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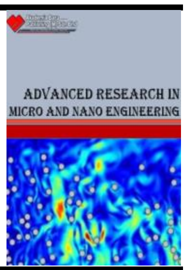

Fracture Mechanism of The Nanocomposite and Optimized Injection Moulding Processing Condition

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ABSTRACT

The importance of innovative technology aimed at conserving natural resources and protecting the environment in the construction sector cannot be overstated. The current trend in recent research efforts at the academic and industrial levels taking place all over the world is the development of novel substitute materials to existing conventional metals, alloys, concrete, and synthetic materials. Industries are focusing more on minimizing atmospheric pollution to earn carbon credits. Utilizing natural resources to create composite materials that are totally or partially biodegradable is a tiny step toward protecting the environment. Engineering and environmental considerations are involved in the usage of natural fibre in polymer natural fibre nanocomposites for pavement application. The problem with using concrete or cement is each ton of cement produced to make a pavement block emits one ton of carbon dioxide CO_2, which has a negative impact on the environment. The development of multifunctional materials and structures for cutting-edge applications has new paths thanks to the usage of these fibres/fillers as reinforcement in a variety of polymeric materials. This article intends to cover the implication of polymer natural fibre nanocomposites to pavement applications and review the fracture mechanism of the nanocomposite and optimized injection moulding processing condition.

1. Introduction

Injection moulding is one of the methods that are highly regarded in the industry. This is because the method can go through bulk production, time savings as well as cost effective compared to other methods such as 3D-printing and thermoforming. The optimization injection moulding processing condition helps to increase the efficiency in terms of quality and reduce the time for production. This review paper also chooses the fracture mechanism and fracture toughness as quantitative measures of the ability of the polymer natural fibre nanocomposites to resist crack extension and estimate material toughness.

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Natural fibre reinforced polymer composites are advantageous due to their outstanding strength, light weight, and environmental friendliness [2]. According to mechanical tests, natural fibre hybridization can produce composites with improved tensile qualities. Using an injection moulding process, polyethylene terephthalate (PET) composites reinforced with areca sheath and Maringa fruit fibre were created [3].

A paving block is one of the most popular flexible surface treatment choices for outside pavement applications such as parking areas, patios, sidewalks, bus stop stations, highway toll stations and recreation areas. Most of the pavement blocks that are used nowadays are made from cement and concrete. Paving blocks were designed to withstand heavy traffic loads like rigid pavement, and they can be easily readjusted if a change in the layout of the pavement is required. The mining of raw materials for the manufacture of cement as well as transportation of cement to the concrete plant have had several negative effects on the sustainable environment. Creating up to 5% of all CO_2 emissions produced by humans worldwide, the cement industry is one of the two biggest producers of gas, with 50% of its production coming from chemical processes and 40% from burning fuel [1]. The reason why carbon emission is so high to produce cement is because cement must be heated to very high temperatures to form clinkers. Massive amounts of CO_2 are released into the atmosphere during the calcination of limestone ($CaCO_3$) to produce cement.

The use of paver block blocks produced from plastic is becoming more popular, finding applications in parking areas, compounds, open spaces, streets, sidewalks and minor roads. Previous research stated that paver blocks produced from plastic have high tensile strength, better water absorption, more resistance to corrosion and good heat absorber compared to blocks produced by cement or concrete. Besides, the idea to add natural fibre in the plastic pavement block may help to increase the quality, morphology, mechanical and physical properties of the blocks through an optimized injection moulding process. The advantages of using a natural fibre as a reinforcement are many such as their benefits of biodegradable properties which ease the disposable problem, low cost, lightweight structure and abundant availability. Table 1 shows the list of natural fibres and their production in the world.

Table 1
List of natural fibres and their production in the world [4]

Fibre source	World production (10^3 tons)
Abaca	70
Ramie	100
Kenaf	970
Sugar cane bagasse	75,000
Grass	700
Flax	830
Hemp	214
Sisal	375
Coir	100
Jute	23000
Bamboo	30,000

2. Natural Fibre as Reinforcement

Natural fibre is categorized into animal fibres and plant cellulose fibres. There are six major types of fibres namely, seed fibres, leaf fibres, fruit fibres, stalk fibres, bast fibres and straw fibres. Typically, plant fibres can be used to make materials that are considerably stiffer and stronger mechanically, but first, they must be mechanically and chemically treated. The type of fibre used as reinforcement in composites generally relies on the intended function for the material. However, natural fibres have their own drawbacks in terms of characteristics and are not without issues. The hydrophilic qualities of natural fibres allow for moisture absorption from the environment, which results in brittle bonds between the fibre and polymer. Because both the chemical structure of the fibres and the matrix are diverse, couplings between natural fibre and polymer are also thought to be difficult.

Kabir and his co-researchers reviewed the chemical processes used to treat natural fibres, and they came to the conclusion that treatment is a crucial consideration when dealing with natural fibres [5]. They discovered that fibres lose hydroxyl groups when they are exposed to certain substances. In addition to increasing the mechanical strength and dimensional stability of natural fibre reinforced polymer composites, this decreases the water repellence of the fibres. They concluded that chemically modifying natural fibres significantly improves NFPCs in general.

A twin-screw extruder was used in a study employing pineapple leaf fibre (PALF) [6] to create green composites. A 40% fibre content significantly improved the tensile properties of composites made of poly lactic acid (PLA) and pineapple leaf fibre. Hemp fibre was used in a study by Hallad *et al.,* [7] that demonstrated better usage of natural fibre in polymer composites. In comparison to a pure epoxy sample, the sample after receiving a 5% NaOH treatment increases in strength by 34 times and load carrying capability by 9 times. Based on their experimental findings, a recent study about the use of 15 % wt. banana fibre as a reinforced composite demonstrates that it has the best mechanical qualities. Numerous research have characterised the mechanical properties of banana fibre, and they have revealed that alkali treatment boosts tensile and flexural strength [8,9].

