Holz als Roh- und Werkstoff (2006) 64: 172–177
DOI 10.1007/s00107-005-0072-x

ORIGINALARBEITEN · ORIGINALS

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Effects of Wood Particle Size and Mixing Ratios of HDPE on the Properties of the Composites

Published online: 2 December 2005

Abstract The main goal of this research is to innovate wood-plastic composites by using various wood particle sizes and different mixture ratios (weight ratio) of HDPE (High Density Polyethylene). After mixing the wood particles (recycled wood waste) and the plastic powder, we use a molding and pressing process to make composites with a thickness of 12 mm. By doing so, the wood particle content can be increased to 75%. This kind of composite provides excellent dimensional stability, its moisture content is under 2.5%, and the thickness swelling rate after 24 hr water absorption is under 7.5%. The maximum static bending strength of this composite reaches 20.7 N/mm^2, and is better than that of general commercial particleboards. The composite made of larger sized wood particles has better strength properties. In addition, when the plastic content ratio increases, the dimensional stability of the composite will increase as well. After the soaking process in boiling water, the static bending strength of wet composite remained at 50%; this shows the good weather resistance of the composite. The surface veneer overlaid peeling strength of the composite showed 1.02–1.63 N/mm. After the evaluation of processing, cost of material and strength properties of the composite, we would suggest that the use of 70% of wood particles and 30% of plastic powder is practical to produce proper sized composites.

Einfluss der Größe der Holzspäne und der Mischungsverhältnisse mit HDPE auf die Eigenschaften von Holz-Kunststoff-Verbundplatten

Zusammenfassung Ziel dieser Untersuchung ist die Herstellung neuartiger Holz-Kunststoff-Verbundplatten durch Verwendung verschieden großer Holzspäne und HDPE (Polyethylen – hoher Dichte) mit unterschiedlichen Mischungsverhältnissen (Masseanteilen). Nach dem Mischen der Holzspäne (recyceltes Holz) und des Kunststoffpulvers wurden durch Formen und Pressen 12 mm dicke Verbundplatten hergestellt. Dabei kann der Anteil der Holzpartikel auf 75% erhöht werden. Diese Verbundplatten verfügen über ausgezeichnete Dimensionsstabilität und einer Holzfeuchte unter 2,5%. Die Dickenquellung nach 24-stündiger Wasseraufnahme blieb unter 7,5%. Die maximale Biegefestigkeit dieser Verbundplatten betrug 20,7 N/mm^2 und ist somit höher als diejenige handelsüblicher Spanplatten. Die aus größeren Holzpartikeln hergestellten Verbundplatten weisen bessere Festigkeitseigenschaften auf. Die Dimensionsstabilität nimmt mit steigendem Kunststoffanteil zu. Nach Lagerung in kochendem Wasser betrug die Biegefestigkeit der nassen Verbundplatten noch 50%, was deren gute Wetterbeständigkeit verdeutlicht. Die Abhebefestigkeit der aufgeklebten Furniere lag zwischen 1,02–1,63 N/mm^2. Nach Überprüfung des Herstellverfahrens, der Materialkosten sowie der Festigkeitseigenschaften der Verbundplatten hat sich ein Holzpartikelanteil von 70% und ein Kunststoffpulveranteil von 30% als für die Herstellung von Verbundplatten herkömmlicher Größe praktikabel erwiesen.

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1 Introduction

The market demand for wood-plastic composites has rapidly increased in recent years. Therefore, many relevant reports about innovating and improving the properties of composites exist (Shiue et al. 2001, Peng and Hwang 1996, Clemons and Ibach 2002, Nicole and Mark 1999). Nevertheless it is difficult to make wood-plastic composites with large sized particles by using an extrusion process as the cost of an extrusion machine is also expensive. When the domestic research units are doing this kind of research, they always needed to ask for assistance from the industry or a research partner of another industry field, but the result of the research was never as good as they had expected. Therefore, in our laboratory we use larger-sized wood particles as materials instead of wood powder to mix with the HDPE powder. After forming the mats are pressed and the composites are produced. In this project, we discuss the effects of wood particle size and different mixture ratios of HDPE on the properties of wood-plastic composites.

