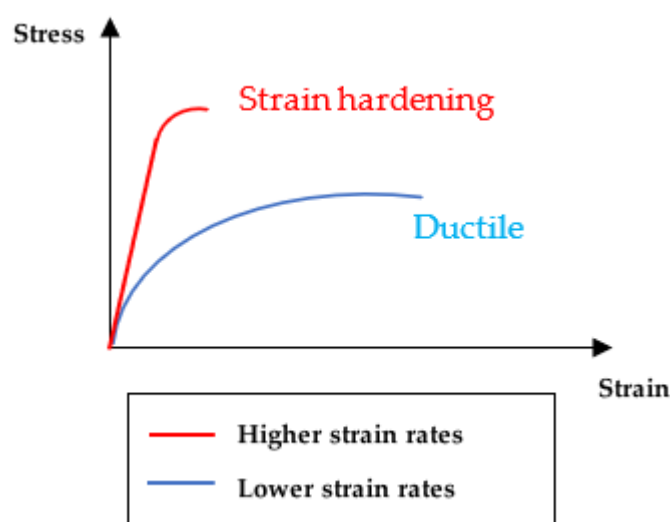

Figure 2. Normalised tensile stress–strain responses as the strain rate increased.

Furthermore, recent studies have found micron/whisker form of fibres can cause the composite to become more crack sensitive and exhibit unpredictable brittle fracture behaviour under varying tensile strain rate. For instance, some micron-sized agriculture

waste fibre like wood and coir are sensitive even under low and small strain rate variations. The crack initiation rate and propagation are highly affected by strain rate variation. The uneven particle sizes can result in micro-cracks and act as localized stress generators, initiating structural heterogeneities and the resulting failure of material [13,26]. The tensile strengths of coir filler composites, in general, were decreasing as the crosshead speed increases (strain rate increases) and crack blunting, crack pining, crack front-twisting contributed as fracture mechanism with micro-sized particle reinforcement [27].

Figure 3 shows the crack propagation behaviour due to the presence of unevenly sized filler which could cause the tensile properties unpredictable under various strain rates. Another study on bamboo–polyester composites has also found that the tensile strengths were fluctuating under various low strain rates [26], where the composite strength gradually increased with increase in strain rate from 0.1 mm/min to 0.5 mm/min and then gradually decreased from 0.5 mm/min to 1 mm/min. After that the strength increased significantly up to 20 mm/min [28].
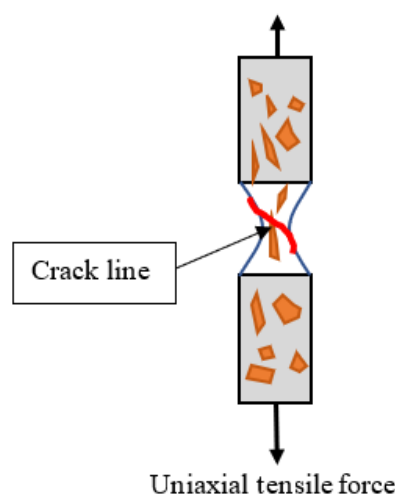

Figure 3. Crack propagation of micron coir filler composite.

There is also research conducted under high strain rates. For instance, flax fibre reinforced composite with similar behaviour as carbon fibre composite shows a significant change of properties under higher strain rates. The strain rate sensitivity of fibre could also be one of the factors affecting the sensitivity of overall NFPCs. The energy absorption (area under stress–strain curves) of the flax fibre composites significantly increases after 79.12 s^{-1} of strain rate [24]. Furthermore, only a single critical fracture perpendicular to the loading direction occurred when the strain rates were less than 79.12 s^{-1} and multiple cross-sectional fractures were formed after 79.12 s^{-1}, which consumed a huge amount of energy (Figure 4).
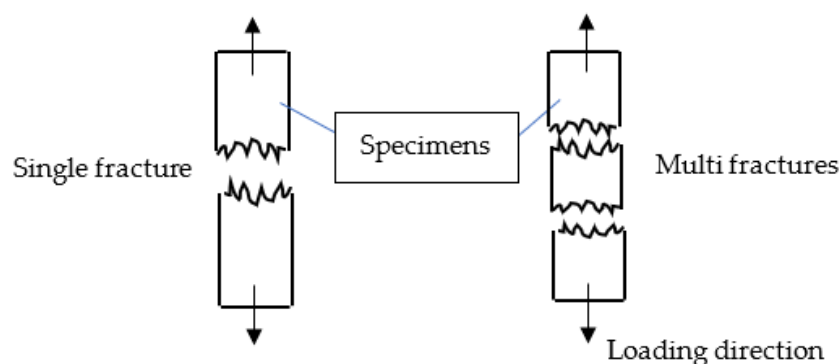