Most of the pavement applications such as pavement block and pavement tiles are mostly made of concrete and cement. But in the past few years, the use of plastic waste as an alternative to make pavement blocks/tiles become a trend for manufacturers to provide an effective recycling solution for plastic waste problems. The use of paver block blocks produced from plastic is becoming more popular, finding applications in parking areas, compounds, open spaces, streets, sidewalks and minor roads. Previous research stated that paver blocks produced from plastic have high tensile strength, better water absorption, more resistance to corrosion and good heat absorber compared to blocks produced by cement or concrete. This article proposed to include natural fibre in the plastic waste in the production of pavement blocks/tiles. The presence of natural fibre will help to increase the quality, morphology, and mechanical properties of the product. Other than that, the advantage of biodegradable natural fibre will help make the product safe for the environment. The advantages and disadvantages of natural fibre composites are given in Table 2.

Table 2
Advantages and disadvantages of natural fibre composites [10]

Advantages	Disadvantages
light weight	Higher moisture absorption
Cheap	Poor mechanical properties (especially impact strength)
Renewable source	Poor fire resistance
Higher flexibility	Lower durability
Good thermal and sound insulation	Poor microbial resistance
Biodegradable	Variation in quality
No residues when incinerated	Restricted maximum processing temperature
No skin irritation	
Eco-friendly	

3. Composition of Polymer Natural Fibre Nanocomposites

Natural fibres' biochemical makeup can differ between different plant tissues, between different plants, and depending on the soil, climate, extraction method, and plant cell maturity. Carbohydrates, or sugar-based biopolymers like cellulose, hemicellulose, and pectin, are the main chemical constituents of dry matter. Every single type of fibre contains different values of compositions and mechanical properties to the other fibres. In addition to the complex polymer of aromatic alcohol known as lignin, these biopolymers also include extractive proteins (e.g., fatty acids, fatty alcohols, free sterols, ferulic acid esters, waxes, and ashes). Table 3 shows the composition of natural fibres based on the type of fibres.

Table 3
Composition of the natural fibre [11]

Fibres	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)	Moisture content /extractive (%)	Ash (%)
Cotton	89	4	0.75	6	0.6	-	-
Jute	45-71.5	13.6 - 21	12 - 26	0.2	-	12	0.5 - 2.0
Hemp	57-77	14 - 22.4	3.7 - 13	0.9	-	9	0.8
Flax	71	18.6 - 20.6	2.2	2.3	1.7	8 - 12	5 - 10
Coir	32-43	0.15 - 0.25	40 - 45	3 - 4	-	8	
Sisal	47-77	10 - 24	7 - 11	10	-	11	0.6 - 1.0
Kenaf	53.5	21	17	2	-	-	2 - 5
Sugarcane bagasse	32-34	19 - 24	25 - 32	-	-	6 - 12	2 - 6
Bamboo	73.83	12.49	10.15	0.37	-	3.16 - 8.9	-
Ramie	68.6-91	5 - 16.7	0.6 - 0.7	1.9	-	-	-

The composition of polymer natural fibre nanocomposites contains other materials used to make the polymer composites that consist of natural fibre, plastic (polypropylene, polyethylene, etc.), compatibilizer (coupling agent), and nano clay [12]. Utilizing natural fibres in composites has some drawbacks, including moisture absorption, rapid deterioration, and weak resistance to high temperatures [13]. Besides, the hydrophilic nature of natural fibres causes swelling and the formation of voids at the interface between the matrix and fibre, resulting in poor mechanical properties of composites containing natural fibres. These natural fibres are wettable but incompatible with some polymeric matrices and absorb a lot of moisture. Mechanical properties of composite materials made from unmodified plant fibres are frequently poor [14].

To solve this problem certain ways are being proposed to use such as a surface treatment or compatibilizing agents are needed to mix in the composite fabrication. When used as a polymeric surfactant, the compatibilizing agent lowers surface tension and promotes interfacial adhesion between the dispersion and matrix polymer phases of a polyblend or alloy, or between the layers of a laminate created by extrusion or coextrusion. As a compatibilizing agent to increase clay dispersibility, polypropylene Maleic anhydride grafted (PPgMA) was utilised. The addition of PPgMA enhances dispersion, but only at concentrations greater than 10 wt.% [15]. As observed by Li *et al.,* [10] was stated, when bamboo fibre and PPgMA were combined, the compatibilizer's effect on the mechanical properties of propylene/bamboo fibre composites resulted in an improvement in tensile strength.

By combining nanoclay with epoxy resin composites, numerous studies discovered that it was possible to significantly strengthen and change the mechanical properties of natural fibre reinforced polymer [16]. Numerous studies have investigated how nanoclay filler affects the mechanical properties of fibre reinforced polymer. Less than 10% by weight of nanoclay was added to epoxy to boost the material's tensile strength and tensile modulus [17]. Drilling composites made of carbon fibre reinforced polymer (CFRP) were the subject of a study by Geier *et al.,* [18] to promote sustainability. In virgin and recycled CFRP, drilling-induced micro- and macro-sized geometrical flaws were analysed and contrasted. According to the results of the analysis of variance, recycled chopped and nonwoven matting reinforced CFRP exhibits less pronounced drilling-induced burr formation than virgin CFRP. Both in recycled and virgin milled CFRP, geometrical flaws of both micro- and macro-scale were insignificant. Regarding drilling-induced burrs and microstructure degradation, this study found no pertinent argument against employing recycled CFRP.

