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Selected properties of particleboard panels manufactured from rice straws of different geometries

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ABSTRACT

The objective is to evaluate the primary mechanical and physical properties of particleboard made from hammer-milled rice straw particles of six different categories and two types of resins. The results show the performance of straw particleboards is highly dependent upon the straw particle size controlled by the opening size of the perforated plate inside the hammer-mill. The static bending and internal bonding strength of polymeric diphenylmethane diisocyanate (pMDI) resin-bonded boards initially increase then decrease with decreased particle size. The thickness swelling, water absorption, and linear expansion of particleboards decrease with increasing particle size. Compared with pMDI resin-bonded panels, the rice straw particleboard bonded using urea-formaldehyde resin exhibits much poorer performance. The optimized panel properties, obtained when using 4% pMDI and straw particles hammer milled with a 3.18 mm opening perforated plate, exceeded the M-2 specification of American National Standard for Wood Particleboard.

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1. Introduction

Rice is the primary food for more than 40%of the world's population, with about 596 million tons of rice and 570 million tons of rice straw produced annually in the world (Pathak et al., 2006; Mohdy et al., 2009). At present, most of these residues are burnt in situ after harvest. The field burning of rice straw and other agriculture residues in wide areas not only results in serious environment issues, but also wastes precious resources. Faced with worldwide shortages of forest resources, environmental pollution and waste of biological resources resulting from field burning of rice straw and other agriculture residues, there has recently been a revival of interest in using rice straw and other agriculture residues to produce building materials including composite panels (Zheng et al., 2007; Ye et al., 2007; Copur et al., 2008).

The properties of rice straw and other agro-residue fibers were reviewed by Rials and Wolcott (1997). Boquillon et al. (2004) found that the properties of wheat straw particleboards using urea-formaldehyde (UF) resins were poor, especially for internal bonding (IB) strength and thickness swelling (TS). Research conducted by Mobarak et al. (1982) showed that bending strength up to 130 N/mm^2 and water absorption as low as 10% could be obtained for bagasse panels produced at 25.5 MPa pressing pressure and 175 °C. Increasing the initial moisture content of pith from 7%to 14%resulted in deterioration of both strength and water resistance. Grigorious (1998) reported that straw was suitable for the production of good quality surface layers for particleboard if bonded with polymeric diphenylmethane diisocyanate (pMDI) resin or a combination of UF and pMDI. Yang et al. (2003) developed a sound absorbing composite from rice straw and wood particles, and confirmed that rice straw could partially substitute for wood particles up to 20%by weight without reducing the bending strength. Han et al. (1999, 2001) investigated the effect of silane coupling agent level and ethanol–benzene treatment on board properties and found that physical properties for both reed and wheat boards were improved. They also reported that bonding performance of UF resin-bonded reed and wheat straw fiberboards could be improved if the fiber was pre-treated under different steam cooking conditions in the refining process. All properties of medium-density fiberboard (MDF) made from the treated reed and wheat straws, except the thickness swelling, could meet Japanese Industrial Standard for Fiberboard (JIS A5905, 1994). In addition to the steam treatment, enzyme pretreatment of wheat straw was also an effective way to improve the bonding performance (Zhang et al., 2003). To reduce the manufacturing cost, some alternative resin systems were used to make biomass based composite panels. Soy protein isolate modified by 10% pMDI was used to make low density straw-protein particleboard and excellent compression

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and tensile strengths were observed (Mo et al., 2001). Interest in using rice straw mixed with low quality bamboo or other bio-based residues to produce composite panels has increased recently (Hiziroglu et al., 2008; Lee et al., 2006).

