Effect of Yarn Structure on Mechanical Properties of Twisted Yarns and Green Composites Reinforced with Twisted Yarn

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Abstract

Natural fiber twisted yarn is often used for green composites as a reinforcement. In a twisted yarn, spun yarns migrate from surface of twisted yarn to inner along the yarn axis. This behavior is called "migration" and has been studied in textile engineering. Tensile properties of composite and yarn are usually explained as a function of twist angle. In this paper, the effect of twist structure on tensile properties of yarn and composite was investigated. The result indicates that the relationship between tensile properties and yarn structure is interpreted more reasonably by using twist contraction ratio rather than yarn twist angle.

1 Introduction

Research and development of materials using biomass resources are widely accepted as a successful process toward the sustainable society. A composite consisting of natural fibers and biodegradable resin, so-called the green composite, is one of the most promising materials in developing biomass products [1-3]. It is known that a continuous spun yarn is formed by twisting natural fibers which are limited in length. Moreover, the spun yarns are often twisted together to produce a plied yarn (also called twisted yarn). If such yarn-based reinforcement is used for green composites, then clarification of mechanical properties of twisted yarns is indispensable in order to promote the use of the composites. Yarn-reinforced composites would also need improvement of their mechanical properties and understanding of their performance for practical use, as seen in the conventional composites. In the past, the mechanics of spun yarn has been studied in textile engineering [4]. Zeidman et al. [5], Rao et al. [6], and Hearle et al. [7] proposed the migration structure model or migration theory. Most of theories are based on ideal migration structure. However, practical migration structure depends on performance of a twisting machine. Mechanical properties could not be exactly explained from ideal migration. Nakamura et al. [8] proposed an experimental equation instead of the ideal migration equation. This equation indicated the validity for agreement with the experimental results when twisted yarns were fabricated at the same condition on the twisting machine. In their paper, however, the parameter used in the experimental equation was unclear in a point how it links the yarn structure. Therefore authors have also verified the applicability of an alternative parameter, the twist contraction ratio (TCR), without considering migration structure [9].

The purpose of this study is to investigate in more detail the effect of yarn twist on tensile properties of ramie twisted yarn and ramie twisted yarn reinforced green composite using TCR. At first, elastic modulus and tensile strength of the yarns and unidirectional composites were experimentally explored. The results show that TCR can reasonably be correlated with tensile properties instead of yarn twist angle.

2 Experimental

2.1 Materials

The reinforcement used in this study is a ramie single yarn (SY, No.16, supplied by TOSCO, Co., Ltd.). Twisted yarns were produced from ramie single yarns using a twisting machine (Mini twister ATM-2W, Marui textile machinery Co., Ltd.) or by hand. These are hereinafter denoted as Type A and Type H, respectively. The numbers of twists prepared were 1.5, 3.5 and 6.5 / inch. Biodegradable thermoplastic resins, polylactic acid (PLA) emulsion type resin (PL-1000, Supplied from Miyoshi Oil and Fat Co. Ltd. Japan), cornstarch based resin film (CPR-F3A, supplied by Nihon Cornstarch Co. Japan), and poly-vinyl alcohol (PVA, supplied from Kuraray Co., Ltd. Japan) were used as matrix materials for the composites.

2.2 Fabrication methods for green composites

In the combination of PLA resin and Type A yarn, the yarns were wound around a thin metallic plate, and the PLA resin was pasted onto yarns and dried. Composite specimens were fabricated by applying a pressure of 2.34 MPa at 150^{o}C for 5 min using a compression molding equipment. After 5 min, it was cooled down to near room temperature while maintaining the same pressure. In order to make CPR composites, first, Type A yarns were wound around a thin metallic plate. Next, the yarns were sandwiched between CPR films and hot pressed using the same method as PLA composites. In the combination of PVA resin, Type H yarns were soaked into PVA liquid for 1 hour and dried at 25^{o}C for 24 hours. This composite is denoted as PVA/Type H.