Figure 4. Single and multi-cross-sectional fractures.

Furthermore, a study found that smaller natural filler sizes (e.g., smaller bagasse particles reinforcement) may further enhance the composite's tensile performance under various low strain rates. The composite's overall strength and toughness are enhanced as the filler size go down. It could delay the filler-matrix debonding process through better filler dispersion and interface stress transfer [29]. Thus, the limitations of micron-sized natural fillers composites under varying strain rates could be addressed by reducing the sizes of fillers to nano-sizes or including other synthetic nanofillers as hybrid composites.

The study also conducted on fibre-matrix interface adhesion of plantain fibres polymer composite and its strain rate sensitivity through the interfacial energetics aspect. For instance, a study found that treating plantain fibres with different chemicals can affect the filler-matrix interface bonding [30]. Consequently, it may further influence the strain rate sensitivity index of the composite depending on the pull-out forces required.

3.2. Compressive Strain Rate

Recently a few researchers have investigated the behaviour of NFPCs under a different form of strain rates apart from tensile. As for compressive strain rate characterisation, it is similar to other forms of strain rates. The quasi-static and low strain rates are tested under universal mechanical tester while for high strain rates, split-Hopkinson pressure bar is commonly used [15,31,32].

According to study, the compressive properties of the composite depend on the types of filler reinforcement and matrix used [32]. From the study, hemp-vinyl ester composite was found less strain-rate dependent compared to glass-vinyl ester composite at strain rates higher than 1400 s^{-1} due to the hemp fibre only dissipate more energy at lower strain rates and the hybrid reinforcement using hemp and glass could result in behaviour intermediate between glass and hemp cases [32]. In addition, the addition of wheat straw fibres to different types of polypropylene (i.e., homopolymer and copolymer) has a different response at high strain rates. The polypropylene copolymer composite was found to exhibit better energy absorption properties at high strain rates compared to homopolymer composite [32].

Another studied on compressive strain rate sensitivity of hemp fibre reinforced epoxy composites found the stress–strain behaviour of hemp fibre-epoxy composite was quite different between quasi-static and high compression strain rate [15]. It can be described using normalised ductile and brittle stress–strain response curves (Figure 5). Under quasi-static compression, the composite shows different deformation stages similar to ductile deformation. The hemp fibre-epoxy composite shows initial elastic deformation and the crack initiated (Figure 5a (i)). Followed by Figure 5a (ii), a yield point where the crack continues grew with the fibres began to be pulled out from the matrix. In Figure 5a (iii), the composite finally experienced significant stress increase (plastic stage) and reached the fracture point. While under 2375 s^{-1} compression rate, the composite has an ultimate stress point and then experienced brittle failure represented by the steep decreasing stress after ultimate stress [15].