Some researchers have succeeded in developing substitutes for wood particles using agriculture residues including rice straw, but producing rice straw boards with performance rivaling wood-based boards at lower production cost utilizing a simpler process is still the main challenge to be addressed on a global scale. Compared with wooden material, rice straw contains a high amount of ash and silica (Pan et al., 1999; Pan and Sano, 2000; Hammerr et al., 2001). which results in weak bonding between particles and very low internal bonding strength within panels. Moreover, rice straw stems are hollow and tubular structures. When the straw is cut into small particles, some of the particles cannot be split and they maintain a tubular shape, which prevents the resin from reaching internal surfaces of the straw. In order to have favorable internal bonding strength within rice straw particleboard, it is crucial that most of the straw be split to allow uniform resin distribution on both inner and outer straw surfaces. A hammer mill, which is a typical tool for manufacturing wood-based particleboard panels, was found in our previous trial to be effective at breaking down the rice straw. The opening size of perforated metal plates in the hammer mill to control the geometry of straw particles was closely related to the percentage of split rice straws. The main objective of this project is to explore the technical feasibility of manufacturing composite panels from hammer-milled rice straw particles, and to evaluate some mechanical and physical properties of particleboard as affected by various particle sizes and adhesive types.

2. Methods

Rice straw was obtained from California, United States. Its variety number was Calrose M-206. It was approximately 1 m tall at harvest and cut above the water line leaving the lower third as stubble in the field. This rice was also harvested with a conventional straw walker combine rather than a rotary, which optimizes straw quality by retaining much longer sections of stalks for bailing. The average moisture content of the straw was about 8.1%. After received, the rice straw was broken down into different sizes using a hammer mill. Six different perforated metal plates with opening size of 25.40 mm (1 in.), 19.05 mm (3/4 in.), 12.70 mm (1/2 in.), 6.35 mm (1/4 in.), 3.18 mm (1/8 in.) and 1.59 mm (1/16 in.) were used for processing the rice straw. Screen analysis was also conducted on each particle type using six different sieves.

After hammer milling, a fair amount of rice granules (about 1.4% of total weight) were noticed which were later removed from rice straw particles by the winnowing method. Ten grams rice straw particles from each opening size were randomly chosen and un-split straw particles were visually identified and separated to estimate the percentage of un-split straw particles. The particles for the fabrication of UF-bonded panels were oven-dried at 100 °C to 2–3% moisture content and the particles for the fabrication of pMDI-bonded panel were kept at their previous moisture contents (7.0–9.0%) prior to the resin applications.

The commercial pMDI and UF resins used in this study were acquired from Huntsman International (286 Mantua Grove Rd., West Deptford, NJ, USA) and Arclin Corporation (281 Wallace Road, North Bay. Ontario, Canada), respectively. The UF resin was water dispersed with a solid content of 65%. The resins were sprayed onto the rice straw particles in a rotating drum blender. A resin content of 4% (oven-dried weight basis) was used for pMDI-bonded boards, and 12% or 16% were used for UF-bonded boards. A 91.4-by 91.4-cm Nordberg hot press with a PressMAN Press Control system (Alberta Research Center, Alberta, Canada) was used to manufacture the boards and the platen temperature was 180 °C for manufacturing pMDI-bonded boards and 170 °C for UF-bonded boards. The dimension of the boards made in this study was 559 by 559 mm (22 by 22 in.) with thickness of 12.5 mm (0.5 in.). The target density was 0.70 g/cm^3. Longer hot press time was used to ensure the full cure of resin with 350 s (40 s closing, 260 s at the target thickness, and 50 s opening) for pMDI resin and 510 s (100 s closing, 320 s at the target thickness, and 90 s opening) for UF resin. Two replicate boards were made at each condition.

The modulus of elasticity (MOE). modulus of rupture (MOR), linear expansion (LE), TS, water absorption (WA) and IB of the samples were prepared and tested in accordance with American standard test methods for evaluating properties of wood base fiber and particle panel material (ASTM D 1037-06a). Each measurement presented herein is the average for six samples cut from two different boards. Static bending and IB values were measured using an MTS (Material Testing System 634.11F-24) and universal testing machine (Instron 555). The TS and WA were measured after 24-h immersion in distilled water at 20 °C.