The research has established that nanoclay helps in enhancing the mechanical properties of polymer-based nanocomposites as compared to pure polymer or conventional composites [19]. The addition of nanoclay into polypropylene enhances morphological, thermal, rheological and mechanical properties [20]. This paper discussed the fracture mechanism to the pavement application from the latest research to the different types of material used.

Based on previous research, the effect of three different concentrations of nanoclay on the morphological, thermal rheological and mechanical properties was investigated. According to the Differential Scanning Calorimetry (DSC) results, the degree of crystallinity of polypropylene-nanoclay composites increased in the presence of nanoclay in the polypropylene when the concentration reached the maximum weightage value of 5% [20]. One of the best compositions to make a natural fibre polymer nanocomposite is by adding the polymer plastic (e.g., polypropylene), compatibilizer (PPgMA), nanoclay and natural fibre itself. Figure 1 shows the SEM micrographs of the fractured surface of the tensile test of the samples 30 wt. % bamboo fibre composite without PPgMA. The gap between fibres and polypropylene looks quite clear the presence of gap.

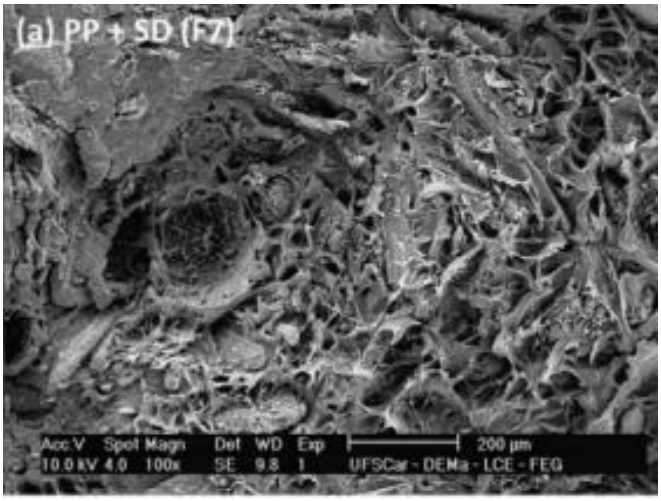

Fig. 1. SEM images of the shattered surfaces of the polypropylene/30% sawdust composite samples' tensile testing without a compatibilizer [21]

Figure 2 shows the tensile fracture surface of 30% wt.% BF composite with 4 wt.% PPgMA. The presence of PPgMA as a compatibilizing agent showed there are reduction in the gaps between the fibres and polymer matrix.

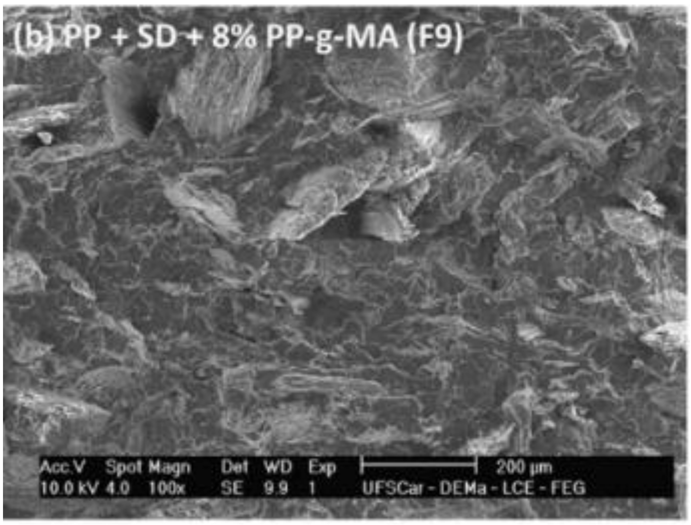

Fig. 2. SEM Micrograph of the fractured surface during stress testing of polypropylene/30 percent sawdust composite samples with compatibilizer [21]

4. Selection of Natural Fibre for Pavement Application

Global innovations in alternative materials shed light on the viability of exploiting natural resources, such as plant fibres, to reinforce the underlying matrix materials. Numerous cellulosic fibres, including flax, sisal, jute, and bamboo, have high specific strength and low density. Due to the biodegradability of all natural fibres, safe disposal of materials at the end of their useful life is guaranteed. So, there are a lot of types of natural fibre that can be proposed for use in the polymer natural fibre nanocomposite for the purpose of pavement application such as bamboo, hemp, jute and more. The selection of natural fibre to use for pavement applications can be selected based on the mechanical properties of the specific fibre. Other than that, previous research studies that perform a series of tests such as tensile, impact or fracture tests from the sample that is reinforced by natural fibre also can be collected. Table 4 shows the mechanical properties of fibre that highly used in the manufacturing industries.