2 Materials and Methods

2.1 Materials

2.1.1 Wood particles

The wood waste from construction sites (tearing, building or finished construction sites) is a mixture of wood species. After nails, metals, pebbles and cement have been removed from the surface, the material was put into the chopping machine. After chopping to chips, a magnet was used to remove the metal from the chips, and then the wood chips were put into the chipping machine of knife ring flakers to produce wood particles. After drying (moisture content lower than 3%), the wood particles were divided into four different sizes and marked as L, S, T and F as described in Table 1.

2.1.2 High Density Polyethylene (HDPE)

The HDPE powders are the recycled plastic waste from the factories making plastic containers. The density of HDPE is $0.95 \sim 0.97\ g/cm^3$ and its melting temperature is $164 \pm 3°$. The size distribution of HDPE powder is 0.6%, 3.2%, 28.4%, 34.0%, 14.2% and 19.4% on the mesh number +10#, −10# ∼ +20#, −20# ∼ +40#, −40# ∼ +60# , −60# ∼ +100# and −100#, respectively.

Table 1 Manufacturing conditions of wood particle-plastic composites
Tabelle 1 Herstellungsbedingungen der Holz- Kunststoff-Verbundplatten

Code	mixing ratio (wood:plastic)	particle size	density expected (g/cm^3)	conditions of hot-press and cold-press
LA	50:50			
LB	60:40	$L \geqq 1.18$ mm	0.9	
LC	70:30	(16#)		
LD	75:25		0.85	
SA	50:50			Hot-press: temperature reaches 185° in the middle layer, average time 15 minutes. Cold-press: temperature reaches 25° in the middle layer, average time 10 minutes.
SB	60:40	1.18 mm > $S \geqq 0.74$ mm	0.9	
SC	70:30	(16#) (24#)		
SD	75:25		0.85	
TA	50:50			
TB	60:40	0.74 mm > $T \geqq 0.59$ mm	0.9	
TC	70:30	(24#) (32#)		
TD	75:25			
FA	50:50			
FB	60:40	$F < 0.59$ mm	0.9	
FC	70:30	(32#)		
FD	75:25			
NA	50:50	N		
NB	60:40	Unscreened with	0.9	
NC	70:30	complex particles		
ND	75:25			

1) L, S, T, F, N indicate particle sizes, 16#, 24# and 32# are the mesh numbers. **2)** Mixing ratio of wood particles and plastic powder indicated as A, B, C, D; A for 50:50, B for 60:40, C for 70:30, D for 75:25.

2.1.3 Soybean oil

The main purpose is to advance the plastic powders spread uniformly on the surface of wood particles. The soybean oil has a viscosity of 55 cps (25°) and a pH of 6.34.

2.1.4 Sliced veneer

Maple (Acer spp.) veneer with a thickness of 2 mm and a width of 95 mm. The moisture content of veneer was kept below 6%.

2.1.5 Adhesive for veneer overlaid

Two kinds of adhesives were used, namely MF (Melamine formaldehyde resin) and RF (Resorcinol formaldehyde resin)

2.2 Methods

2.2.1 Manufacture of composite

The manufacturing conditions of composite are listed in Table 1. There were five size groups of wood particles (L, S, T, F, N). The mixing ratios based on oven dried weight of wood particles and plastic powder were 50:50, 60:40, 70:30 and 75:25 with code A, B, C, and D respectively. The expected density was $0.9\ g/cm^3$. The density of LD and SD (particle size of L and S, mixing ratio of D) was altered to $0.85\ g/cm^3$ due to high compression. Dried particles were put into a plowshare adhesive-spraying machine. Then the soybean oil was slowly poured in (5% soybean oil based on oven dried wood particles by weight). The wood particles were mixed for five minutes. In this case the plastic powders can uniformly stick on the surface of wood particles. Then the solution was slowly poured into the plastic powder and mixed for another five minutes. From this mixture a mat was made by hand. A temperature sensor was set in the middle of the layer of the mat in order to measure the temperature changes during the hot pressing of mat. After pre-press, the mat was put into a hot-press under the conditions of 190° and 2.5 MPa. The temperature was raised to 185° in the middle layer of the mat (about 15 minutes), and then the mat was moved to the cold-press. The temperature was controlled around $12.5 \pm 1°$ with the pressure remaining the same at 2.5 MPa. When the temperature in the middle layer of the mat decreased to 25° (about 10 minutes), the pressure was released and the composite was moved to room temperature for a week.