3. Results and discussion

Six different perforated metal plates were used for processing rice straw with opening sizes of 25.40mm (1 in.), 19.05 mm (3/4 in.). 12.70 mm (1/2 in.), 6.35 mm (1/4 in.), 3.18 mm (1/8 in.) or 1.59 mm (1/16 in.). Basically. six categories of rice straw particles using the six different perforated metal plates in the hammer mill were prepared in this study. The distribution of particle size of the six types of rice straws varied considerably. Table 1 summarizes the distribution of particle size based on mesh analysis. The largest mass fraction remained on 3, 3, 16, 20, 35 and 35 mesh sizes when the opening size in the perforated metal plates was 25.40, 19.05 12.70, 6.35, 3.18 and 1.59 mm. respectively. With the decrease of the perforated metal opening size. the mass ratio of particles which passed through a sieve of larger dimension decreased, and that of particles which passed through a sieve of smaller dimension increased. The un-split hollow stems appeared considerably when the dimension of the opening size was greater than 6.35 mm. The percentages of un-split straw particles were 1.3%. 4.4%. 9.7% and 17.4% when the opening size were 6.35, 12.70, 19.02 and 25.40 mm. respectively. The presence of un-split straw particles in the mat significantly decreases the IB strength of boards and increases the variability because of the lack of resin distribution to the internal surfaces of un-split particles. It is also observed that when the opening size of the perforated metal plates inside the hammer mill is less than 3.18 mm. the rice straw particles can be thoroughly split in the hammer mill and effect of the un-split particles on the bonding strength is negligible (Fig. 1).

It was well known that board density is one of the important factors that affect mechanical properties of particleboard. In our

Table 1
Distribution of particle prepared with different sieve opening size bared on mesh analysis.

Mesh size	Mass ratio (%)					
	D = 25.40	D = 19.05	D = 12.70	D = 6.35	D = 3.18	D = 1.59
13	33.33	23.15	2.14	0.00	0.00	0.00
3–9	9.43	12.97	20.53	1.38	0.00	0.00
9–16	11.55	16.35	23.62	17.20	1.62	0.00
16–20	13.57	16.90	18.87	28.57	20.65	2.96
20–35	15.87	15.69	17.87	26.18	34.63	43.15
35–60	9.99	8.48	10.03	14.27	23.26	30.06
>60	6.26	6.46	6.94	12.39	19.84	23.83

D denotes the diameter of sieve opening in perforated metal plate, mm
Distribution is expressed as percentages bared on the total weight.

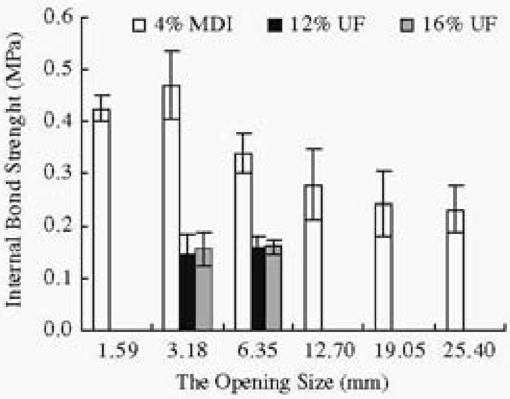

Fig. 1. Effects of particle size and resin type on IB strength of rice straw particleboard.

study, all boards were produced with a target density of 0.70 g/ cm^3. The results showed that the range of measured densities among the boards was between 0.67 and 0.75 g/cm^3 with the coefficient of variance being only 5.86%. The density variation among the boards was small and its influence on mechanical properties of particleboard was not taken into consideration in this study.

Particle size, which is classified by the opening size in perforated metal plates in this study, is a very important factor affecting the IB strength of rice straw particleboard panels. The delamination or separation in the middle of UF-bonded boards occurred because of excessively low IB strength when rice straw particles were prepared using an opening size greater than 12.70 mm. That was also the reason why the UF resin-bonded boards were fabricated using only two particle sizes (opening size 6.35 and 3.18 mm) in our study.

