Enhancing the properties of damar (*Agathis loranthifolia Salisb.*) wood by making hybrid bamboo-wood composite

D R Trisatya¹, M Iqbal², and I M Sulastiningsih¹*

¹Center for Standardization of Sustainable Forest Management Instruments, Jl. Gunung Batu No. 5, Bogor, Indonesia
²Center for Standardization of Disaster and Climate Change Instruments, Jl. Gunung Batu No. 5 Bogor, Indonesia

*E-mail: ignasiasulastin@gmail.com

Abstract. This study was carried out to investigate the characteristics of laminated bamboo and damar (*Agathis loranthifolia Salisb.*) wood as the core layer of the bamboo-damar hybrid composite beam. Andong bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja) and mayan bamboo (*Gigantochloa robusta* Kurz.) were used as the face and back layers of the beam, glued with isocyanate adhesive. Four types of composite beam were produced with various number of laminated bamboo layers. Results showed that the four layers (two layers for each face and back sides) laminated andong bamboo performed superior mechanical properties than others hybrid composite beam, while the four layers (two layers for each face and back sides) laminated mayan bamboo demonstrated the highest compression and bonding strength. The density, MOR, MOE and compression strength of the hybrid composite beam improved 31.3%, 25.95%, 37.81% and 25.12%, respectively, as the outcomes of the incorporation of laminated andong bamboo on the outer layers of the damar board. This paper proves that the number of laminated bamboo layers enhances the properties of the bamboo-damar hybrid composite beam. Furthermore, it shows promising result for complementing furniture and interior design materials as the bamboo-damar hybrid composite beam has remarkable properties.

1. Introduction

Log and plywood production in Indonesia 2019 escalated for 4.34% and 3.70%, respectively, compared to 2018 [1,2]. More than 85% of the log production sourced from the Industrial Timber Estate [2]. Fast growing trees are a subject of rising interest of researchers for satisfying the high demand of wood material in Indonesia. Damar (*Agathis loranthifolia Salisb.*) is one of fast grown wood species that has a remarkable production flow in 2019 (30,844.35 m³) in comparison to 2018 (11,165.29 m³) [1,2]. It is lightweight softwood and widely used for paneling, moulding, packaging, furniture, and construction under cover and decorative plywood paneling [3]. Nevertheless, damar has inferior mechanical and durability properties (strength class III, durability class IV) due to its low specific gravity (0.44) [4]. To defeat the drawbacks of this fast grown wood species, many efforts were made to improve the properties of damar, including the manufactured of composite products such as particleboard, plywood, glue laminated lumber, plyboard [5-10]. The use of material with excellent properties was clearly viable to improve the performance of fast grown species composite products. Bamboo has a potential to substitute wood material due to its remarkable mechanical properties.
properties, renewability characteristics, and economical consideration [11,12]. The development of composite products using bamboo as a reinforced material has been emerging in China, Malaysia, Indonesia, and other countries [13-20].

Hybrid wood-bamboo composite is one of the engineered materials that utilize the advantages of bamboo to provide greater performance of the inherent variability of original raw materials [21,22]. A wide range of studies have been conducted in manufacturing hybrid composite using laminated bamboo and veneer or solid wood plank [13,15,16,18-21]. They utilized jabon (Anthocephalus cadamba Miq.), manit (Maesopsis eminii Engl.), sengon (Paraserianthes falcataria (L.) Nielsen), tusam (Pinus merkusii Jungh.), poplar (Populus ussuriensis Kom.), acacia (Acacia mangium Willd.) and reinforced with the following bamboos: andong (Gigantochloa pseudorundinacea (Steud.) Widjaja), apus (Gigantochloa robusta Kurz.), mayan (Gigantochloa atrovio lacea Widjaja), cizhu (Neosinocalamus affinis Keng) and moso (Phyllostachys edulis (Carr.) J. Houz). The findings revealed that the hybrid-bamboo composite is a promising material for substituting wood. In this study, an attempt is made to hybrid andong and mayan bamboo with damar wood. The physical and mechanical properties of bamboo-damar hybrid composite beam as opposed to damar solid wood were investigated.