2.3 Tensile test

Cross-sectional area of the yarns was calculated from fineness and density. Gauge length of the yarn tensile specimen was 200 mm. Tensile test of the yarns was carried out following JIS L 1095 (JIS: Japanese Industrial Standards) using a tensile and compressive testing machine (JT Toshi Co., 1kN load-cell capacity). The cross-head speed was 20 mm/min, and the number of samples was 10.

Tensile specimens were cut off from fabricated composites. The longitudinal length along the yarn axis was 100 mm, and their width and thickness were 15 mm and 1 mm, respectively. The gauge length was 50 mm. GFRP tabs were attached with epoxy adhesive on both ends of the composite specimens. A strain gauge was attached at the center of the specimen surface to measure uniaxial strain along the longitudinal direction. Tensile tests of specimens were performed using an Instron-type testing machine (Autograph IS-5000, Shimadzu Co. Ltd., Japan) at room temperature. The tensile speed was 0.5 mm/min to give a strain rate of 0.01/min. The number of samples was five for each condition.

2.4 Twist contraction ratio

Twisted yarns of type A and type H were cut in 250mm length and divided into single yarns. After that, the length of each single yarn was measured, and twist contraction ratio (TCR) was calculated from following equation.

$$TCR = L/Q$$

Where, L is the twisted yarn length (250mm), and Q is the single yarn length after divided.

2.5 Observation of migrations

Migration of TypeH and PVA/TypeH was observed through a digital-microscope (KH-1300, Hirox Co., Ltd.) from two directions being contrary each other. Typical migration patterns are shown in Fig.1. Single yarns migrate from surface to inner as shown in the arrows of Fig.1. The number of migrations was manually counted along the longitudinal direction of the yarn or composite.

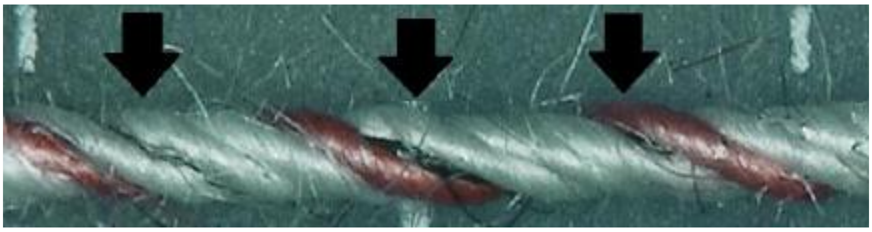

Fig.1 Migration in a Type H twisted yarn including dyed single yarns

3 Results and discussion

3.1 Relation between twist contraction ratio and tensile properties of twisted yarn

Tensile properties and yarn structure of Type A and Type H were explored through tensile test and yarn surface observation, respectively. Figs. 2(a) and (b) show photographs of these twisted yarns, each of which contains a dyed yarn. The dyed yarn in Type A is irregularly passing accompanied with migration, while that in Type H appears regularly. Typical stress-strain curves of Type A and Type H are illustrated in Fig. 3, both of which have almost the same twist angles, i.e. 19^{o}-21^{o} and 34^{o}-42^{o}. As seen in the figure, the two less twist angle yarns show higher strengths and less fracture strains, irrespective of the yarn type. Regarding the comparison between Type A and Type H, the formers show steeper slope in stress-strain relation, and present less fracture strains than the latter. This is related to difference in TCR of Type A and Type H. Type A was not enough twisted because of the twisting machine, while that of Type H was almost perfect. It leads to high and low TCR for Type A and Type H, respectively. Higher TCR yarn can sustain more loads at the initial behavior, so that it yields the different stress-strain behaviors from the lower TCR yarn. Thus, Type H yarn modulus is lower than Type A. In addition Type A indicated a larger variation in TCR, as compared to Type H. This also yields an unbalanced stress in each constituent yarn, and it brings premature fracture of single yarns which triggers the final fracture. This causes the difference in fracture strain. On the other hand, the tensile strengths of Type A and Type H are almost the same. This is because Type H can approach the stress level corresponding to Type A due to the balanced stress distribution without the premature yarn fracture.