2.2.2 Veneering process

The composites made of wood particles with the size L are basically made to test the surface veneer overlaid peeling strength. The composite boards were conditioned under room temperature for a week, and sanded to a thickness of 11.5 mm. MF or RF adhesive was spread on the composite with $180\ g/m^2$ for one side. Then 2 mm-thick maple veneer was set on the composite

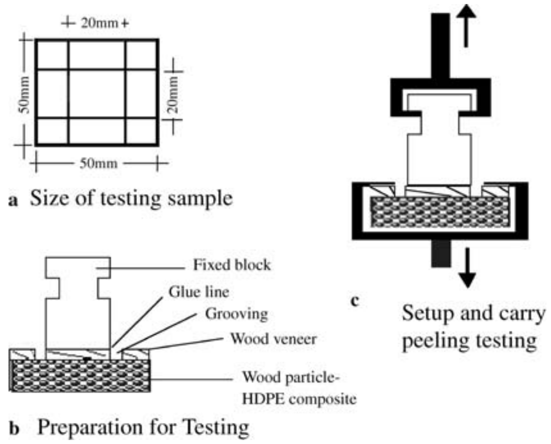

Fig. 1 Diagram of specimen preparation for surface peeling test and setup for testing
Abb. 1 Schematische Darstellung des Prüfkörpers und der Prüfvorrichtung für den Abhebeversuch

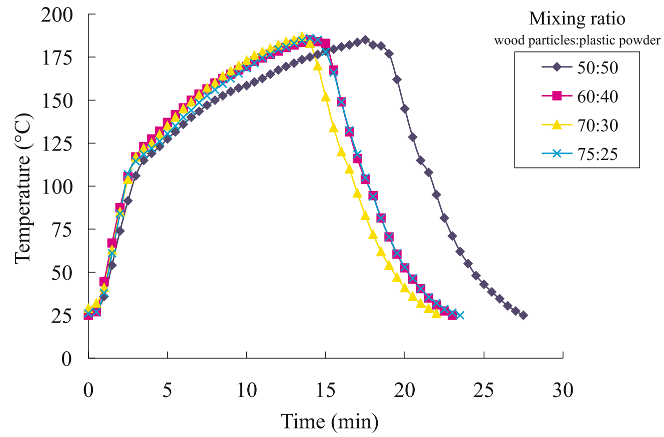

Fig. 2 Temperature changes in the middle layer of composites with different mixing ratios during hot pressing
Abb. 2 Temperaturverlauf der Mittellage der Verbundplatten während des Heißpressens bei unterschiedlichen Mischungsverhältnissen

to be pre-pressed for 30 minutes and hot-pressed for five minutes (1.2 MPa).

2.2.3 Determination of composite properties

Each of the specimens was measured according to the standards of ASTM D 1037. In order to determine the properties of the composite board several tests have been conducted including density, moisture content (the specimens were set in room temperature environment for one month), thickness swelling rate of water absorption, MOR, MOE and wet condition bending strength. For this test specimens were placed in boiled water for two hours and then transferred to water kept at room temperature for one hour before conducting the bending test.

Additional the surface peeling strength of the composite in dry condition was carried out to detect the veneer overlaid properties according to the standard ASTM 897. The cutting size of testing specimen was $50 \times 50\ mm^2$, the efficient bending area of testing specimen $20 \times 20\ mm^2$. The specimen preparation and testing are shown in Fig. 1. Pull speed was 2 mm/min.

2.2.4 ANOVA analysis

The ANOVA (Analysis of variance between groups) and Duncan's New Multiple Range Analysis were applied for this research.