Additionally, woven based NFPCs such as woven flax-epoxy composites, their final deformations are found to be different under various compressive strain rates. Based on the study from Hu et al. [33], the woven-flax epoxy composites have broken into small pieces under the highest compressive strain rates (2800 s^{-1}) due to flax weave rupture. The energy absorption of woven flax-epoxy was found increased as strain rate increases at the same level of strain. It was deduced that apart from viscoelastic nature of flax fibre and epoxy itself, this phenomenon may also occur due to the crack formation and crack growth, which consumed more energy at higher strain rates.
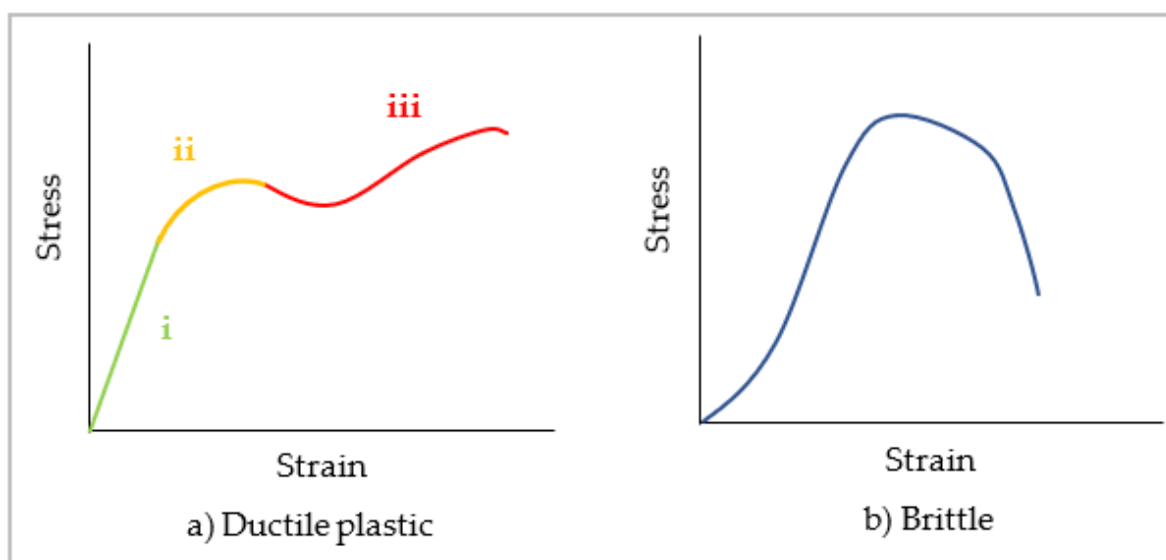
Figure 5. Normalised compressive stress–strain responses (**a**) Ductile, (**b**) Brittle.

As the viscoelastic polymer composite's behaviour keeps changing under different strain rates, it is important to develop a constitutive model for the properties prediction. Hu et al. [31] have studied the use of simplified Johnson–Cook model to describe the compressive strain rate dependent on flax fibre reinforced composites. The simplified Johnson-Cook is commonly used to describe the coupling factors among stress, strain and strain rate. The dynamic behaviour of flax fibre composites was expressed using simplified Johnson-Cook as

$$\sigma = (A + B\varepsilon^n)\left(1 + Cln\dot{\varepsilon}^*\right) \tag{1}$$

where σ represent the stress; A is the yield stress; B and n are the effect of strain hardening; C is material constant depending on specific material representing its strain rate dependency; ε is the equivalent plastic strain; $\dot{\varepsilon}$ represent strain rates and $\dot{\varepsilon}^*$ is the dimensionless plastic strain rate expressed as $\frac{\dot{\varepsilon}}{\varepsilon_0}$ with $\dot{\varepsilon}_0 = 0.006s^{-1}$ based on quasi-static experiments. The Equation (1) was found good fit with the flax fibre composites stress–strain experimental data under various strain rates [31].

The simplified Johnson–Cook model verified to be accurate with a slight difference between experiment and FEA numerical simulation. Nevertheless, the challenges still exist as simplified Johnson–Cook model without damage initiation and evolution could not precisely predict the failure under complex stress state [31].

Another research further analysed the failure of kenaf reinforced polymer at very high compressive strain rates using the finite element model. The study validated that the composite failed at more shattered fragment at higher compressive strain rates. Interestingly, it shows that the damage begins at the tip of fibres and propagate parallelly to the compression direction. Fibre tow was said to be responsible for carrying the stress and may still hold external loads even after corner area has failed Thus, it causes a non-linear behaviour in stress–strain response [34].