Table 4
Mechanical properties for selected natural fibre [22]

Fibres	Elongation (%)	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Decomposition temperature (°C)
Cotton	3 - 10	1.5 - 1.6	5.5 - 12.6	287 - 597	232
Jute	1.5 - 1.8	1.3 - 1.46	10 - 30	393 - 800	215
Hemp	1.6	1.48	70	550 - 900	215
Flax	1.2 - 3.2	1.4 - 1.5	27.6 - 80	345 -1500	220
Coir	15 - 30	1.2	4 - 6	175 - 220	285 - 465
Sisal	2 - 14	1.33 - 1.5	9 - 38	400 - 700	205 - 220
Kenaf	1.6 - 4.3	0.6 - 1.5	11 - 60	223 - 1191	229
Sugarcane bagasse	6.3 - 7.9	1.1 - 1.6	5.1 - 6.2	170 - 350	232
Bamboo	1.9 - 3.2	1.2 - 1.5	27 - 40	500 - 575	214
Ramie	2.3 - 3.8	1.5	44 - 128	220 - 938	240

Bamboo is a standout amongst the vast majority of plants that quickly developing for great flexibility and is no doubt made under different items of wood composites. Bamboo fibre is a potential environmentally friendly fibre with great biodegradable textile material and equivalent strength to standard glass fibre. Bamboo fibre is bacteriostatic, antifungal, antibacterial, hypoallergenic, hydroscopic, naturally deodorising, and resistant to UV light. In addition, it is exceptionally durable, stable, and robust, with a high tensile strength [23].

One of the plants with the highest rates of growth, bamboo has a low density, low cost, great mechanical strength, stiffness, and the capacity to fix atmospheric carbon dioxide. With approximately 70 genera and 1200 species, bamboo is a crop that is part of the grass subfamily Bambusoideae (family Poaeae). Its yearly production is estimated to be between 15 and 20 million tonnes of material [24]. Natural fibres like bamboo and rattan are replacing glass fibres in composite materials as reinforcement because they are more affordable and appear to be more environmentally friendly [25].

Due to bamboo's strong strength and weight, it has historically been utilised to make a variety of homes and equipment. This characteristic results from the fibres' longitudinal orientation. Bamboo's microfibrillar angle ranges from 2 to 10 degrees, and it has a large amount of lignin and 60 percent cellulose. Controlled bamboo fibre extraction is required in addition to the fabrication of composites made of bamboo. Its varied structural characteristics, mechanical attributes, fibre extraction, chemical modification, and thermal characteristics have made it adaptable for usage in the composites sector. Bamboo fibres are brittle relative to other natural fibres while having finer mechanical qualities; this is because they contain more lignin than other natural fibres.

The tensile strength, flexural strength, and surface hardness of the bamboo-epoxy composites were assessed in a study of bamboo natural fibre composites [45]. On the bamboo epoxy composite, the impact of fibre loading on tensile strength, flexural strength, and surface hardness was also investigated. In this investigation, it was discovered that the bamboo-epoxy composite's maximum value for tensile strength, flexural strength, and micro surface hardness was attained at 25 percent weight of fibre loading. The selection of the bamboo fibre for the pavement application was made based on its abundant availability in the market and low cost. Other than that, the mechanical properties due to high tensile strength and flexural strength really help to counter the problem in the pavement application. Figure 3 shows the recent bamboo composite in building applications. Bamboo fibre is already used widely especially for home decoration and textile production because of the properties of bamboo fibre that are long lasting and increasing the properties of the polymer composites.

Fig. 3. Recent bamboo composite for building and pavement application

5. Selection of Natural Fibre for Pavement Application

According to a study on fracture mechanics in pavement design by Denneman *et al.,* [26], pavement materials are subjected to a high-cycle loading regime. In conventional design approaches, the Palmgren-Miner damage hypothesis was used to forecast the fatigue life of pavement materials.

The growth of a crack is dependent on energy dissipation and related to crack initiation to stress, which is incorporated in the current design methodology. Only when both the stress at which fracture begins and the usual fracture energy to increase a crack by a unit area are known, the growth of a crack can be accurately predicted. It is possible to categorise many of the bonded materials used in pavement engineering as quasi-brittle, and their fracture is significantly influenced by size effects.

The application of linear elastic, elastic plastic, and time-dependent (viscoelastic) fracture theories to asphalt binders at lower service temperatures has been investigated [27]. Only temperatures below the glass transition temperature were determined to be appropriate for linear elastic fracture mechanics (LEFM). Asphalt binders behave as time-dependent viscoelastic materials in this temperature range, necessitating the employment of time-dependent fracture mechanics models. Below the glass transition temperature, neither elastic nor elastic plastic fracture mechanics are appropriate for asphalt binders. Early fracture mechanics applications based on linear elastic fracture mechanics (LEFM) and Paris's law produced erratic forecasts of pavement performance, according to Ioannides *et al.,* [46]*,* It was discovered that fracture mechanics was a very promising technical field in which pavement operations may adopt new technologies.

5.1 Fracture Mechanism

Mechanical engineering's discipline of fracture mechanics investigates how cracks spread through materials. It largely makes use of analytical and experimental solid mechanics to ascertain the materials' fracture resistance. An important technique for enhancing the crack development performance of mechanical elements is fracture mechanics. To anticipate the macroscopic mechanical behaviour of those pieces, it applies the stress and strain behaviour of materials, notably the theories of elasticity and plasticity, to the tiny crystallographic flaws seen in real materials. The core of damage tolerance mechanical design is the prediction of crack propagation. Three main forms of deformation for a cracked component can be established based on the relative displacements of the crack faces, as shown in Figure 4 [28].