3 Results and discussion

3.1 Temperature changing in the composite mats during hot pressing

As shown in Fig. 2, the composite mat with the mixing ratio 70:30 reached the target temperature (185°) in the middle layer within the shortest time (about 13 minutes) among the four different mixing ratios. The composite mat with mixing ratio 50:50 needed the longest time (17.5 minutes) to reach the target temperature. Then in the cold press process, the mat with the mixing ratio 50:50 took the longest time (10 minutes) to cool down to the target temperature as well. The other three groups took about 9 minutes to cool down. The reason for the composites with a higher plastic content to require more time to heat up and cool down might be the higher heat value needed in plastic melting process. Therefore, the testing mat of the 50:50 mixing ratio required the longest pressing time (17.5 minutes in hot press and 10 minutes in cold press, total 27.5 minutes) to finish the board, and meanwhile, the testing mat of the 70:30 mixing ratio only required 22 minutes. The other two testing mats (mixing ratios 60:40, and 75:25) required about 23.5 minutes in the board pressing process. Regarding its energy consumption and production speed, the mixing ratio with 70:30 had the lowest cost and fastest manufacturing speed.

3.2 Properties of composites

The tests included density, moisture content, thickness swelling rate and water absorption after 24 hr soaking, bending strength and wet condition bending strength. The results are shown in Table 2.

3.2.1 Density

The densities are arranged at 0.9 and 0.85 g/cm^3 (Table 1), but the measured densities of the composites ranged between 0.75 and 0.89 g/cm^3. The lowest density 0.75 g/cm^3 was found in composites made from wood particles larger than #16 and with a mixing ratio of 75:25 (code LD) whereas the highest density 0.89 g/cm^3 was found in composites made from wood particles smaller than #32 and with a mixing ratio of 50:50 (code TA). The composite made from larger sized wood particles with a higher content may have more and larger pores. Smaller wood particles make a thinner mat and the compaction ratio is higher.

Table 2 Properties of wood-plastic composites
Tabelle 2 Eigenschaften der Holz- Kunststoff-Verbundplatten

Code	density (g/cm^3)	moisture content (%)	thickness -swelling (%)	water absorption (%)	bending strength (N/mm^2) MOR	bending strength (N/mm^2) MOE	bending strength in wet condition (N/mm^2) MOR	bending strength in wet condition (N/mm^2) MOE
LA	0.83	1.2	2.4	4.2	20.0	1835	17.1	1453
LB	0.83	1.3	3.8	6.5	20.7	2218	15.8	1520
LC	0.80	1.6	5.8	10.4	18.1	2100	11.2	1097
LD	0.75	1.9	7.0	13.7	13.2	1574	8.8	887
SA	0.84	1.4	2.0	5.4	18.5	1611	15.0	1241
SB	0.84	1.4	3.5	7.1	16.4	1805	12.4	1104
SC	0.80	1.8	5.7	11.3	11.9	1395	9.0	796
SD	0.80	2.0	7.3	14.5	10.5	1315	6.3	739
TA	0.86	1.1	2.2	5.0	17.0	1588	13.7	1128
TB	0.86	1.2	2.9	6.7	14.8	1659	11.3	1078
TC	0.80	1.4	6.1	11.6	11.2	1394	7.7	863
TD	0.79	1.8	6.9	13.2	8.4	1044	5.4	665
FA	0.89	1.1	1.4	4.8	18.7	1737	12.2	1058
FB	0.87	1.4	2.6	6.2	13.5	1594	10.2	1026
FC	0.85	1.7	4.4	9.6	10.7	1360	6.9	813
FD	0.86	2.5	5.8	10.2	7.7	1194	5.0	693
NA	0.84	1.2	2.2	5.0	16.9	1660	14.9	1338
NB	0.86	1.3	3.5	6.8	15.9	1746	13.8	1270
NC	0.85	1.7	5.1	9.8	13.2	1786	10.7	1127
ND	0.82	1.8	6.7	13.6	11.8	1583	7.7	906

1) Particle sizes L,S,T,F,N as indicated in Table 1. **2)** Mixing ratio of wood particles and plastic powder as indicated in Table 1

3.2.2 Moisture Content

The moisture content of the composites ranges between 1.1 ∼ 2.5%. The moisture content increases along with a higher content of wood particles. The result is similar to the previous research result (Shiue et al. 2001) . The main reason for this is that plastic doesn't absorb water. This value is close to the moisture content (2.5%) with a mixing ratio of 50:50 of wood fiber-plastic composite in Clemons's research (Clemons 2002). It is also lower than the composite made by refined wood particle (4%).