3.3. Flexural Strain Rate

In the case of the flexural strain rate, numerous studies have been available. Composites such as cork-powder epoxy were flexural strain rates sensitive. However, hybrid reinforcement of cork-powder epoxy composite using Kevlar and Carbon exhibited different bending strain rate sensitivity. A linear relationship observed between the logarithm of strain rate and bending properties which can be used to predict the strain rate effect. The bending strain rate sensitivity seems to be affected by the filler properties. Hence, the normalised stress–strain behaviours are similar to the cases under tensile loadings, but it

could have non-linear response before fracture at higher strain rates (Figure 6). For instance, according to Silva et al. [14], Kevlar composites with pure resin, the maximum bending stress increases from 188.1 MPa at $1.3 \times 10^{-1} \, \text{s}^{-1}$ to 243.3 MPa at $1.3 \times 10^{-1} \, \text{s}^{-1}$, represents an increment around 29.3%. The stress–strain curve exhibit two region-a quasi-linear region and followed by a nonlinear region. Further filled the resin with cork powder, the flexural strength values are 182.9 MPa and 227.2 MPa, represents an increment around 24.2%. However, the bending stiffness also increased as the strain rate increase indicating the strain hardening effect.
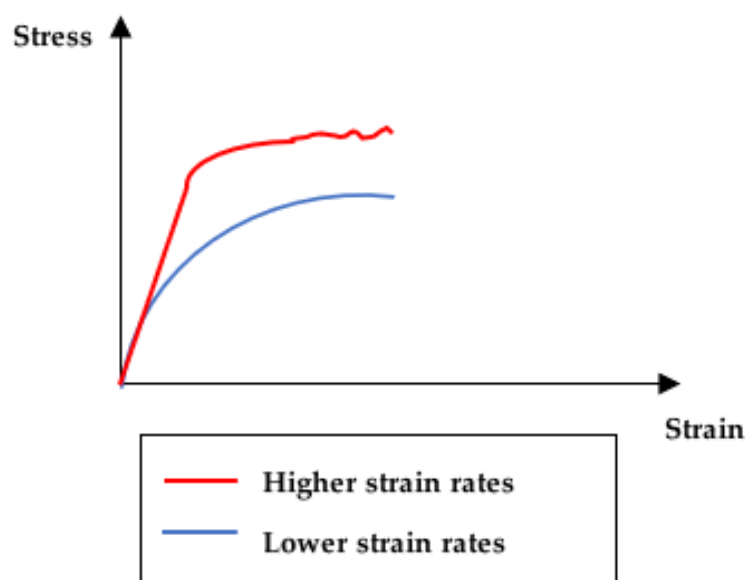

Figure 6. Normalised flexural stress–strain responses.

Furthermore, another study found that natural fibre loading content also plays an important role in the flexural performances of composites under dynamic strain rates. A research found that 3% coconut fibre reinforced composite can absorb about 83.23 J of energy under flexural high impact strain rates. However, the dynamic increase factors (*DIFs*) were solely influenced by strain rate (not by the fibre content of composites), where all 1%, 3% and 5% coconut fibre composites have a similar relationship between dynamic factors and strain rates, $DIF = 0.043 \left[log\dot{\varepsilon} \right]^2 + 0.436 log\dot{\varepsilon} + 1.0468$ [35].

Another study investigated the effect of time (low strain rate—0.0026 to 0.26 s^{-1}) towards flexural properties of wood-polypropylene composites to predict their long-term performance. It was found that the flexural strength of composites would increase linearly with strain rate. Storage modulus as a function of frequency also found to support the trend. The long-term performances of such composite were deduced to depend on their matrix and amount of wood filler incorporated. The research also showed that the relaxation time is reduced with the increase of strain rate resulting the strain of break of composite decreased [36].

Additionally, a study on jute reinforced polyester composite found that alkali-treated jute fibre could increase the loading rate sensitivity of composite under three-point bending [37]. The results show that fibre pull-out was the primary failure mechanism in alkali-treated conditions and interlaminar shear strength was increased due to the increase of composite stiffness at higher strain rates (strain hardening). The matrix has become brittle at higher strain rate as less crack-blunting was found under the microstructure using a scanning electron microscope [37].

