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Screw Driving Torques in Wood Polymer Composite Compatibilized with Maleic Anhydride-grafted Polypropylene

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Abstract

This study aimed to investigate the characteristics of screw driving torques in wood-polymer composite (WPC) compatibilized with maleic anhydride-grafted polypropylene (MAPP). To meet this objective, pine wood flour, polypropylene with coupling agent (maleic anhydride grafted polypropylene) were compounded in a twin screw extruder. The process of screw driving had two main torques, one of which was the seating torque defined as the torque required to clamp parts and other one was the stripping torque defined as the maximum torque right before screw strips in the material and the torque drops suddenly because of the formed screw threads being stripped in wood-based composites. However, there is no such a study about the screw driving torques in WPC compatibilized with MAPP. Therefore, the characteristics of screw driving torques was investigated in this material. Results indicated a good margin between seating and stripping torques when driving screws in the face of WPC compatibilized with MAPP.

Keywords: Screw, pilot hole, OPK, seating torque

Maleik Anhidrit ile Graftlanmış Polipropilen ile Muamele Edilmiş Odun Polimer Kompozitlerde Vidalama Torklarının Belirlenmesi

Öz

Bu çalışmada, maleik anhidrit ile graftlanmış polipropilen ile muamele edilmiş (MAPP) odun polimer kompozitlerde vidalama torkunu etkileyen faktörlerin araştırılması amaçlanmıştır. Bu amaç doğrultusunda çam odun unu, polipropilen ve uyum sağlayıcı madde çift vidalı bir ekstruder içerisinde karıştırılmıştır. Vidalama işleminde iki ayrı vidalama tork değeri mevcuttur. Bunlardan bir tanesi vidanın malzemenin içerisine tam oturduğu ve sıkıştırma işleminin başladığı anda ki tork değeridir. Diğeri ise, vidanın malzeme içerisinde boşta dönmesinden hemen önceki tork değeridir ve maksimum tork olarakta adlandırılır. Vidalama torku genellikle yonga levhalarda ve liflevhalarda çalışılmıştır. Maleik anhidrit ile graftlanmış polipropilenin (MAPP) odun polimer kompozitler de ki vidalama performansı araştırılmamıştır. Bu malzeme üzerinde vidalama torkları kılavuz deliği ve vida türü faktörlerinin etkileri incelenmiştir. MAPP ile muamele edilmiş odun polimer kompozitlerin yüzeylerinde yapılan bu çalışmanın en önemli sonucu, kılavuz deliği ve vida türünün oturma torku ve maksimum tork üzerine istatiksel olarak önemli etkisinin olduğu bulunmuştur.

Anahtar Kelimeler: Vida, Kılavuz deliği, OPK, Oturma torku, Kılavuz deliği

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1. Introduction

Wood polymer composites (WPCs) are used in many structural and non-structural applications such as decking, automobile and furniture frame components, garden and yard products, fences, household items and packaging (La Mantia et al., 2008; Serce et al., 2009; La Mantia and Morreale, 2011; Bazant et al., 2014; Zhang et al., 2015; Ratanawilai and Taneerat, 2018). Despite the many advantages of wood-polymer composites, some shortcomings (i.e., relatively low modulus, low impact resistance, and creep performance) have led researchers to use various compatibilizers or particles that serve as interfacial adhesives to improve the performance of wood-polymer composites. Nano-sized reinforcing materials have the potential to provide significant improvements of physical and mechanical properties of wood-polymer composites. Thus, WPCs are expected to become high performance and value added material for end use with advantages such as high modulus value, high shock resistance, thermal stability, less abrasiveness and less environmental impacts (Hill et al., 2015; Vimalanathan et al., 2016; Bütün et al., 2018). In the case of fastening parts in decking, fencing, furniture and building construction made of WPCs, screws are widely used mechanical fasteners because of their good performance and low cost. Therefore, knowledge of driving performance of screws will help the manufacturers of WPCs to understand the stability and durability of their products. There are few studies about the characterization of screw driving torques in materials such as oriented strandboard (OSB) and particleboard (PB) (Tor et al., 2015; Yu et al., 2015), plastics (Boulanger, 2009; Robert, 2012), wood-plastic composite (Kuang et al., 2017), and human bone (Bahr, 1994). In a study, the process of screw driving was divided into three sections of thread forming; screw seating (I), clamping (II), and screw stripping (III). There is difference in section I related to thread forming in plastics (Robert, 2012), OSB and PB (Tor et al., 2015; Yu et al., 2015). In plastics, the screw formed the threads without cutting material since the screw driving torque increased with a decreasing rate whereas in OSB and PB, the screw formed the threads with cutting materials as screw driving torque increased with an increasing rate. There were two main screw driving torques defined by Tor et al. (2015) and Yu et al. (2015). The seating torque (SET) was termed at the point where the head of screw flushed with the countersink of the upper plate and started clamping with the seated screw. Another term called stripping torque (STT) is the point where the screw reached the maximum torque. After the STT, the torque value started to decrease and loosened the screw in the tested materials. Screw driving torques are affected by pilot-hole diameter, screw penetration depth, embedded screw orientation, screw type, screw geometry, and material type. There was a strong relationship found between the screw driving torques and screw holding performance in wood-based composites. Screw withdrawal resistance at the torque level of 2.5 N.m, which was the closest level to the SET, was the highest whereas at the STT level whereas it was lowest when screws were withdrawn from the face of OSBs (Carroll, 1970; Eckelman, 1990; Tor et al., 2016).