Fig. 1 shows the effect of particle size (or opening size) on IB strength of rice straw particleboard made by using 4% pMDI, 12% UF, and 16% UF resin. It appears that for pMDI resin-bonded boards, the IB strength initially increases from 0.23 to 0.47 MPa and then decreases to 0.42 MPa when the opening size changes from 25.40 to 1.59 mm. The IB strength reached the maximum value when the opening size was 3.18 mm. Generally, particleboard made from larger particles showed better mechanical properties (Viswanathan et al., 2000; Yang et al., 2003). However, the results in our experiment indicate that IB can be increased by decreasing the particle size (or opening size) when the opening size is greater than 3.18 mm. This was also observed in previous studies using wood flakeboard and wheat straw particleboard (Boquillon et al., 2004; Miyamoto et al., 2002). As rice straw particles decrease in size, the new surfaces that do not contain outer surfaces emerge and thus the proportion of outer surface relative to overall particle surface is reduced. The increase of IB could be mainly due to the increased new surfaces that do not contain wax or inorganic substance so that stronger bonding between particles may occur. In addition, a decrease of particle size leads to less un-split rice straw particles in the mat. As a consequence, IB strength can also be improved. However, the IB strength of boards decreases when the opening size is below 3.18 mm. This may be caused by the over-sized specific surface with less resin per unit area of the smaller particle. Moreover, when the opening size is below 3.18 mm, the rice straw stem can be fully split leaving few un-split particles. Hence, the IB could not be further improved by decreasing un-split particles. The minimum internal bonding strength required by the ANSI A208.l Standard for medium density Wood Particleboard is 0.31 MPa (Table 2). When the opening size is 1.59, 3.18 and 6.35 mm, the IB strength of particleboard with 4% pMDI resin content can meet the American National Standard for Wood Particleboard for class M-2, M-2 and M-0, respectively. When the opening size is beyond 6.35 mm, the particleboards do not meet the minimal requirements for IB strength.

The effect of particle size on MOE and MOR of rice straw particleboard is shown in Figs. 2 and 3. MOE initially increases from 2673 to 2911 MPa and then decreases to 1548 MPa. While, MOR first increases from 20.67 to 22.19 MPa and then decreases to 8.61 MPa with decrease in opening size while reaching the maximum value when the opening size was 19.05 mm. When the opening size changes from 19.05 to 1.59 mm, the decrease of MOE and MOR is probably due to the decrease of the fiber form factor

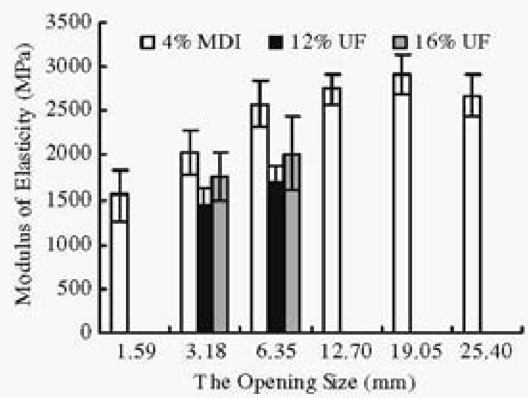

Fig. 2. Effects of particle size and resin type on MOE of rice straw particleboards.

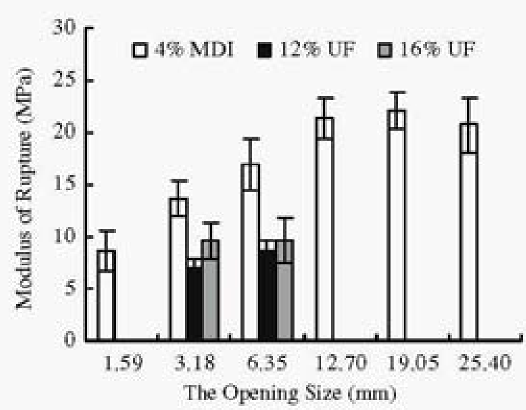

Fig. 3. Effects of particle size and resin type on MOR of rice straw particleboards.

Table 2
The IB, MOE, MOR and IE valuer required to meet ANSI208.1.

Class	Internal bond (MPa)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)	Linear expansion (%)
M-0	0.31	1380	7.6	NS
M-1	0.36	1550	10.0	0.40
M-S	0.36	1700	11.0	0.40
M-2	0.40	2000	13.0	0.40
M-3	0.50	2500	15.0	0.40

(length/diameter ratio). Other studies of natural fiber-reinforced composites have shown that the MOR and MOE are widely influenced by the fiber form factor (Boquillon et al., 2004). When the opening size increases form 19.05 to 24.05 mm, the proportion of un-split particles in the mat increases and the contact area between the resin and the straw particle decreases which leads to the decrease of MOE and MOR. Moreover, the decrease in new surfaces that do not contain wax or inorganic substances is also the important factor to decrease static bending. When the opening size are 1.59, 3.18, 6.35, 12.70, 19.05 and 25.04 mm, the MOE and MOR of particleboard with 4% pMDI resin content meets the ANSI Standard A208.l-2009 for Wood Particleboard of class M-0, M-2, M-3, M-3, M-3 and M-3 (Table 2). respectively. The *F*-test statistical analysis revealed that the effect of particle size (or the opening size) on mechanical properties including IB, MOE and MOR was significant at the 95% confidence level. In addition, the two tailed pair-wise t-test was used to investigate whether there are any significant differences among different straw particle sizes. The result shown in Table 3 confirms the observation made from previous *F*-test.