3.2.3 Thickness swelling and water absorption

Dimensional stability is one of the advantages of wood-plastic composite. As shown in Table 2, the thickness-swelling of composite ranges between 1.4% ∼ 7.3%, and it increases along with higher wood particle content.

3.2.4 MOR and MOE

The MOR of the composites shown in Table 2 ranges between 7.7 N/mm^2 and 20.7 N/mm^2. The MOR increases with enlarged size and with decreased content of wood particles.

The tendency of the MOE test result is very similar to the MOR. The MOE ranges between 1044 N/mm^2 and 2218 N/mm^2. Other domestic research references (Shiue et al. 2001, Peng and Hwang 1996) indicated that the MOE of composite will increase with higher wood content, but in this research, the MOE of composite with 70% wood particles is not higher than the composite with 60% wood particles. Because the other domestic researches used not more than 60% of wood particles, the MOE of composite increases along with higher wood particle content. When the wood particle content exceeds 60% then the properties of composites get weaker because the plastic material cannot totally cover fine wood particles. This might be the main reason for decreasing MOE.

3.2.5 MOR and MOE in wet condition

MOR of the wet sample is lower than MOR under normal condition. The lowest MOR in wet condition is found for composites made of small sized wood particles with a high content. The MOR in wet condition of the SD, TD, and FD is between 5.0 N/mm^2 and 6.3 N/mm^2. But in other groups, the MOR in wet condition of the composites is between 6.9 N/mm^2 and 17.1 N/mm^2. The influence of size and content of wood particles on the MOE in wet condition of composites showed a similar tendency for the MOR in wet condition. The MOE in wet condition showed between 665 N/mm^2 and 1520 N/mm^2. The retention rate of MOR and MOE in wet condition was at least 52.2%.

3.2.6 The effect of wood particle sizes on the properties of composites

Samples of the same wood particle size are included in one group. ANOVA (Analysis of Variance between groups) was applied to analyze the statistical significance of wood particle size on the composite properties. Table 3 shows the statistical significance of composite density affected by wood particle sizes. The composite density increases with smaller sized wood particles. The moisture content is not affected by particle sizes. In the thickness-swelling rate test, the composite made of smallest sized particles has lower thickness-swelling. Other groups showed no significant difference. The water absorption showed a similar tendency. Regarding the bending strength of the composites, the MOR of composite increases significantly with larger sized wood particles; MOR in the wet condition showed a similar tendency. Regarding the MOE, the composite made of largest sized particles showed the highest value, the composite made of unscreened wood particles showed the second highest score; and the other three groups showed no significant difference. Regarding the MOE in wet condition, composite made of particle size L and N showed no significant difference. The other three groups had a lower score (S, T and F), and they showed also no significant difference.

3.2.7 Effects of plastic content on composite properties

Table 4 shows the relative effect analysis of plastic content towards the composite disregarding wood particle size. The table indicates that plastic content decreased moisture content, water absorption and thickness swelling of the composite. It showed positive properties. On the other hand, plastic content increased density and bending strength of the composite. In all properties,

Table 3 Evaluation of effects of wood particle size on composite properties
Tabelle 3 Einfluss der Größe der Holzpartikel auf die Eigenschaften der Verbundplatten

wood particle size	density (g/cm^3)	moisture content (%)	thickness swelling rate (%)	water absorption rate (%)	normal condition bending strength (N/mm^2)		bending strength in wet condition (N/mm^2)	
					MOR	MOE	MOR	MOE
L	0.80^{d}	1.5^{a}	4.7^{b}	$8.7^{a,b}$	18.0^{a}	1934^{a}	13.3^{a}	1239^{a}
S	$0.82^{c,d}$	1.7^{a}	4.6^{b}	9.5^{b}	14.3^{b}	1532^{c}	$10.8^{b,c}$	986^{b}
T	$0.83^{b,c}$	1.4^{a}	$4.4^{a,b}$	$9.1^{a,b}$	$12.9^{b,c}$	1421^{c}	$9.7^{c,d}$	943^{b}
F	0.87^{a}	1.9^{a}	3.6^{a}	7.7^{a}	12.6^{c}	1467^{c}	8.6^{d}	898^{b}
N	0.84^{b}	1.5^{a}	$4.4^{a,b}$	$8.8^{a,b}$	14.4^{b}	1694^{b}	11.8^{b}	1160^{a}

