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Wood Plastic Composites

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1. Introduction

Plastic and wood wastes have been a main environmental concern. Plastic is the biggest problem due to its high amount of waste generated, non biodegradability and the fastest depletion of natural resources regarding its short life cycle, therefore increased amount of material utilized in its production, and waste generated. The same applies to wood with lesser degree where it is depleting trees and forests and the wastes mainly are either burned or disposed; resulting in extra consumption, depletion, and pollution of nature. Several worldwide attempts have been adopted; especially in the developed countries, to take advantage of these types of waste especially with the raised need for alternatives to virgin materials (Winandy, et al. 2004). Wood plastic composite (WPC) is a product which could be obtained from plastic and wood. WPC is a composite with a rapid growing usage consisting of a mixture of wood waste and polymeric material (Soury, et al. 2009). Many trials of obtaining a WPC product were basically built on the concept of a Cradle to Cradle approach where the material is recycled at the end of its life cycle to produce a Cradle (new) product and thus close the loop and imitate the natural ecosystem (McDonough and Braungart 2002) & (El-Haggar 2007). As a consequence, this minimizes the solid waste content and conserve the natural resources. Therefore, costs, energy, and depletion of virgin materials are reduced. In addition, it assures the sustainability over the incoming years for future generations' use (Youngquist, et al. 1992).

WPC has become currently an important address of research that gained popularity over the last decade especially with its properties and advantages that attracted researchers such as: high durability, Low maintenance, acceptable relative strength and stiffness, fewer prices relative to other competing materials, and the fact that it is a natural resource (Bengtsson and Oksman 2006) & (Winandy, et al. 2004). Other advantages have been strength points including (Wechsler and Hiziroglu 2007): the resistance in opposition to biological deterioration especially for outdoor applications where untreated timber products are not suitable, the high availability of fine particles of wood waste is a main point of attraction which guarantees sustainability, improved thermal and creep performance relative to unfilled plastics where It can be produced to obtain structural building applications including: profiles, sheathings, decking, roof tiles, and window trims.

On the other hand, WPCs are not nearly as stiff as solid wood; however, they are stiffer than unfilled plastics. In addition, they do not require special fasteners or design changes in application as they perform like conventional wood (Clemons and Caufield 2005).

As mentioned, the reasons for using WPC are many; however, there are other causes that enforced many countries to tend for using alternative sources to virgin materials. In the United States, for example, the U.S. Environmental Protection Agency, by the beginning of 2004, has phased out the usage of wood treated with chemicals such as the chromated copper arsenate (CCA) to prevent environmental and microbial degradation (Yeh and Gupta 2008). As this type of wood was used in the building products' market concerned with residential applications such as decking, the need for the alternative survived the WPC market (Yeh and Gupta 2008). In Europe, environmental concerns are focused on limiting the use of finite resources and the need to manage waste disposal; therefore, the tendency to recycle materials at the end of their useful life has increased tremendously (Yeh, et al. 2009). Recycling polymers in Europe was less preferred than other types of materials such as metal; however, illegality of land filling and waste management priority in many European countries were the motive to do so (Yeh, et al. 2009). In addition to the enforced environmental policies, the growth of environmental awareness led to a new orientation to use wasted natural materials for different applications and industries such as the automotive, packaging and construction industries (Yeh, et al. 2009).

2. Market potential

The awaiting market for WPC is huge due to the high production of plastics and wood which constitutes a significant amount of solid waste which is mostly disposed not recovered (Adhikary, et al. 2008). Najafi, et al. 2007, mentioned that WPC presents a promising raw material source for new value added products due to the large amount of daily waste generation and low cost (Najafi, et al. 2007). WPC commercial products are increasingly replacing many products in many applications especially the construction related ones (Yeh, et al. 2009). WPCs have gained an ever larger share; especially for decks and other outdoor structures (Youngquist, et al. 1992). Other production lines of fencing, roofing, and siding have started to get a noticeable market share (Winandy, et al. 2004). WPC usage is extensively spread especially in strips; where wood peel layers are tilted in the same direction, used in furniture industry (Augutis 2004). WPC is also used in producing panels where it is produced by mixing wood flour and plastics giving a material which can be processed similar to 100% plastic-based products (Wechsler and Hiziroglu 2007). Approximately one-half of all industrial materials used in the United States are wood-based; thus, the finding that the WPC market is increasing is not a surprise (Falk 1997). The growth of WPC decking in the U.S. has started from less than 1 % in mid-90's to over 10% today with growth projected by several studies to reach 20% before the end of 2010 (Winandy, et al. 2004). Two large sectors, the decking and fencing sector, the siding and roofing sector started to use the WPCs commercially in the U.S. (Winandy, et al. 2004). Concerning the decking and fencing in the U.S., a study was done in 2002 which showed that there were 1.4 million new houses constructed (for single families) and 0.3 million new houses for multi-families; where the house averaged about 215 m^2 made from wooden decks (Winandy, et al. 2004). Winandy, et al. 2004, concluded that all this huge amount of consumed wood could be substituted by WPC. The U.S. decking market alone uses a sum total of nearly 18.5 million m^3 of wood where 90% uses natural treated wood and 10% WPC (Winandy, et al. 2004). In addition, the U.S. fencing market was divided into 45% wood, 44% metal, 7% plastic and 5% other material (Winandy, et al. 2004). It was calculated at $US 2.6 billion in 2002 and was expected to grow approximately 5% per year and therefore a great potential of WPC domination was expected (Winandy, et al. 2004).