There is no information in the literature has been found in the case of screw driving process in WPCs compatibilized with MAPP. The objectives of this study were to 1) obtain SET and STT values, 2) to investigate the effect of pilot-hole diameter 3) to investigate the effect of screw type, 4) quantify the significant factors on the SET and STT. The results from this study will help manufacturers of wood polymer composites to improve their products and meet some torque requirements when driving screw into their products. The results will also give a range between SET and STT that the operators of screw driving process can easily understand how much torque needed to drive the screw in to the material which consequently affects the screw withdrawal resistance. Depending on this range, the operators will also minimize the screw stripping in the material, which hold screws.

2. Material and Method

2.1. Material

The wood polymer composites (WPC) prepared from black pine wood flour (Pinus nigra J.F. Arnold subsp. nigra var. caramenica (Loudon) Rehder) as lignocellulosic filler. The wood flour passing through a 40-mesh screen was retained on an 80-mesh screen. Black pine wood flour (WF) was provided by a wood-polymer composite deck manufacturer (Semadeck, Tekirdag, Turkey). Polypropylene (PP) was purchased from Borealis Incorp in Austria. The PP had a density of 0.9 g/cm3, a melt point of 170 °C and a melt flow index of 2.5 g/10 min. at 230 °C. Maleic anhydride grafted polypropylene (MAPP) as compatibilizing agent was also used to eliminate the incompatibility between the polypropylene and pine wood flour and to increase the bonding. The MAPP was provided by Pluss Polymers Pvt. Ltd. Gurgaon in India. The MAPP had a density 0.91 g/cm3 and a melt flow index about 120 g/10 min at 190 °C. The PP, WF and MAPP were used as purchased from the manufacturer. The readymade WF was oven-dried at 103°C ± 2°C for 24 h. to minimize the moisture in lignocellulosic fillers which could cause bubbles to form during the extrusion and injection molding processes, leading to performance loss. The surface of wood polymer composite material is shown in Figure 1. Two different types of 16-mm-length-self-drilling screws were used in the experiment. One of the screw types was zinc-plated (ZP) and another was phosphate-zinc-plated (PZP). The minor and major diameters of the screws were 2.5 and 3.0 mm, respectively.

2.2. Production of the wood-polymer composites

The production of WPCs was carried out in two phases: pellet production and composite production. In the first phase, small granules (pellets) were produced, while in the second phase, the samples were produced by injection molding. Prior to the production, the wood flour was dried until the moisture was reduced to below 1%. The dried wood flour was melted in the extruder (Aysa Machine, Istanbul, Turkey) by premixing it with the PP and MAPP according to the production prescription and then pushed into the die with the screw in the double screw extruder. The molten material that exited through the die in the extruder end was cooled with cold water and left to dry. Composite samples in the shape of fine rods dried at 80 °C for 3 h were made into pellets via plastic crusher (ZHL-SA, TSP Machine, Tekirdag, Turkey). The pellets were oven-dried until reaching a rate of 1% to 2% moisture before the injection molding process. The dried pellets were made into a test sample in an injection molding machine (TSPX 60; TSP Machine, Tekirdag, Turkey) operating at a screw speed of 40 rpm and a temperature of 185 °C to 200 °C. The injection pressure was set to 5 MPa to 6 MPa, the injection speed was 80 mm/s, and the cooling rate was 30 s.