2. Materials and Methods

2.1. Materials

Damar (Agathis loranthifolia Salish.), age 5-years and andong bamboo (Gigantochloa pseudorundinacea (Steud.) Widjaja), mayan bamboo (Gigantochloa robusta Kurz.), age 4 years were collected from Sukabumi, West Java Province, Indonesia. The chemical used in this study was a commercial Water Based Polymer Isocyanate (WBPI) as adhesive and boron solution as preservative.

2.2. Methods

2.2.1. Preparation of board. Damar log was converted into board with the targeted thickness of 3.5, 4.5, and 5.5 cm. The boards were air-dried to reach 15% moisture content and then they were split to 15 cm width. Then, the boards were planned and sanded to attain 3, 4, and 5 cm thickness. Depending on the board thickness, they were immersed for about 24-48 hours in boron solutions with concentration of 7% to targeted retention of 6 kgm⁻³. The preserved boards were then sun dried and kiln dried for 4 days to attain 12% moisture content.

2.2.2. Preparation of bamboo strips. Andong and mayan bamboo culms were cut at 50 cm from the lower growth height in order to achieve a regular shape. The 1.25 m long culms were split into 2.5 cm wide strips. Afterwards, the outer and inner skin of the strips were scrapped out and planned to attain the targeted thickness of 5 mm. Similar to the preservation of the board, the strips were then soaked for 2 hours in 7% boron solutions with the targeted retention of 6 kgm⁻³. Afterwards, the strips were then air dried for one day and continued with sun dried until 25% moisture content and then kiln dried for 4 days to reach the 12% moisture content.

2.2.3. Production of bamboo sheets. The dimension of bamboo sheets was 120 cm (length) x 14 cm (width) x 0.5 cm (thickness). They were produced by adhering side by side six andong or mayan bamboo strips. Isocyanate (WBPI) glue was applied to manufacture the laminated specimens with the glue spread of 250 gm⁻². A wooden clamp was used to press the specimens for one hour.

2.2.4. Production of hybrid composite beam. Hybrid Composite Beams (HCBs) were produced from damar wood as the core layer of the beam with four different face and back layers compositions, as presented in Table 1. A 5 cm thick damar board was also prepared for the control. The dimension of the HCBs was 120 cm (length) x 14 cm (width) x 5 cm (thickness). They were manufactured by assembling the bamboo sheets and wood planks in symmetric structure with the grain in parallel direction. The WBPI adhesive with the glue spread rate of 250 gm⁻² and cold pressed for one hour in a wooden clamp were applied. Three replications were prepared for each layer compositions. The HCBs were then conditioned for two weeks prior to testing.
2.2.5. Testing. The HCBs were trimmed and cut to desire specimen dimensions for testing their physical and mechanical properties. The tests were carried out in accordance with the Japanese Agricultural Standard for Glued Laminated Timber JAS 234:2003 [23], while the test for compression strength was performed using the ASTM D 143-94 [24]. Three replications were set for each treatment, with the layers compositions as the treatment factor.

2.2.6. Data analysis. All the results of laboratory tests for physical and mechanical properties were analyzed by using Minitab 17 software. Analysis of variance and the Tukey’s Honest Significance Difference test were applied to determine significant differences among treatments.

3. Results and Discussion

3.1. Physical properties of bamboo-damar hybrid composite beam

3.1.1. Moisture content. The mean values of moisture content and density are presented in Table 2. The value of moisture content was ranged from 11 to 11.15% and no significant difference was observed (p>0.05). The moisture content values in this study met the accepted air dried moisture content for glued laminated timber in Japanese Standard [23] and the Indonesian Standard for wood based panel such as plywood [25] and particleboard [26]. The average moisture content of the beam in this study was relatively similar to the previous study on jabon-bamboo laminated board [18]. The incorporation of two layer of laminated andong bamboo in the previous study had the lowest moisture content value (10.8%), compared to others [18]. Comparatively, the combination of one layer of laminated andong bamboo and one layer of laminated mayan bamboo in this study had the highest moisture content value. Another study showed that layer compositions significantly affected the moisture content value of bamboo composite lumber [19]. The lowest moisture content (12.2%) was recorded for composite lumber with Antocephalus cadamba Miq plank as the core layer [19].