Rice straw particleboard bonded using UF resin (content of 12% and 16%) exhibited much poorer mechanical properties, especially IB strength, than particleboard bonded using pMDI resin (content of 4%). It has been well known that conventional water-based wood adhesives such as UF could not effectively wet the straw surface due to the hydrophobic wax and inorganic silica on the outer surface of the straw. In addition, the curing of pH-sensitive UF resin was inhibited by the high pH and buffer capacity of the rice straw. However, pMDI. could effectively wet the outer surface of rice straw and enhance chemical bonding through hydrogen bonds and polyurethane covalent bonds. In addition, the isocyanate groups of pMDI could react with water in the straw generating cross-linked polyureas for better mechanical bonding (Chelak and Newman. 1991; Mo et al., 2003). All UF resin-bonded boards, except those made with a resin content of 12% and particles prepared with opening size of 3.18 mm, exceeded the minimal requirements for MOE and MOR, but the IB strength for all UF resin-bonded boards was far from the minimal requirements even when the UF resin content was raised to 16%. These results clearly indicate very poor compatibility between rice straws and UF resin. This leads us to doubt if UF-bonded rice straw particleboards can be made to meet required standards without developing modified UF resins, additives or fiber-pretreatment process to increase the compatibility of UF resin and the rice straw.

LE and TS are key parameters in describing dimensional stability of wood composites. Particularly, LE is considered as the control factor in qualifying the behavior of wood panels exposed to moisture (Cai et al., 2004). The influence of rice straw particle size on the dimensional stability (including in LE, TS and WA) of particleboards was examined in this study. The results presented in Figs. 4–6 show the decrease in LE, TS and WA of particleboard with increasing particle size or opening size. For the pMDI resin-bonded panel, LE decreases from 0.36% to 0.16%. TS from 22.62% to 10.98%. and WA from 62.70% to 31.56% when the opening size changes from 1.59 to 25.40 mm. The reason for these decreases is probably due to the lessening of specific surface of the particles with the increase of the particle size resulting in less water or moisture absorption. The same result was observed in studies where the effect of particle shape on LE of particleboard was studied (Miyamoto et al., 2002). The *F*-test statistical analysis among multiple mean values and two tailed pair-wise *t*-test (Table 3) showed the particle size (or opening size) had a positive effect on the dimensional stability of particleboards at a significance level of 95%. In our

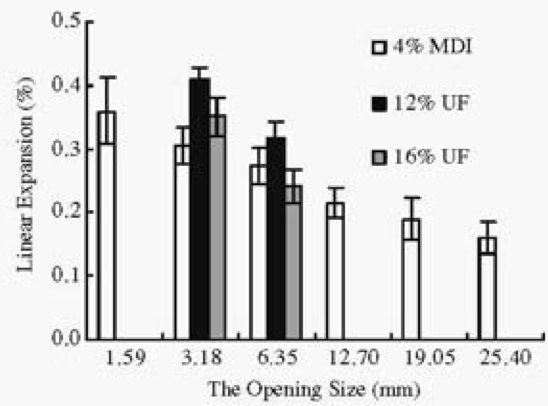

Fig. 4. Effects of particle size and resin type on LE of rice straw particleboards.

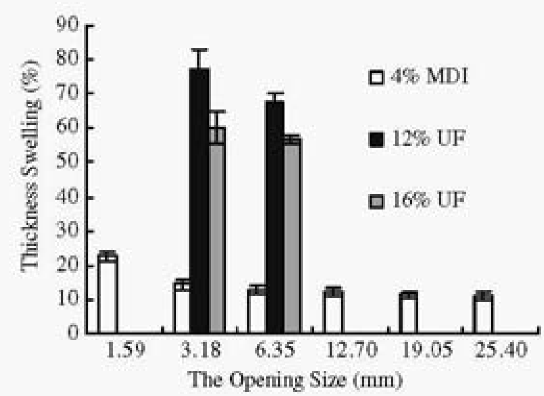

Fig. 5. Effects of particle size and resin type on TS of rice straw particleboards.