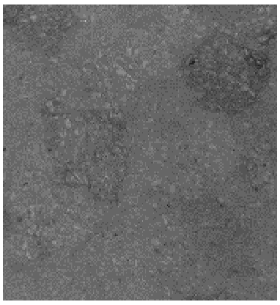

Figure 1. Surface of wood polymer composite material

2.3. Screw driving torque measurement

All testing blocks were cut along the length direction of full-sized WPC panel and were conditioned at 20±2°C and relative humidity (RH) of 50±5% for at least 40h (ASTM D 618-13, 2013). Pilot holes were drilled at the center of the face of each WPC testing block. Pilot-hole depths were drilled 2 mm deep which is the half thickness of the testing block. The torque measurements were measured by Kraftform torque screwdriver set which included two different screwdrivers based on the torque ranges (Figure 2). The torque of first screwdriver ranged from 0.3 to 1.2 N.m and second one ranged from 1.2 to 3.0 N.m. The measurement accuracy was ± 6% which complies with the requirements of ISO 6789-2 (2017). A 10 mm metal plate was used to be consistent about the screw penetration depths in the testing block. The test setup for evaluating SET and STT was showed in Figure 2.

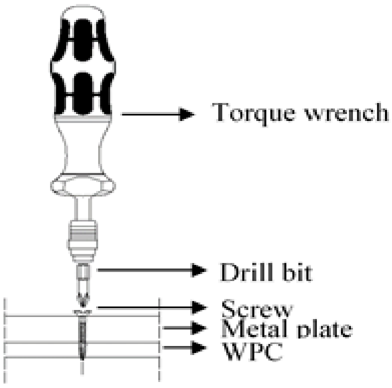

Figure 2. The test setup for evaluating SET and STT of driving screw into face of WPCs

2.4. Experimental design

A complete two-factorial experiment with 15 replicates per combination was conducted to evaluate effects of factors on seating torque (SET) and stripping torque (STT) of driving screws into face of wood polymer composites. Two factors were pilot-hole diameter (0, 1,1.5, 2 and 2,5 mm) and screw type (zinc plated and phosphated zinc plated self-drilling screws (Table 1). Testing blocks were prepared in accordance with ASTM D 1037-12 (2012). Therefore, a total of 300 data points of screw driving torques were obtained from 30 testing blocks. Each testing block had nominal 300 mm long × 20 mm width × 4 mm thick.

Table 1. Minor and major diameters of a screw and pilot-hole diameters and their percentages based on the minor and major diameter of the screw.

Minor diameter (mm)	Major diameter (mm)	Pilot-hole diameter (mm)	Minor diameter (%)	Major diameter (%)
		0	0	0
		1	40	33
2.5	**3.0**	**1.5**	60	50
		2	80	67
		2.5	100	83

For statistical analyses of the data, the general linear model of analysis of variance (ANOVA) procedure was performed on the balanced individual data points of SET and STT using SAS 9.4 software (SAS Institute INC, 2016) to analyze main effects and their interactions on SET and STT at the 5% significance level. In order to determine mean differences among treatment combinations, the interactions between pilot-hole diameter and screw type was analyzed, then the protected least significant difference (LSD) multiple comparison procedure was followed (Hu et al., 2016).

3. Results and Discussion

3.1. Mean screw driving torques comparisons

Table 2 summarizes mean SET and STT values for WPCs. In general, the mean SET values ranged from 0.37 to 0.45 N.m and STT values ranged from 0.74 to 1.00 N.m for driving wood screws into face of WPC material whereas the mean SET values ranged from 0.30 to 0.47 N.m and STT values ranged from 0.70 to 1.29 N.m for driving drywall screws into face of the material. SET and STT data were analyzed separately for ANOVA and mean comparisons since the mean STT values were significantly higher than SET values. ANOVA results indicated that the two-factor interaction between pilot-hole diameter and screw type was significant for both data sets of SET and STT. Therefore, a one-way classification of 10 treatment combinations was created for SET and STT data sets to evaluate mean differences by LSD multiple comparison procedure. Fig. 3 and 4 summarize mean comparisons of SET and STT values using the single LSD value of 0.04 and 0.07 N.m.

Table 2. Summary of mean SET and STT values and their ratios based on the screw type and pilot-hole diameter.