However, most of the research towards bending is limited within low strain rates. It could be due to the lack of a standard testing method for strain rate-dependent tests. A commonly used technique for bending strain rate-dependent test is dynamic or impact 3-point bending. Such a setup is typically applied using conventional mechanical tester

which cannot handle a high strain rate. Specimen thickness and support span length are subjected to optimisation for reducing contact lost between specimen and impactor, which is challenging at higher strain rates due to induced vibration [38].

3.4. Literature Summary

The studies of NFPCs under different forms and strain rates in this review are summarised in the Table 2 below. Based on this review, the NFPCs generally exhibit brittle failure as the strain rate increases no matter the forms of deformations (tensile, compression or bending) due to the strain hardening effect. However, with suitable reinforcement the properties seem to be further improved as the embrittlement delayed to a higher strain rate. Hence, more research is required to further understand and control the reinforcement from multiple aspects for example types of fillers, filler surfaces treatments, matrix etc.

Table 2. Summary of key findings from literature regarding NFPCs.

Strain Rate Forms	Authors and Date	Composite	Key Findings
Tensile	Fotouh et al. (2014)	Hemp-HDPE	Young modulus and tensile strength of composite increase as the strain rate increase due to strain hardening effect.
	Patel and Chokshi (2017)	Bamboo-polyester	Fluctuating composites tensile strengths under varied low strain rates.
	Giuliania et al. (2018)	Flax-epoxy	Composite exhibits both viscoelastic and viscoelastic behaviours which cause its properties to be highly dependent on strain rate.
	Chokshi and Gohill (2018)	Bamboo, Banana, Flax-polyester	Composite strain rate sensitivity is reliant on the type and form of natural fibres reinforcement.
	Wang et al. (2018)	Flax-epoxy	Composite shows significant increment of strength under high strain rate loading compare to low strain rate. Fibre sensitivity affects overall sensitivity of NFPCs.
	Kumar et al. (2018)	Coir-epoxy	The rate of crack initiation and propagation are extremely affected by strain rate variation.
	Kumar et al. (2018)	Wood-epoxy	The tensile strengths of wood filler composites, in general, were decreasing as the strain rate increases. Crack blunting, crack pining, crack front-twisting as fracture mechanism with micro-sized particle reinforcement.
	Kumar and Bhowmik (2019)	Coir-epoxy	The rate of crack initiation and propagation are extremely affected by strain rate variation. Uneven particle sizes result in micro-cracks and act as localised stress generators, initiating structural heterogeneities and resulting in early failure.
	Debnath et al. (2020)	Bagasse-epoxy	The composites with smaller filler size exhibit higher tensile strength and toughness under various low strain rates.
	Sinebe et al. (2020)	Plantain-polyester	Different chemical treated fibre can influence the strain rate sensitivity of polymer composites through the interface adhesion strength.

Table 2. *Cont.*

Strain Rate Forms	Authors and Date	Composite	Key Findings
Compressive	Kim et al. (2012)	Hemp-vinyl ester, glass-vinyl ester, hemp/glass-vinyl ester, wheat straw-polypropylene (homopolymer & copolymer)	Hemp-vinyl ester was found less strain-rate dependent compared to glass-vinyl ester at strain rates higher than 1400 s^{-1}. Hybrid reinforcement using hemp and glass resulted in composite behaviour intermediate between glass and hemp cases. Polypropylene copolymer composite was found to exhibit better energy absorption properties at high strain rates compared to homopolymer.
	Hu et al. (2018)	Flax-epoxy	Significant increment in ultimate Compressive strength (61.2%) under varied strain rates. Composites broken into small pieces under highest compressive strain rates (2800 s^{-1}) due to flax weave rupture.
	Abu Seman et al. (2019)	Kenaf-polyester	Validated that the composite failed at more shattered fragment at higher compressive strain rates causing a non-linear behaviour using finite element analysis (meso-scale model).
	Hu et al. (2019)	Flax-epoxy	Use of simplified Johnson-Cook model to describe compressive strain-rate dependent of flax fibre reinforced composites.
	Xiang et al. (2020)	Hemp-epoxy	The stress–strain behaviour of the composite was found different between quasi-static and high compression strain rate.
Flexural	Wang and Chouw (2017)	Woven flax fabric-epoxy wrapped coir-concrete	3% coconut fibre reinforced composite can absorb about 83.23 J of energy under flexural high impact strain rates.
	Silva et al. (2019)	Kevlar/cork powder-epoxy & Carbon/cork powder-epoxy hybrid composites	Hybrid reinforcement of cork-powder epoxy composite using Kevlar and Carbon can cause the different bending strain rate sensitivity depending on the filler properties.
	Wang et al. (2019)	Wood-polypropylene	Flexural strength of composite increased linearly as the strain rate increase. The strain at break of composite decreased as the strain rate increased due to shortened stress relaxation time.
	Kumar et al. (2020)	Jute-polyester	Alkali-treated jute fibre could increase the loading rate sensitivity of composite under three-point bending.