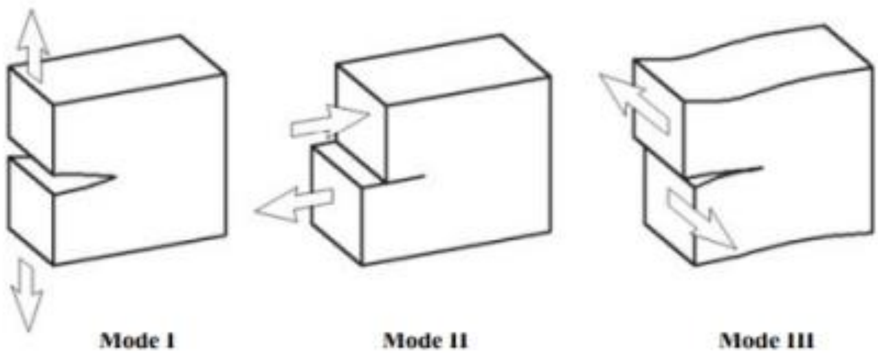

Fig. 4. Three major modes of deformation in cracked components [28]

In Mode I, also known as the opening mode, the crack faces outward without slipping. In-plane sliding, also known as Mode II, occurs when crack faces move in relation to one another in the direction perpendicular to the fracture front. Mode III, sometimes known as the "tearing mode," is characterised by the relative sliding of the crack faces along the fracture front. The fracture toughness test has 3 different modes and every mode has its own specific test through the classification of fracture toughness test methodologies based on loading. For Mode I, the methods that can be used are the double cantilever method, compact tensile shear method and single-edge notch bend test.

Mode II only has one method which is the end-notched flexure test. Lastly, in Mode III, the method used is the split cantilever beam method, edge crack torsion test and mixed mode bend test.

As shown in Figure 5, the supports used in the single-edge bend test (SENB) are like those used in flexural testing, and the specimens are tested with the beginning crack facing away from the direction of loading. The crosshead speed can be between 0.5 and 20 mm/min. The following data reduction scheme uses the fracture load P_Q, derived from testing, to calculate K_{IC} values ($MPa \cdot m^{\frac{1}{2}}$) as a measure of fracture toughness.

$$K_{IC} = \left(\frac{P_Q}{BW^{\frac{1}{2}}}\right) f(x) \tag{1}$$

where $f(x) = 6x^{\frac{1}{2}} \frac{(1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2))}{(1+2x)\left(1 - x^{\frac{3}{2}}\right)}$ (2)

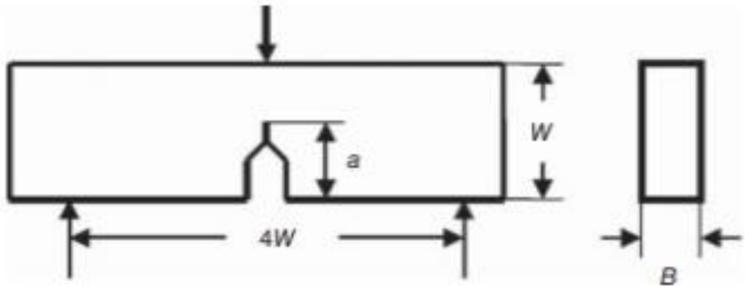

Fig. 5. Test setup of the single-edge notch bend (SENB) test [28]

According to earlier research by Hamza *et al.,* [29], three-point bending tests were performed on normalised prismatic specimens with lateral notches (SENB), and a computational formula was created to determine the concrete toughness as the foundation for the R-curve approach. The curve relating the applied load to the crack mouth opening displacement (CMOD) was used to derive the R-curve. For C0.7 concrete, the critical stress intensity factor has an average value of 1.05 $MPa \cdot m^{\frac{1}{2}}$. One of the primary materials used to create a typical pavement block for use in pavement applications all around the world is concrete.

In a study by Subramanya *et al.,* [8], a fracture toughness test (compact tension) was carried out on treated and untreated banana fibre epoxy composites. Using the fracture toughness equation K_{IC}, the critical stress factor and energy release rate of treated and untreated banana fibre composites were computed. The values obtained are 318.22 $MPa \cdot m^{\frac{1}{2}}$ and 201.70 $MPa \cdot m^{\frac{1}{2}}$, respectively.

5.2 Recent Studies on Fracture Mechanism

Inadequate interlaminar fracture toughness has been a significant problem in thermoset polymer composites reinforced with carbon fibre. Previous studies have suggested fracture toughness augmentation of polymer nanocomposites, nanoparticle (NP) toughening of epoxy resins, and multiscale modelling framework [30,31]. Results indicate that the core/shell particles, particularly when the soft polymer is the core and the rigid polymer is the shell, give the GIC (epoxy), GIC (composite), and GIIC (composite) enhancements of 851%, 185%, and 43%, respectively, over the control specimen. Particles that are homogeneous are substantially less efficient. Fracture morphology study suggests that strong, evenly distributed particle-resin and resin matrix-fibre interfaces are necessary for composites to be effectively toughened. In addition, the elastoplastic constitutive law of interphase and interfacial energy was affected by the nanoparticulate radius.

The study by Chen *et al.,* [32] and Zheng *et al.,* [33] compares the fracture toughness and fatigue threshold of polymer networks with different amounts of chain entanglement using a model material comprised of polyacrylamide hydrogels. Results reveal that an untangled polymer network has nearly the same fracture toughness and fatigue threshold. An entangled polymer network's fracture toughness can be almost ten times greater than its fatigue threshold, demonstrating a significant toughness boost brought on by chain entanglement. Utilizing crucial work of fracture test, the fracture of 3D printed Poly-ether-ether-ketone polymer (PEEK) is explored [34]. The value of fracture toughness demonstrated a significant raster orientation dependence on different 3D printed doubled edge notched tension on constant thickness. The highest value for 0° raster orientation (perpendicular to the crack plane) and the lowest value for 90° raster orientation were shown to be associated with the onset of fractures (parallel to the crack plane).