Pilot-hole diameter (mm)	Screw type				Ratio STT / SET	
	Wood screw		Drywall screw			
	SET	STT	SET	STT	Wood	Drywall
	------------------------N.m---------------------------					
0	0.37 (9)*	0.74 (5)	0.47 (17)	1.29 (9)	2	2.7
1	0.38 (12)	0.78 (9)	0.39 (14)	0.89 (7)	2.1	2.3
1.5	0.39 (15)	0.82 (6)	0.35 (13)	0.85 (5)	2.1	2.4
2	0.41 (7)	1.00 (9)	0.32 (13)	0.76 (6)	2.4	2.4
2.5	0.45 (8)	1.00 (7)	0.3 (13)	0.70 (13)	2.2	2.3

* Values in paranthesis represent the coefficient of variance (%)

3.2. Effects of pilot-hole diameter

In general, there was an increase trend in mean SET values when pilot-hole diameter increased from 0 to 2.5 mm when driving wood screws in the face of WPCs (Figure 3). The 2.5-mm pilot-hole diameter had the highest SET values, but lowest when no pilot-hole diameter was drilled. The SET significantly did not differ from each other in the terms of pilot-hole diameters of 2.0 and 2.5 mm. In the case of driving drywall screws in the face of material, the opposite trend was obtained in which the SET decreased when the pilot-hole diameter increased from 0 to 2.5 mm. The SET at the no-pilot-hole diameter was significantly higher than the other pilot-hole diameters. Similar study by Yu et al. (2015), the characteristics of driving screws into six different PBs were investigated. The results of the study indicated that mean SET values for driving screw in face of PB materials ranged from 0.9 to 1.92 N-m, whereas the mean stripping torque values ranged from 3.73 to 6.55 N-m, and mean ratio for STT-to-SET ranging from 2.5 to 5.0. The SETs and STTs in PB materials with pilot-holes were significantly lower than their corresponding ones without pilot-holes.

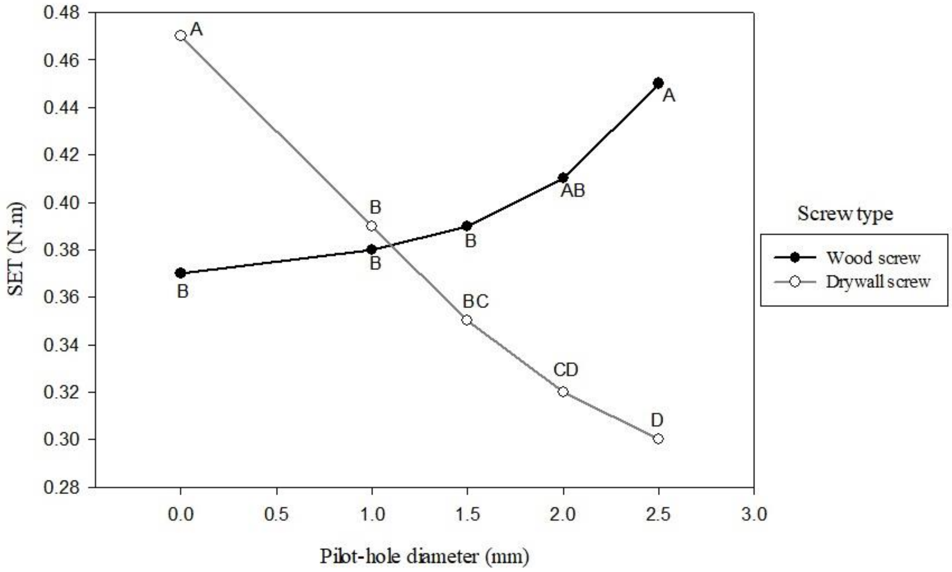

Figure 3. Mean comparisons of SET for pilot-hole diameter within each screw type. Means not followed by a common letter are significantly different at the 5% significance level.

Figure 4 indicated that the STT increased as pilot-hole diameters increased from 0 to 2.5 mm driven by wood screw while the STT decreased as pilot-hole diameters increased from 0 to 2.5 mm driven by drywall screw. Significant difference occurred when no pilot-hole diameter was drilled in the face of the material. The STT by drywall screw was almost twice higher than the one by wood screw. There was no significant difference in the STT between the pilot-hole diameter of 2.0 and 2.5 mm