Table 3
The two tailed pair-wise *t*-test statistical results of IB, MOE and MOR, LE, TS and WA valuer of pMDI bonded panels among different opening size levels.

Opening size (mm)	Opening size (mm)					
	1.59	3.18	6.35	12.70	19.05	25.40
1.59	–	NYYYYY	YYYYYY	YYYYYY	YYYYYY	YYYYYY
3.18		–	YYYYYN	YYYYYY	YYYYYY	YYYYYY
6.35			–	YYYYNY	YYYYYY	YNYYYY
12.70				–	YNNNNN	YNNYYN
19.05					–	NYYNNN
25.04						–

The *t*-test results among different opening levels are shown in the sequential order of IB, MOE, MOR, LE, TS and WA values of pMDI bonded panels. Y indicates the significant while N represents insignificant difference at the 95% confident level. For example, in order to find the *t*-test results for MOR of panels fabricated using two different particle geometries (6.35 and 19.05 mm opening size). The intercept cell (highlighted in gray) of the row of 6.35 mm and the column of 19.05 mm should be located first in the table and then the third letter (MOR is the third in the sequential order, highlighted in white) need to be indentified. The third letter is Y which indicates that the difference of MOR mean values between the two different opening sizes is significant at the 95% confidence level.

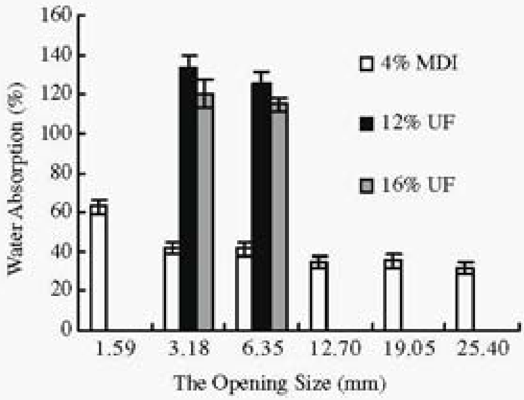

Fig. 6. Effects of particle size and resin type on WA of rice straw particleboards

experiment, the LE for all pMDI resin-bonded panel can meet the ANSI Standard for Wood Particleboard (Table 2).

As shown in Fig. 4 and 5, the dimensional stability of particleboards bonded using UF resin is much poorer than that of particleboards bonded using pMDI resin. Values for TS and WA were particularly high mainly due to decreased IB strength within UF resin-bonded boards. As mentioned in the previous section, UF resin could not effectively wet and penetrate the rice straw surface due to the hydrophobic wax and inorganic silica on the outer surface of rice straw, Morover, the rate of resin penetration into straw was observed to be several orders of magnitude slower than penetration into wood (Boquillon et al., 2004). However, pMDI resin could effectively wet the outer surface of rice straw particle and form better mechanical bonding, which resulted in improved mechanical and dimensional stability properties of pMDI resin-bonded particleboard compared with UF resin-bonded panel.

The LE of UF resin-bonded boards made with resin contents of 12% and 16%, with the exception of those made with 12% resin and a particle size of 3.18 mm, can generally meet the requirement of the ANSI Standard. Here, it must be stressed that no wax was used in the manufacturing of the particleboards. The addition of wax could reduce LE, TS and WA, and improve the dimensional stability of particleboards substantially.

4. Conclusions

The results show the performance of straw particleboards is highly dependent upon the straw particle size. The static bending and internal bonding strength of pMDI resin-bonded boards initially increases then decreases with decreased particle size. The LE, TS and WA of particleboards decrease with increasing particle size. Compared with pMDI resin-bonded panels, UF resin-bonded particleboard exhibits much poorer performance due to the poor compatibility between rice straw and UF resin. The best panel properties obtained in this study can meet class M-2 requirement in ANSI Standard for Wood Particleboard.

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