3.1.2. Density. As presented in Table 1, the minimum and maximum density of the composite beam produced in this study was 0.471 gcm$^{-3}$ and 0.604 gcm$^{-3}$, while the density of damar wood was 0.416 gcm$^{-3}$. The density of damar wood in other study was 0.46 gcm$^{-3}$ [10]. The average specific gravity of damar wood reported by [27] were 0.48 for Agathis alba Foxworthy, 0.47 for A. borneensis Warb. and A. labillardieri Warb, respectively. The internodes and parts with nodes specific gravity of andong bamboo is 0.5-0.7 and 0.6-0.8, respectively, while the specific gravity of mayan bamboo ranges from 0.38 to 0.62 [28] and 0.73 [29].

This study demonstrated that the incorporation of bamboo in the beam increased the density of the composite product, as it was found in the earlier studies [18,19]. The lumber with all bamboo strips (vertically and horizontally glued) had the highest density (0.754 gcm$^{-3}$) compared to the other compositions [19]. Similar to this, composite boards composed of bitung bamboo sheets and mayan bamboo sheets performed the highest density (0.89 gcm$^{-3}$) in comparison to andong bamboo sheets and composite boards with jabon and sengon as the core layer [16]. Moreover, it was found that the perpendicular to the grain orientation of the
composite board core layer slightly increase the density of bitung and mayan bamboo composite boards to 0.9 g/cm³ [16].

Bamboo laminated had the higher density compared to the density of raw bamboo. This is due to the application of adhesive and pressure in the lamination process [18,19]. The incorporation of two layers bamboo sheets in this study (AAD and MMD) increased the density of composite beam with the single layer bamboo sheet (Table 2). The ANOVA revealed that the layer compositions had highly significant influence on density.

### Table 2. Physical properties of bamboo-damar hybrid composite beam.

| Properties          | Layer compositions | ANOVA results |
|---------------------|--------------------|---------------|
|                     | D      | AD   | AAD  | MD   | MMD  |          |
| Moisture content, % | 11.0±  | 11.5± | 11.3± | 11.5± | 11.0± | 2.90**   |
|                     | (0.249) | (0.191) | (0.390) | (0.266) | (0.155) |          |
| Density, g/cm³      | 0.416± | 0.484± | 0.604± | 0.471± | 0.55±  | 275.19** |
|                     | (0.005) | (0.010) | (0.007) | (0.005) | (0.008) |          |

Remarks: D, AD, AAD, MD, MMD refer to Table 1. Values of moisture content and density are the means of three replicates. Values in parentheses indicate standard deviations. Values followed with the same letter within the same row are not significantly different.

** not significant at 95%; *** highly significant at 95%

### 3.2. Mechanical properties of bamboo-damar hybrid composite beam

#### 3.2.1. Modulus of rupture

The MOR values (574.7 kgcm²) and 709.3 kgcm² from series 0, 1 to 2 layers of andong bamboo. Likewise, the incorporation of mayan bamboo in the beam performed better properties than the solid damar. The solid damar, however, performed the lowest MOR value (524.6 kgcm²). This value was also inferior to the MOR values of densified damar boards (1562 kgcm²) [10]. The MOR values (574-709 kgcm²) of the hybrid composite beam in the current study were higher than the MOR values (41.29-60.25 MPa or 421-614 kgcm²) of glulam beam of pinus wood [30]. Colombian glued laminated bamboo (Guadua angustifolia Kunth.) fabricated using PVA adhesive had MOR value of 81.9 MPa or 835 kgcm² [31].

### Table 3. Mechanical properties of bamboo-damar hybrid composite beam.

| Properties          | Layer compositions | ANOVA Results |
|---------------------|--------------------|---------------|
|                     | D     | AD    | AAD  | MD   | MMD  |          |
| MOR, kg/cm²         | 524.6 | 574.1 | 709.3| 592.5| 691   | 8.55*    |
|                     | (2.94) | (42.5) | (63.2) | (55.8) | (45.0) |          |
| MOE, kg/cm²         | 71,660± | 97,371± | 115,227± | 97,262± | 111,490± | 22.80** |
|                     | (4296) | (5018) | (8244) | (2326) | (8700) |          |
| Compression strength, kg/cm² | 313± | 366.9± | 415.6± | 327.1± | 417.9± | 48.82** |
|                     | (8.65) | (15.7) | (9.03) | (15.88) | (8.43) |          |
| Bonding strength, kg/cm² | 57.34± | 58.13± | 64.94± | 67.52± | 67.52± | 3.50**   |
|                     | (1.285) | (1.210) | (2.13) | (8.89) |          |          |

Remarks: D, AD, AAD, MD, MMD refer to Table 1. MOR= modulus of rupture; MOE= modulus of elasticity. Values in parentheses indicate standard deviations. Values followed with the same letter within the same row are not significantly different.