Adjusting the stress-strain system while under mechanical load allowed for the creation of wood-epoxy polymer composites (WEPC) with good mechanical properties [35]. The WEPCs had improvements in their flexural strength, modulus, compression strength, and impact strength of up to 110.3%, 86.5%, 137.3%, and 110.6%, respectively. The flexural strength of 140.5 MPa was significantly higher than rosewood's strength class TB20 (98 MPa). To examine the impact of hygrothermal circumstances on the nonlinear viscoelastic fracture behaviour of epoxy resins and their nanocomposites at finite deformation, Rash *et al.,* [36] construct a phase field formulation. When compared to neat epoxies, epoxy nanocomposite exhibits mechanical characteristics including strength and fracture toughness that are remarkable. Experiments on fracture toughness are performed at 296 K and a deformation rate of 10 mm/min.

In laboratory research, rubber modification of asphalt improves several asphalt mixture qualities [37]. For several original and modified binder systems, a fracture mechanics-based test was developed. The findings of this testing revealed that rubber-modified specimens showed increasing ductile-type failures as the rubber modification level increased, but untreated polymer and polymer-modified specimens failed in a brittle manner. High density polyethylene compact tension specimens under static loading were used to study the rate of crack propagation of environmental stress cracking [38]. When solvents cause plasticization, crack growth in surface active media is considerably accelerated. This is followed by strong blunting, which significantly slows down both break initiation and crack propagation. It is discovered that the Paris-Erdogan law applies to the fracture propagation rate for static loads as a function of the stress intensity factor in all environments.

Utilizing the vacuum assisted resin infusion procedure, biolaminates of lxtle and Henequen natural fibres reinforced by bio-based epoxy resin were created [39]. At 1, 2, and 3 weight percent, ZnO nanoparticles were introduced to the bio-based epoxy resin. At greater filler concentrations, the mechanical qualities of the lxtle biolaminates declined, but Hanequen biolaminates demonstrated superior mechanical properties just above the 2 wt.% of ZnO. The ZnO percentage caused some moderate alterations in toughness in the fracture behaviour of mode I, which led to altered behaviour in the interlaminar adherence of the layer. When compared to polymer composites, hybrid composites perform better and have better mechanical properties, however, there aren't many studies that have looked at the performance of biocomposite materials reinforced with natural fibres. The mechanical characteristics of randomly oriented Calotropis gigantea fibre (CGFs) and Palmyra fibre (PFs)-reinforced Phenol-Formaldehyde (PF) hybrid composites have been investigated in a study by Sekar *et al.,* [40]. By changing the fibre proportion, the samples have been created. The findings suggest that the mechanical properties of hybrid composites were enhanced by the addition of CGFs composites. Fibre length variation has a significant impact on mechanical qualities. With an increase in the proportion of fibre volume, the composite absorbed more water.

6. Processing Parameters of The Injection Moulding Method for Pavement Application

Plastic injection moulding is one of the most important polymer processing operations in the plastic industries nowadays because of their benefits such as efficient high production, low cost, high details, and low waste of materials. Injection moulding is one of the methods that has been widely used to produce plastic parts all over the world due to its advantages in the mass production of complicated shapes in a short period of time and plays a significant role in the field of plastic processing. The most process injection moulding parameters that analyse the mechanical properties are pressure, time, and temperature. For example, considering Table 5, extending the infusion weight, or increasing the mould temperature can result in shrinkage to illustrate the effects of handling conditions on infusion-forming objects. In the interim, reducing the weight and the temperature of the solution can also result in reduced debasement. These examples demonstrate how closely the basic trim parameters interact and how altering the preparation conditions in one area can affect the value of any attribute in another. Understanding this relationship makes it feasible to reduce the number of modifications needed when a process variable changes unexpectedly, resulting in the need to make a correction.

Table 5
Parameter change vs property effect [47]

Parameter	Properties effect
Injection pressure increased	Less shrinkage, higher gloss, less wrap, harder to eject
Injection pressure decreased	More shrinkage, less gloss, more wrap, easier to eject
Back pressure increased	Higher density, more degradation, fewer voids
Back pressure decreased	Lower density, less degradation, more voids
Melt temperature increased	Faster flow, more degradation, more brittle, flashing
Melt temperature decreased	Slower flow, less degradation, less brittle, less flashing
Mold temperature increased	Longer cycle, higher gloss, less wrap, less shrinkage
Mold temperature decreased	Faster cycle, lower gloss, greater wrap, higher shrinkage

It is no longer effective to regulate the process parameters for injection moulding through trial and error. The wrong choice of these parameters results in a reduction in the mechanical qualities of injected moulded components as well as the addition of new issues, such as increased warpage and shrinkage. These issues might be resolved by creating optimization models that relate the answers and the process parameters. The technique of modifying one parameter while maintaining the others has disadvantages as well, such as the requirement for considerable experimentation and years of experience, which raises the expense of the procedure. To get the required results, an appropriate optimization method is utilised in conjunction with the DOE employing the Taguchi approach to look for fine-tuning of parameter values. Using the Taguchi approach, it is easy and efficient to determine the best combination of designs for quality, performance, and computational cost. The Taguchi method is a useful technique for analysing variation using the signal-to-noise (S/N) ratio. The Taguchi research on the S/N ratio includes the larger-the-better, nominal-the-better, and smaller-the-better situations [47].

Based on earlier research by Othman *et al.,* [41] the best conditions for processing polypropylene-nanoclay-bamboo fibre during injection moulding were identified in order to minimise shrinkage and warpage. Bamboo fibre made up 1% of the mixture, which also included 79 % polypropylene, 15 % compatibilizer, and 5% nanoclay. The mixing was done on a Brabender plastograph machine. The

Taguchi method was used to complete the optimization procedure. The findings indicate that there is no difference in the value of warpage and shrinkage defects when bamboo fibre makes up one weight percent of the compound compared to when it does not. However, shrinkage can be greatly decreased by using the ideal settings of 170 °C melt temperature, 35% packing pressure, 30% screw speed, and 2 seconds for filling.