Fig. 4 shows relationship between twist angle and elastic modulus of the single yarn, Type A and Type H. Elastic modulus was calculated in the 0.5 % strain range which exhibits the maximum slope in the stress-strain diagram, to compare with the composite elastic modulus. This may be called the maximum gradient ratio. Elastic moduli of Type A and H decreases with increasing twist angle. Type A modulus is higher than type H in the whole range. Fig. 5 shows relation between twist angle and tensile strength of the single yarn, Type A and Type H. Although the both strengths tend to decrease as twist angle increases, Type A strength is slightly higher than Type H in the range of low twist angles.

Elastic modulus and tensile strength were also related to TCR, a structural parameter of twisted yarn, as shown in Figs. 6 and 7, respectively. It seems in Fig. 6 that these data are plotted on an identical curve. In other words, if the same TCR is given, the yarn elastic modulus is measured as the same value. This means, the elastic modulus is characterized as an average, irrespective of balanced or unbalanced stress in each yarn. On the other hand, Type H strength is obviously higher than Type A, although the both yarns decrease with decreasing TCR. As mentioned above, TCR of Type A varies widely comparing to that of type H. This means, Type A contains a large variation in yarn length and is non-uniform in twisting, while Type H presents a uniform yarn length distribution and is uniform. It is estimated that such structural uniformity can raise the tensile strength, even if the average TCR is the same. Thus, it is concluded that TCR can interpret reasonably changes in elastic modulus and tensile strength.

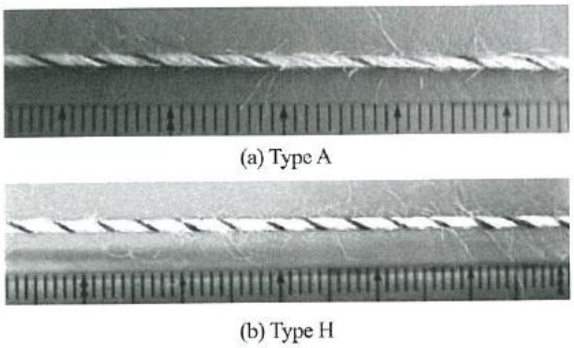

Fig. 2 Yarn structure of (a) Type A and (b) Type H (Each includes a dyed single yarn)