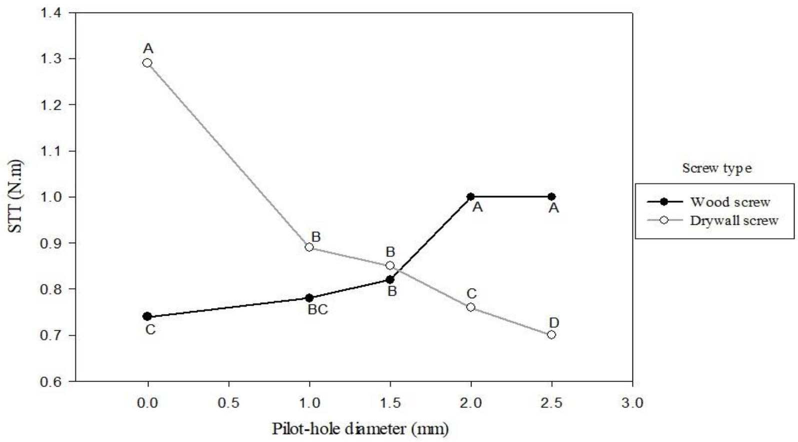

Figure 4. Mean comparisons of STT for pilot-hole diameter within each screw type. *Means not followed by a common letter are significantly different at the 5% significance level.

3.3. Effects of screw type

In the case of comparing the screw types for each pilot-hole diameter, drywall screw at the no-pilot-hole diameter had statistically higher SET than the corresponding ones with wood screws (Fig. 5). This could be explained by the ability of the polymers to form around the thread of the drywall screw better than the wood screw when no-pilot-hole diameter drilled in the face of the material. At the larger pilot-hole diameter of 2.0 and 2.5 mm, the SET by wood screw was significantly higher than the ones by drywall screw. Meanwhile, there was no significant difference between the screws at the 1-mm pilot-hole diameter drilled. The reason could be because of wood screw has better shear strength then the drywall screw in the literature.

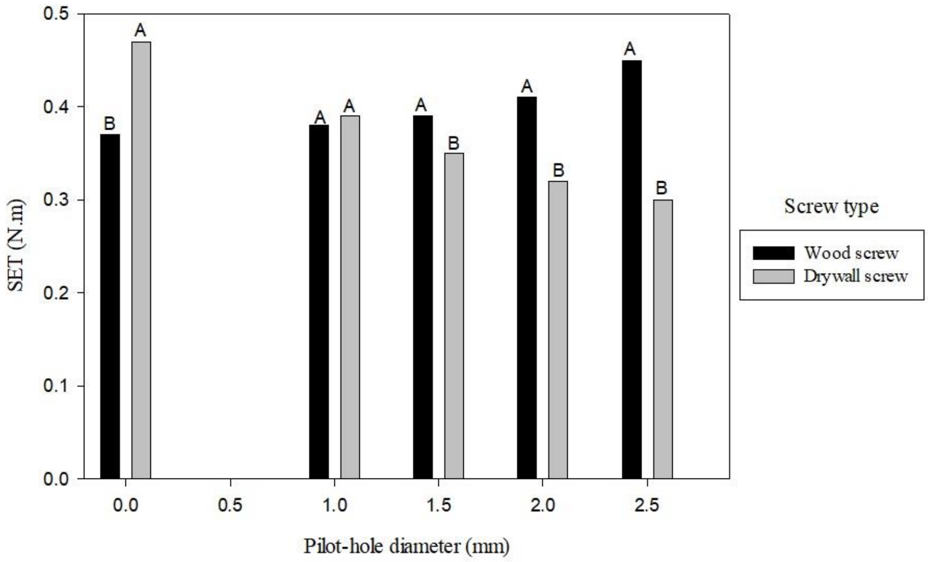

Figure 5. Mean comparisons of SET for screw type within each pilot-hole diameter. Means not followed by a common letter are significantly different at the 5% significance level.

The general trend in the STT, at the narrower pilot-hole diameters driven by drywall screws had higher the ones driven by wood screws (Fig. 6). However, at the larger pilot-hole diameters of 2.0 and 2.5 mm driven by drywall screw were lower than the ones driven by wood screws. There was no significant difference in STT between drywall and wood screws when the pilot-hole diameter of 1.5 was drilled.