The drilling performance of hybrid composites reinforced with banana fibre and fly ash filler in polyester matrix was then assessed [42]. The Taguchi L27 orthogonal array was used for drilling tests. Using Taguchi and Analysis of variance (ANOVA) techniques, it was possible to determine the effects of feed rate (A), cutting speed (B), and filler content (C) on thrust force, surface roughness, and the entry and exit of delamination factors. The findings showed that minimum thrust was achieved at filler content (A) of 1%, speed (B) of 3000 r/min, and feed rate (C) of 100 mm/min, minimum surface roughness was achieved at filler content (A) of 3%, speed (B) of 2000 r/min, and feed rate (C) of 100 mm/min, and minimum peel up and push out delamination was achieved at filler content This study offers machining insights on polymer composites made from agricultural and industrial waste that are used in structural applications.

A study by Zubaidah *et al.,* [43] stated that optimization injection moulding processing conditions via Taguchi method helps to reduce the shrinkage and warpage during the production. Figures 6 and 7 show the results for warpage and shrinkage for 3 different bamboo content (0 wt.%, 3 wt.% and 6 wt.%) in graph analysis. From the observation of the results, the value of both shrinkage and warpage for 0wt% bamboo fibre are lower than 3 wt.% and 6wt.% bamboo fibre which is 0.003 mm for warpage and 0.3829 for shrinkage. The value of warpage and shrinkage for 3 and 6 wt.% in optimization results are also the same which is 0.00667 mm for warpage and 0.000383 mm for shrinkage.

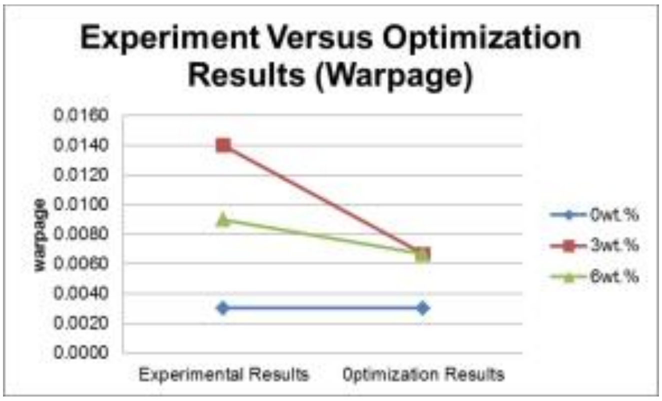

Fig. 6. Warpage test result [43]

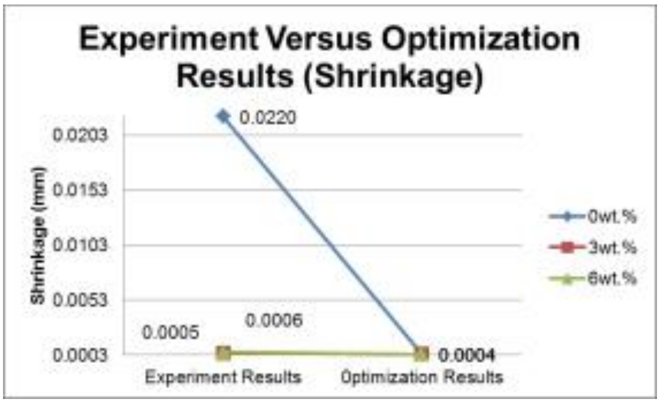

Fig. 7. Shrinkage test result [43]

A study by Rajendra *et al.,* [44] investigated the use of response surface methodology to optimise injection moulding process parameters. The response surface methodology was applied to injection moulding parameters of polybutylene terephthalate (PBT) material. The response surface methodology (RSM) that focuses on the method in central composite design (CCD) was used to investigate the parameters of injection moulding processing conditions including injection pressure, time of injection process and temperature of mould. The percentage of defective later then was discovered to decrease from 9.22% to 3.00%. Table 6 summarises several research findings regarding the injection moulding processing conditions with optimization.

Table 6
Summary of optimization injection moulding processing condition method and the findings

Author (Year)	Method of Optimization	Findings
Zubaidah *et al.,* 2018 [43]	Taguchi method, Design of experiment	Optimization of injection moulding parameters towards shrinkage and warpage used the Taguchi method including flexural modulus and strength
Othman *et al.,* 2017 [41]	Taguchi method	Optimization of injection moulding parameter towards shrinkage and warpage used the Taguchi method
Rajendra *et al.,* 2019 [44]	Response surface methodology (RSM)	Optimum processing conditions for temperature, pressure and time

7. Pavement Application

One of the most popular flexible surface treatment choices for outside pavement applications is the paver block or paving block. These blocks are attractive, comfortable to walk on, long-lasting, and simple to maintain. Concrete blocks are mass manufactured to standard sizes. One side of a normal concrete block is smooth, while the other is rough. The concrete block is designed for heavy-duty applications, with the ability to hold large weights while resisting shearing and breaking forces. Basically, there are two types of paving blocks that are widely used which are concrete and clay paving blocks. But the most common use in the industry is the concrete paving block. Because the demand for concrete is growing every day, and cement is being used to meet the demand for infrastructure development, each ton of cement produced emits one ton of carbon dioxide (CO_2), which has a negative impact on the environment.