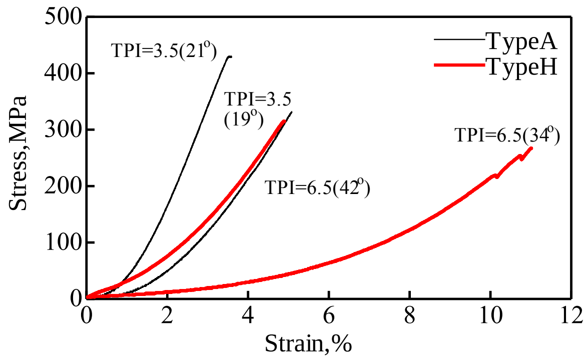

Fig. 3 Typical stress-strain curves of Type A and Type H twisted yarns

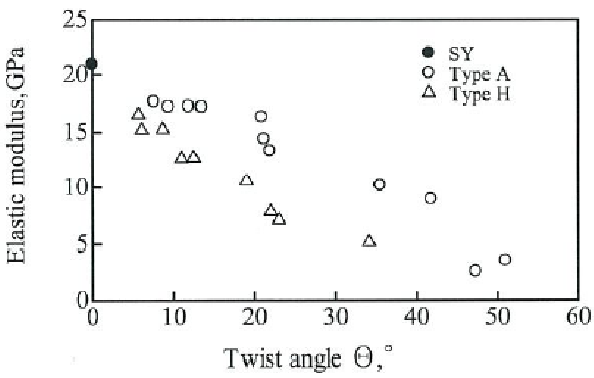

Fig. 4 Relation between yarn elastic modulus and twist angle

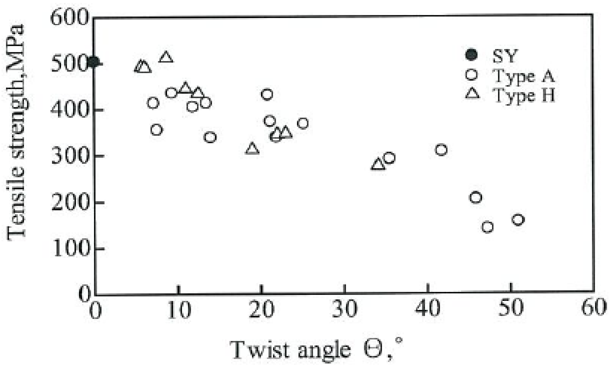

Fig. 5 Relation between yarn tensile strength and twist angle

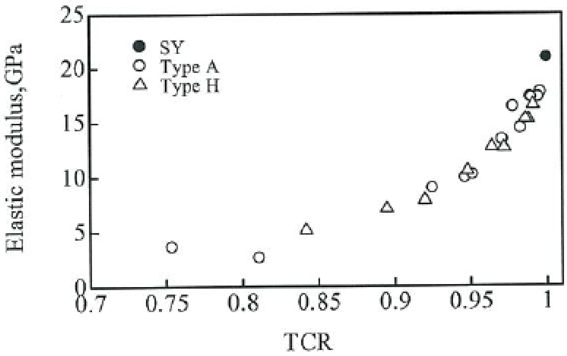

Fig. 6 Relation between yarn elastic modulus and TCR

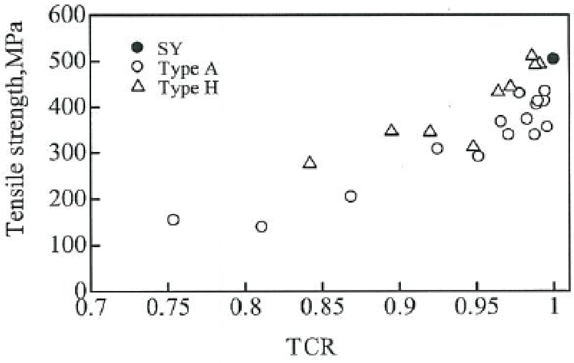

Fig. 7 Relation between yarn tensile strength and TCR

3.2 Tensile properties of twisted yarn composites

Table 1 shows tensile test results for various composites. The data clearly indicate that the normalized Young's moduli (E/V_f) of CPR, PLA, and PVA composites decrease with increasing twist angles. Fracture strains of PLA and PVA composites tend to increase with an increase in twist angle.

Table 1 Tensile properties of ramie twisted yarn composites with various twist angles

Matrix type	TPI	TCR	V_f (%)	Young's modulus (GPa)	Tensile strength (MPa)	Fracture strain (%)	E/V_f* (GPa)	σ/V_f* (MPa)
CPR/TypeA	0	1	41	16.7	187.5	1.76	40.6	456
	1.5	0.990	48	16.9	237.8	1.63	35.5	500
	3.5	0.978	54	11.7	196.7	2.90	21.9	366
	6.5	0.925	35	6.09	104.6	2.06	17.5	311
PLA/TypeA	0	1	39	18.6	165.5	1.75	47.7	424
	1.5	0.990	47	19.6	201.7	2.04	41.7	429
	3.5	0.978	41	16.7	170.9	2.11	40.5	414
	6.5	0.925	52	15.6	172.7	2.51	29.8	340
PVA/TypeH	0	1	51	11.0	326	2.93	21.6	639
	1.5	0.986	70	8.45	196	3.44	12.1	280
	3.5	0.948	73	4.36	201	4.81	5.97	275
	6.5	0.842	76	2.52	133	9.23	3.32	175

*V_f means fiber volume fraction

Yong's modulus and tensile strength of composites were marshaled with TCR. The results are depicted in Figs. 8 and 9 in addition to the yarns' data. Values shown here were normalized by values of the single yarn and single yarn composite. As shown in Fig. 8, elastic moduli of the composites almost overlap with those of yarns. It is considered that yarn properties dominate elastic module of the composites. As shown in Fig. 9, on the other hand, the strength level of Type A-based composites are raised up to the level of Type H or Type H-based composite, different from comparison between the yarn moduli in Fig. 7. It is guessed that the resins play an important role for the improvement in strength. We estimate that stress transfer mechanism between the yarn and resin can improve the unbalanced stress state occurring in Type A. In addition, the results also show that difference of resin seems to be not much effect on these properties. It is concluded that TCR can successfully be linked to elastic modulus and tensile strength in the both yarns and composites.