** not significant at 95%; *significant at 95%; *** highly significant at 95%
A notable MOR values were also observed for the laminated lumber with vertically glued andong bamboo as the core layer (1162 kgcm\(^2\)); composite board with laminated andong bamboo glued parallel to the outer layers (1241 kgcm\(^2\)); and vertically glued laminated andong bamboo beam in parallel orientation (958.3 kgcm\(^2\)) [13,19,32]. For the addition of wood layer in the core of the board, it is worth noting that the values of MOR increased as the density of the wood species increased. This result proves the recent study who reported that the density of full-size wood composite panel have statistical significant influence on the MOR [33]. The MOR values of the hybrid composite beam in the current study had comparable values to wood strength class III (500-725 kgcm\(^2\)) [4].

3.2.2. Modulus of elasticity. As shown in Table 3, ANOVA revealed highly significant influence at p>0.05 for layer compositions. The integration of two layers bamboo sheets in the beam amplified the MOE values from 97,371 to 115,227 kgcm\(^2\) and from 97,262 to 111,490 kgcm\(^2\), respectively for andong and mayan damar hybrid composite beam. This trend was similar to what was previously reported by [18] for laminated bamboo board. The MOE values for two layers laminated mayan and andong bamboo boards were greater (107,196 and 111,545 kgcm\(^2\) than one layer laminated mayan and andong bamboo boards (82,070 and 79,956 kgcm\(^2\)) [18]. The integration of low density material tends to lessen the MOE values, as it can also be observed from [16]. Their study revealed that the integration of sengon as back layer in andong and mayan composite boards had highest MOE values (42,660 kgcm\(^2\) and 73,403 kgcm\(^2\), respectively) compared to the MOE values of andong and mayan composite boards with the integration of sengon and jabon as the core and back layers of the board. Other study found that the average MOE of LBL (laminated bamboo lumber), LVL (laminated veneer lumber) and PSL (parallel strand lumber) were 9.1 GPa or 92,794 kgcm\(^2\), 11 GPa or 112,169 kgcm\(^2\) and 11.6 GPa or 118,287 kgcm\(^2\), respectively [34].

3.2.3. Compression strength. Table 2 depicts the compression strength values of bamboo-damar hybrid composite beam, which varied from 366.9 kgcm\(^2\) to 417.9 kgcm\(^2\), while the compression strength of damar wood was 313 kgcm\(^2\). The compression strength values of the composite beam are in the range of wood strength class III (300-425 kgcm\(^2\)) of the Indonesian wood strength classification [4]. Moreover, the incorporation of the laminated bamboo improved the compression strength compared to the damar solid wood (wood strength class V). The ANOVA revealed that the compression strength of the composite beam was highly affected by layer compositions. The compression strength of damar wood (313 kgcm\(^2\)) in this study was greater than the compression strength of jabon wood (261.1 kgcm\(^2\)) [18], the composite beam that produced in this study had superior compression strength compared to the previous study [18]. The highest compression strength value of the jabon-laminated bamboo board was 357.3 kgcm\(^2\) with the incorporation of two layers laminated mayan sheet [18]. Similar to this, the incorporation of two layers of laminated mayan sheet resulted in the highest compression strength value (417.9 kgcm\(^2\)) of the composite beam.

Composite lumber in the earlier work [19] which studied two layers of laminated andong bamboo, two layers of andong zephyr and wood (jabon, manii or sengon) as the core layer had slightly less compression values (407 kgcm\(^2\), 397.7 kgcm\(^2\) and 364.6 kgcm\(^2\), respectively) compared to the current study that assembled two layers of laminated andong bamboo with damar wood as the core layer of the beam (415.6 kgcm\(^2\)). This might suggest that in spite of wood species, the form of bamboo determine the value of compression strength. Similarly, the vertically glued laminated andong bamboo beam that assembled in parallel orientation of the grain increased the exceptional compression strength values for 18%, 13% and 19%, consecutively for all bamboo layer, manii and sengon in comparison to the values of the beam with cross orientation core layer of the beam [13]. Colombian glued laminated bamboo (Guadua angustifolia Kunth.) fabricated using PVA adhesive had compression strength value of 47.6 MPa or 485 kgcm\(^2\) [31] which was greater than the values found in this study.