To reduce the use and production of ordinary Portland cement (OPC) and carbon dioxide (CO_2). This research has developed pavement application using polymer natural fibre nanocomposites using the optimized injection moulding process which is environment friendly and reduces carbon dioxide emission. In comparison to traditional composites, hybrid composites have distinctive qualities that allow them to meet a variety of design requirements more effectively and affordably. These properties include advantages like high strength and stiffness, improved fatigue, and impact resistance, among others. The interest in natural fibres among academics and industry has significantly increased over the past few decades because of rising consumer demands for sustainability and environmentally friendly products. Natural fibre-based composites also have a smaller carbon footprint, use less energy, and have lower costs.

Based on the previous report, incorporating bamboo fabric could improve the tensile strength, tensile modulus, flexural strength, flexural modulus, and Charpy impact strength of polypropylene composites by 238 percent, 110 percent, 180 percent, 170 percent, and 160 percent, respectively, according to a few studies on hybrid nanocomposites. The addition of bamboo fabric to the composites enhanced the melting temperature and crystallinity somewhat. When compared to pure polypropylene, the composites' heat of fusion was found to be 40% lower. When the bamboo content of the composites was increased, the perforation impact energy, peak load, and energy absorbed all rose. The addition of fabric reinforcement in the composites also minimised crack damage. These findings suggest that bamboo cloth is a strong contender for manufacturing high-quality, low-cost light-weight composites for use as interior components in automobiles, as well as for making pavement. Figure 8 proposed the steps of making pavement from Polypropylene-nano-clay-Gigantochloa Scortechinii (PPNCGS). More research related to this application needs to be carried out, based on the summary of significant studies related to fracture mechanism, optimised injection moulding, natural fibre composites and pavement applications, as displayed in Table 7. This summary shows there are gaps that need to be filled for further research and development in this issue. The gaps can become the potential areas of new research and advancement related to polymer natural fibre nanocomposites.

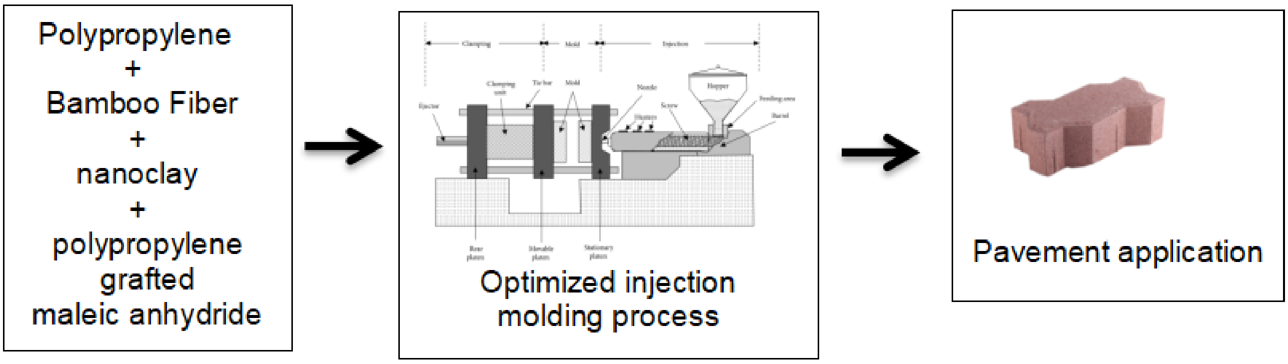

Fig. 8. The Steps of Making Pavement from Polypropylene-nano-clay-Gigantochloa Scortechinii (PPNCGS)

8. Conclusion

Details about the fracture mechanism of polymer natural fibre nanocomposites and optimized injection moulding processing conditions for pavement application have been discussed, with particular emphasis on the processing, properties, mechanism, and potential applications that can be applied. With proper preparation and the right formulation, the results of using this material will show some advantages compared to other composites such as improved mechanical properties and produced a significant increase in the thermal stability of the product. Based on the topic that was discussed above, the use of polymer natural fibre nanocomposites for pavement application may not be as strong as the standard materials used in the current day which is by using concrete, cement, and asphalt in terms of quality and properties. But for the light usage and low load impact use for pavement applications like a bicycle track, walking pavement, recreation areas, pavement tiles and parking areas are suitable for the product usage. The idea of mixing plastic waste and natural fibre to form a polymer natural fibre nanocomposite for pavement application will ultimately save the environment from pollution and conserve nature.

Table 7
Summary of significant studies related to fracture mechanism, optimised injection moulding, natural fibre composites and pavement applications

Author (year)	Fracture mechanism	Optimized injection moulding processing	Natural fibre nanocomposites	Pavement application
Ning *et al.,* 2022 [30]	X			
Wang and Shin, 2022 [31]	X			
Zubaidah *et al.,* 2018 [43]	X	X	X	
Denneman *et al.,* 2009 [26]				X
Gauthier *et al.,* 2011 [27]				X
Rajendra *et al.,* 2019 [44]		X	X	
Zheng *et al.,* 2022 [33]	X			
G. Sharma *et al.,* 2022 [34]	X			
Chen *et al.,* 2022 [32]	X			
Arash *et al.,* 2022 [36]	X			
Guo *et al.,* 2022 [35]	X		X	
Rath *et al.,* 2022 [37]	X			
Thuy *et al.,* 2022 [38]	X			
Chaurasia *et al.,* 2022 [19]			X	
Geier *et al.,* 2022 [18]			X	
Kannan and Thangaraju, 2022 [42]		X	X	
Torres *et al.,* 2022 [39]	X		X	
Sekar *et al.,* 2020 [40]			X	
Prabhudass *et al.,* 2022) [2]	X		X	

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