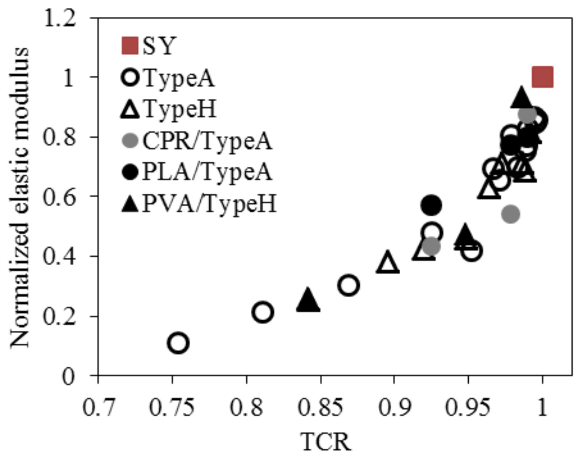

Fig. 8 Relation of normalized elastic modulus to TCR

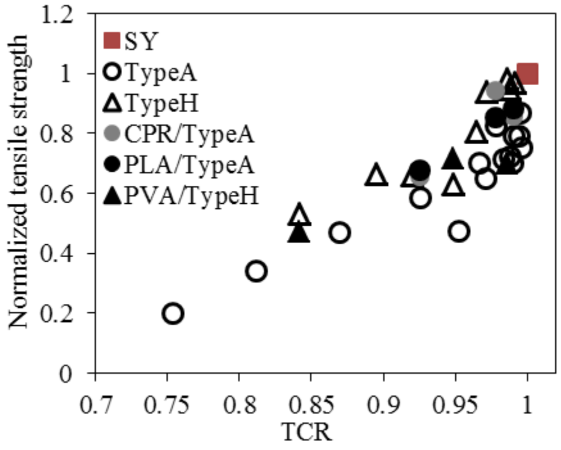

Fig. 9 Relation of normalized tensile strength to TCR

3.3 Relation between number of migrations and tensile strength

Number of migrations is considered to be another factor to decide tensile strength. Type H and PVA/Type H with different TPI were tensile-tested. Fig.10 illustrates relation between the number of migrations and normalized tensile strength. It seems that difference of tensile strength depends on TPI, which is also the same meaning as TCR dependency. The number of migrations indicates a wide range at the same TPI twisted yarn, however the tensile strength shows almost a constant value, as seen in the slope obtained by the linear approximation. This result suggests that number of migrations contributes little to change in tensile strength if TCR is given as a constant.

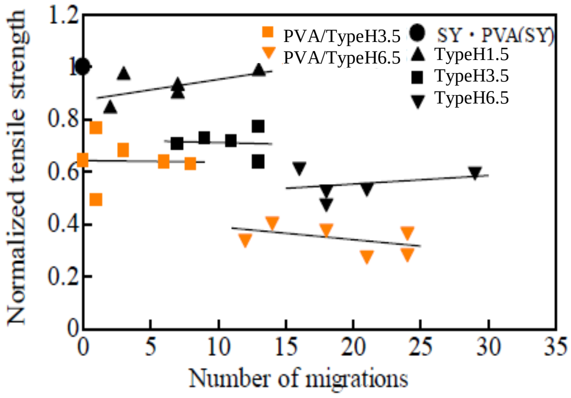

Fig. 10 Relation between the number of migrations and normalized tensile strength of twisted yarn and PVA/Type H composites

Conclusions

In this study, effect of twist contraction ration (TCR) on tensile properties of twisted yarns and twisted yarn composites was investigated using two types of twisted yarns, which were

twisted by a twisting machine and manually, denoted as Type A and Type H, respectively.
The major conclusions are:

1. Elastic modulus and tensile strength of twisted yarns can be marshaled reasonably by TCR being a parameter of yarn structure, rather than twist per inch (TPI).
2. Various composites using cornstarch-based, polylactic acid and polyvinyl-alcohol resins were tensile-tested. These properties could also be marshaled by TCR.
3. Number of migrations has little effect on tensile strength under the same TCR.

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