3.2.4. Bonding strength. Statistical analysis with 95% confidence interval showed that the layer compositions had not affected the bonding strength. It was recorded that the values varied from 57.34 to 67.52 kgcm\(^2\). All of the composite beams in the current study fulfilled the Japanese Agricultural Standard for Glued Laminated Timber [23]. A similar result has been reported by [18] who found that
the bonding strength values of jabon laminated bamboo board bonded with isocyanate adhesive ranged from 62.71 to 67.8 kg/cm². This is, however, contrary to [13] who found that there was a significant effect on the layer compositions to the bonding strength values. They found that the laminated bamboo beam with the parallel orientation of the core layer had 65-166% enhancement of bonding strength values in comparison to laminated bamboo beam with the perpendicular orientation of the core layer [13].

4. Conclusion
The presence of andong and mayan bamboo laminated sheets apparently had statistical significant influence on the beam’s characteristics. The performance of the properties improved with increasing number of bamboo laminated board layer. To conclude, the hybrid composite beam has superior physical and mechanical characteristics in contrast to solid damar wood thus shows promising result to substitute wood material.

References
[1] [BPS] Badan Pusat Statistik 2020 Statistik Produksi Kehutanan 2019 (Jakarta: Badan Pusat Statistik)
[2] [BPS] Badan Pusat Statistik 2020 Statistik Perusahaan Pembudidaya Tanaman Kehutanan 2019 (Jakarta: Badan Pusat Statistik)
[3] Soerianegara I and Lemmens R H M J 1994 Timber Trees: Major Commercial Timbers Plant Resources of South East Asia 5(1) p. 610
[4] Oey D S 1990 Specific Gravity of Indonesian Woods and its Significance for Practical Use (Bogor: Forest Products Research and Development Centre)
[5] Hadi Y S 1978 Some properties of particle wood made from Agathis loranthifolia Salisb; Albizia falcatoria (L.) Fosberg and Hevea brasiliensis Muell Arg. Woods Bulletin Berita Ikatan Alumni Fakultas Kehutanan IPB
[6] Sutigno P, Memed R, and Kliwon S 1980 The effect of assembly time and wood species on the bonding strength of plywood (Shorea leprosula; Dipterocarpus gracilis; Agathis loranthifolia; Pinus merkusii) Laporan Lembaga Penelitian Hasil Hutan No 146 Bogor
[7] Santoso A 1995 Pengaruh tebal venir dan berat labur perekat terhadap keteguhan rekat kayu lapis damar Jurnal Penelitian Hasil Hutan 13(7) 266-74
[8] Yanti N 1998 Pengaruh kombinasi sudut sambungan terhadap sifat mekanis balok laminasi kayu agatis (Agathis loranthifolia Salisb.) [Skripsi] Institut Pertanian Bogor
[9] Nugraha S 2000 Studi hubungan sifat kekakuan bahan dan kekuatan lentur balok laminasi kayu damar (Agathis loranthifolia Salisbs.) pada berbagai ketebalan lamina [Skripsi] Institut Pertanian Bogor
[10] Rilatupa J, Surjokusumo S, and Nandika D 2004 Keandalan papan lapis dari kayu damar (Agathis loranthifolia Salisbs.) terpadatkan sebagai pelat buhul pada arsitektur konstruksi atap kayu Jurnal Ilmu dan Teknologi Kayu Tropis 2(1) 51-6
[11] Khalil H A, Bhat I U H, Jawaid M, Zaidon A, Hermawan D, and Hadi Y S 2012 Bamboo fibre reinforced biocomposites: A review Mater. Des. 42 353-68
[12] Rassiah K, Ahmad M M H M, and Ali A 2014 Mechanical properties of laminated bamboo strips from Gigantochloa scortechiniiI polyester composites Mater. Des. 57 551-59