1) significance level $\alpha = 0.05$ **2)** particle sizes L,S,T,F,N as indicated in Table 1.

plastic content has most relative effect on thickness swelling of the composite ($r = 0.867$); and it has the least relative effect on MOE under normal condition ($r = 0.288$).

3.3 Properties of veneer overlaid composites

Most of the surface veneer overlaid peeling strength of RF-bonded composites is better than MF-bonded composites, except for composites with a mixing ratio of 50:50. In the four groups using RF as adhesive, composites with a mixing ratio of 60:40 have the strongest surface veneer overlaid peeling strength ($1.6\ N/mm^2$), and the mixing ratio of 75:25 has the weakest surface veneer overlaid peeling strength ($0.9\ N/mm^2$). Besides, the wood failure rate of the sample for surface veneer overlaid peeling strength test increases along with higher wood particle content. The reason for the higher wood failure rate in the composite with higher wood particle content is that there are more wood particles in the composite which attach to the veneer. But this doesn't mean higher surface veneer overlaid peeling strength. In the composite with high wood particle content the wrapping ability of plastic material around wood particles is smaller than the adhesive strength between the wood particles and the veneer; therefore, the failure happened in the composite (the combining layer of wood particle and plastic) when conducting the test. After analyzing the result by using Duncan's New Multiple Range Analysis, it showed that the composites with a mixing ratio of 60:40 have strongest surface veneer overlaid peeling strength. When using MF as adhesive for veneer overlaid, the composites with a mixing ratio of 70:30 and 75:25 have the weakest surface veneer overlaid peeling strength. There is no significant difference of surface peeling strength in other testing groups.

Table 4 The relationship between plastic content and composite properties
Tabelle 4 Beziehung zwischen Kunststoffanteil und verschiedenen Eigenschaften der Verbundplatten

items	regression equations	correlation coefficient (r)
density	$Y = 0.001917X + 0.762$	0.326
moisture content	$Y = 0.03094X - 2.669$	0.442
thickness swelling rate	$Y = 0.186X - 11.091$	0.867
water absorption rate	$Y = 0.328X - 20.703$	0.833
normal condition MOR	$Y = 3.085X + 33.2$	0.619
normal condition MOE	$Y = 130.423X + 11371$	0.288
wet condition MOR	$Y = 3.15X + 5.96$	0.725
wet condition MOE	$Y = 186.302X + 3681$	0.597

Significance level $\alpha = 0.05$; X: plastic content, Y: composite properties, r: correlation coefficient

4 Conclusions

1. By using the manufacturing method of mixing mats and flat presses as particleboard production, wood particle-plastic composite with high wood particle content can be prepared. The strength properties and dimension stability of this composite is higher than that of commercial particleboard.
2. Wood particle size has a positive effect on the bending strength of composite. The bending strength of composite increases with the use of larger sized particles. On the other hand, larger sized wood particles decrease the composite density.
3. Plastic content decreases moisture content, thickness-swelling and water absorption of composite. It has also a positive effect on density and bending strength.
4. After the boiling water soaking process, the strength retention of composite in wet condition increases with higher plastic content, and all of the strength retention of composite showed at least 52.2%. This indicates good weather resistance of the composite.
5. After analyzing manufacturing time, strength properties and veneer overlaid properties, it can be concluded that the composite with a mixing ratio of 70:30 (wood particle 70%, HDPE 30%) has a faster producing speed.

Acknowledgement This project was sponsored by the National Science Council, Taiwan (Grant number NSC 91-2313-B-005-141)

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