4. Future Research Direction

In strain rates characterisations, challenges remain in acquiring consistent and accurate data. Particularly at high strain rates, the dynamic nature and vibration of data-acquisition equipment often interrupt the result obtained. Higher strain rates characterisation would require more expensive and sophisticated machines, while a mechanical tester is only capable of collecting data within a limited strain rate range. Based on the literature, the reliability of specimen clamping forces, high-speed data capture and specimen positioning are still challenging at higher strain rate testing. Thus, more research scope is available towards developing high standard strain rate-dependent material testing methodology.

Numerous studies are available on NFPCs under different forms of strain rates in the literature. Nonetheless, most of the research work had focused on tensile strain behaviour. As such, more investigation is needed towards compressive and flexural properties. In

the case of NFPCs under compressive strain rate, most of the studies has focused on either very low or high strain rates. Intermediate strain rate range has been ignored, which bring discontinuity of information. Similar research gaps also exist in flexural properties where most of the studies focused only on low strain rates due to the limitation of techniques or equipment available for wide bending strain rate test. Additionally, research regarding further enhancement of NFPCs under different strain rates was always in trend. Particularly for micron-sized natural filler reinforced composites, some limitations reported in the literature. For instance, further enhancement using nano-filler, hybrid reinforcement and chemical surface treatment.

Last but not least, a few works on compressive strain rates studies in literature incorporated finite element analysis. Nevertheless, investigations on tensile and flexural strain rates employing numerical modelling for further insight in stress distribution and failure prediction of NFPCs are scarce in the literature.

5. Conclusions

Based on the literature, a broad range of research have been conducted towards mechanical properties (e.g., tensile, compressive, flexural) NFPCs under various strain rates. This review has encapsulated the findings on the techniques or methods used for strain rates characterisation and challenges remain in mechanical properties characterisation across a wide range of strain rates. The review has also highlighted important findings on the failure behaviour of NFPCs under various strain rates. Finally, the possible future research trends are revealed. The strength of NFPCs is generally found proportional to the strain rate up to a certain degree. Nevertheless, fibre-matrix debonding occurs after reaching interface adhesion limit at a high strain rate. Moreover, the composite experiences brittle fracture due to shortening the relaxation time causing the decrease of strain at break at a high strain rate. These embrittlement and fibre-matrix debonding are the main reasons that hinder composite's high performances as the strain rate increases. The mechanical properties, amount and sizes of natural filler as well as polymer matrix types are found to be key factors affecting the performances of the composite under various strain rates. Optimizing these factors could delay the embrittlement at a higher strain rate and provide better interface bonding between fibre-matrix. The polymeric composite was viscoelastic in nature and the real application such as automotive, aerospace and any machines were not operated in constant quasistatic conditions. Hence, this review would benefits researchers to further understand the NFPCs mechanical behaviours by simulating real application that involve varying strain rates. However, future studies are still required, especially to develop more strain rate-dependent testing methodology; further enhancement using nano-filler and hybrid reinforcement; employment of a various numerical methods for visualisation of stress distribution and failure prediction of NFPCs under different strain rates.

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