[13] Sulastiningsih I M, Santoso A, and Krisdianto 2016 Karakteristik balok bambu lamina susun tegak dari bilah bambu andong (Gigantochloa pseudoarundinacea) (Stud.) Widjaja Jurnal Penelitian Hasil Hutan 34(3) 167-77
[14] Chen Y, Zhu S, Guo Y, Liu S, Tu D, and Fan H 2016 Investigation on withdrawal resistance of screws in reconstituted bamboo lumber Wood Res. 61(5) 799-810
[15] Ibrahim M I, Abd Karim S R, Tuan Mohd Saipudin T A N, and Salleh A H 2016 Physical and mechanical properties of hybrid laminated bamboo-wood veneer board (HLBWVB) for furniture components Adv. Mater. Res. 1134 143-46
[16] Santoso A, Sulastiningsih I M, Pari G, and Jasni 2016 Pemanfaatan ekstrak kayu merbau untuk perekat produk laminasi bambu Jurnal Penelitian Hasil Hutan 34(2) 89-100
[17] Chen F, Deng J, Li X, Wang G, Smith L M, and Shi S Q 2017 Effect of laminated structure design on the mechanical properties of bamboo-wood hybrid laminated veneer lumber Eur. J. Wood Wood Prod. 75(3) 439-48
[18] Supriadi A, Sulastiningsih I M and Subyakto 2017 Karakteristik laminasi bambu pada papan jabon Jurnal Penelitian Hasil Hutan 35(4) 263-72
[19] Sulastiningsih I M, Damayanti R, Abdurachman, and Supriadi A 2018 Some properties of bamboo composite lumber made of Gigantochloa pseudoarundinacea J. Agric. Sci. Technol. B 8 122-30
[20] Galih N M, Yang S M, Yu S M, and Kang S G 2020 Study on the mechanical properties of tropical hybrid cross laminated timber using bamboo laminated board as core layer J. Korean Wood Sci. Technol. 48(2) 245-52
[21] Chen F, Wang G, Li X, Simth L M, and Shi S Q 2016 Laminated structure design of wood–bamboo hybrid laminated composite using finite element simulations J. Reinf. Plast. Compos. 35(22)1661-70
[22] Sun X, He M, and Li Z 2020 Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation Constr. Build. Mater. 249 118751
[23] [JAS] Japanese Agricultural Standard 2003 Glued Laminated Timber (JAS) 234:2003 (Japan: Ministry of Agriculture Forestry and Fisheries)
[24] [BSN] Badan Standardisasi Nasional 2016 Kayu Lapis Penggunaan Umum SNI 5008.2:2016 (Jakarta: Badan Standardisasi Nasional)
[25] [BSN] Badan Standardisasi Nasional 2006 Papan partikel (Particleboard) SNI 03-2105:2006 (Jakarta: Badan Standardisasi Nasional)
[26] Martawijaya A, Kartasujana I, Kadir K, and Prawira S A 2005 Atlas Kayu Indonesia Jilid I (Edisi Revisi) (Bogor: Pusat Penelitian dan Pengembangan Hasil Hutan)
[27] Dransfield S W E 1995 Plant Resources of South East Asia No 7: Bamboos Leiden: Backhuys Publishers
[28] Damayanti R, Jasni, Sulastingsih I M, ..., and Abdurahman 2019 Atlas Bambu Indonesia 1 (Bogor: IPB Press)
[29] Yoresta F S 2014 Studi eksperimental perilaku lentur balok glulam kayu pinus (Pinus merkusii) Jurnal Ilmu dan Teknologi Kayu Tropis 12(1) 33-8
[30] Correal J F and Lopez L F 2007 Mechanical properties of colombian glued laminated bamboo in Modern Bambo Structures (The First Conference on Modern Bamboo Structures) 2 121-7
[31] Sulastiningsih I M, Nurwati, and Santoso A 2005 Pengaruh lapisan kayu terhadap sifat bambu lamina Jurnal Penelitian Hasil Hutan 23(1) 15-22
[32] Guan C, Liu J, Zhang H, Wang X, and Zhou L 2019 Evaluation of modulus of elasticity and modulus of rupture of full-size wood composite panels supported on two nodal-lines using a vibration technique Constr. Build. Mater. 218 64-72
[33] Mahdavi M, Clouston P L, and Arwade S R 2011 Development of laminated bamboo lumber: Review of processing, performance and economical considerations J. Mater. Civ. Eng. 23(7) 1036-42