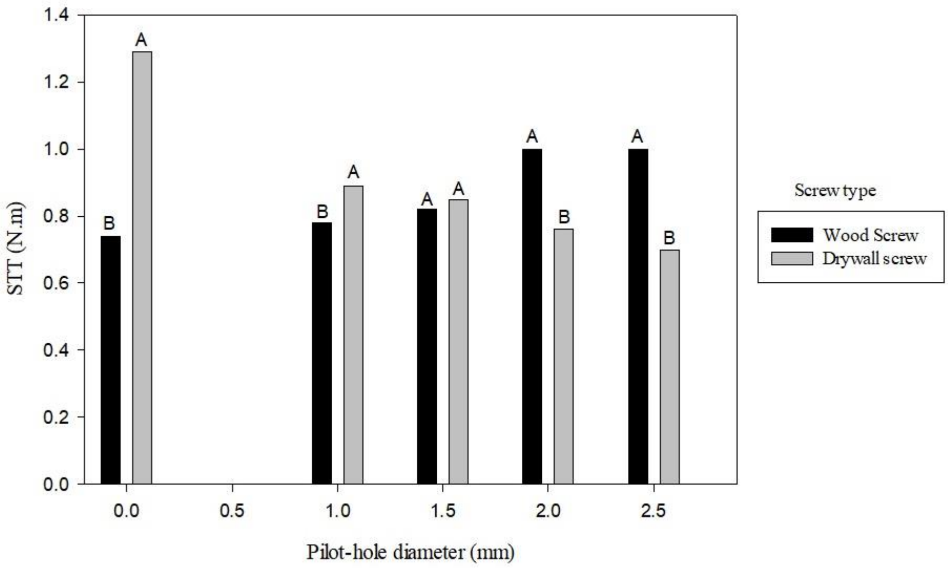

Figure 6. Mean comparisons of STT for screw type within each pilot-hole diameter. Means not followed by a common letter are significantly different at the 5% significance level.

3.4. Development and verification of estimation equations

ANOVA results indicated that the pilot-hole diameter and screw type had significant effects on SET and STT driving screws into face of WPCs. The power equation regression technique was used to quantify the effects of these two significant factors on SET and STT of WPCs, separately (Li et al., 2018). Table 2 gives the mean SET and STT values and their ratios of STT/SET of WPCs. The average ratios are 2.16 and 2.42 for wood and drywall screw, respectively. Therefore, SET and STT can be estimated using the following two equations, which were simply derived through multiplying two to each of the power equations.

$$SET = -0.3873 \times P^{-0.1433} \times S^{-0.0586} \quad (1)$$

$$STT = -0.0933 \times P^{-0.1865} \times S^{0.1490} \quad (2)$$

Where SET = mean seating torque, STT = mean stripping torque, P = pilot-hole diameter, S = screw type. To provide a practical evaluation of how well the values estimated by these two empirical equations agreed with observed values, the ratios between observed and estimated SET and STT values were calculated and shown in Table 3. The ratio ranged from 0.88 to 1.27 for SET and from 0.83 to 1.43 for STT. These ratios indicate Eqs (1) and (2) reasonably estimate SET and STT, driving screws into face of WPCs.

Table 3. Comparison of estimated and observed SET and STT of driving wood and drywall screws in five pilot-hole diameters in the face of WPCs.

Screw type	Pilot-hole diameter (mm)	Screw driving torques (N.m)					
		SET			STT		
		Observed	Estimated (Eq 1)	Ratio	Observed	Estimated (Eq 2)	Ratio
Wood screw	**0**	0.37	0.41	0.90	0.74	0.89	0.83
	1	0.38	0.39	0.97	0.78	0.86	0.91
	1.5	0.39	0.38	1.03	0.82	0.83	0.99
	2.0	0.41	0.38	1.08	1.00	0.82	1.22
	2.5	0.45	0.37	1.22	1.00	0.81	1.23
Drywall screw	**0**	0.47	0.37	1.27	1.29	0.90	1.43
	1	0.39	0.36	1.08	0.89	0.86	1.03
	1.5	0.35	0.35	1.00	0.85	0.84	1.01
	2.0	0.32	0.34	0.94	0.76	0.83	0.92
	2.5	0.3	0.34	0.88	0.70	0.81	0.86

Conclusion

The effects of pilot-hole diameter and screw type on screw driving torques were investigated in WPCs compatibilized with MAPP. Mean SETs range from 0.37 to 0.45 N.m, STT from 0.74 to 1.00 N.m and their corresponding ratios from 2.0 to 2.4 for wood screws while the mean SETs range from 0.30 to 0.47 N.m, STT from 0.70 to 1.29 N.m, and their corresponding ratios from 2.3 to 2.7 for drywall screws driven into face of WPCs. Statistical analyses indicated that the pilot-hole diameter and screw type significantly affect both screw driving torques. As the pilot-hole diameter increased from 0 to 2.5 mm, the SET and STT decreased for drywall screws and increased for wood screws. These results give a good margin between SET and STT when driving screws in the face of WPCs compatibilized with MAPP. The operators of screw driving process can easily set how much torque they need to drive the screw in to the material. Depending on this range, the operators can minimize the screw stripping in the material, which hold screws, and the health issues related to handling the screw driving tools.

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