3. Applications

Advantages, desired properties, environmental regulations, and awareness have led to the substitution of using conventional woods with the WPC. Its production is growing over time due to its several applications (Adhikary, et al. 2008). Main motives include:

- It can be molded in any particular mold with a variety of shapes and angles, so it can give any desired design (Takatani, et al. 2007).
- It can be treated in the same manner as the conventional wood using the same cutting and sawing equipment (Winandy, et al. 2004).

Therefore, it is easy to use any conventional wood workshop with WPC products which have proven to give the same functionality as conventional wood in many areas (Wechslera and Hiziroglu 2009). Various WPC products are available in the US market substituting some of the conventional wood products such as outdoor deck floors (Winandy, et al. 2004). It is also used for railings, fences, landscaping timbers, siding, park benches, molding and trim, window and door frames, panels and indoor furniture (Winandy, et al. 2004).

In addition, Wood plastic composites can also substitute neat plastics in applications where the need for an increase in stiffness is an addition; where the wood fiber elasticity is almost 40 times higher than that of polyethylene and the overall strength is approximately 20 times greater (Bengtsson and Oksman 2006). It has also higher thermal and creep performance compared to plastics and thus could be used in many structural building applications (Wechslera and Hiziroglu 2009).

A high potential of using WPC in a large scale to produce pallets is raised by Soury, et al. 2009; whereas the amount of consumed wooden pallets is huge (400 million pallets) accounting for about 86% of all pallets sold worldwide. In addition, product degradation due to environmental factors, which is one of the main disadvantages of wood, made WPC as an best alternative option (Soury, et al. 2009).

WPC started to be utilized in siding market in 2003 based on studies done in 2002 that revealed that wood occupied about 17% of the materials share of the U.S. siding market (960 million square meters) (Winandy, et al. 2004). Therefore, a promising market was opened for WPC products which gave a promising performance over other materials such as aluminum and vinyl and similar to wood (Winandy, et al. 2004).

4. Material

4.1 Material utilized in WPC

Wood and plastics (virgin or recycled) with various types, grades, sizes, and conditions are the main materials utilized in WPC production. WPC is composed mainly from a plastic matrix reinforced with wood and other additives sometimes are added using the appropriate processing procedures. Several ingredients of WPC are found in literature. Najafi, et al. 2007, mentioned that WPC is a composite composed from a natural fiber/filler (such as kenaf fiber, wood flour, hemp, sisal etc.) which is mixed with a thermoplastic. They added that virgin thermoplastic materials (e.g. high and low density polyethylene (LDPE and HDPE), polypropylene (PP), polyvinyl chloride (PVC)) are commonly utilized. In addition, any recycled plastic which can melt and be processed in a temperature less than the degradation temperature of the wood filler (200 C) could be used to produce WPC (Najafi, et al. 2007). Morton and Rossi 2003, said that the huge majority of WPC utilizes polyethylene and they classified the types of plastic used in WPC as follow: polyethylene

(83%), polyvinyl chloride (9%), polypropylene (7%), others (1%) (Morton and Rossi 2003). Clemons and Caufield added that wood flour is obtained from wood wasted from wood processors. They said also that it should be from high quality and free of bark, dirt, and other foreign matter. Moreover, species are mainly selected based on regional availability of high quality flour and color. Pine, oak, and maple are the most common used in the United States (Clemons and Caufield 2005). Adhikary, et al. 2008, used recycled and virgin high density polyethylene (HDPE) with wood flour (Pinus radiata) as filler. The HDPE utilized was obtained from a plastics recycling plant and sawdust was collected from a local sawmill (Adhikary, et al. 2008).

4.2 Advantage of WPC ingredients over other materials

The fact that WPC ingredients are mainly composed from wood and plastic has led to the rapid worldwide growth of its production due to the high availability of non-utilized plastic and wood wastes. Dividing the subject into two main sub-subjects, the plastic waste has the highest contribution regarding its huge available quantities which gives a strong advantage to WPC. The market potential regarding the usage of plastic waste into other utilizations is huge due to the high amounts of its disposition which constitutes the largest share of the global municipal and industrial solid waste. Kikuchi, et al. 2008, mentioned that the plastic waste constitutes more than 60% of the total MSW, 22% was recovered and 78% disposed (Kikuchi, et al. 2008). In United States, the waste of plastics; in 2005, was calculated as 11.8% of the 246 million tons of MSW generated (USEPA 2006). In India, Plastic in municipal solid waste makes up to 9–12% by weight of the total in addition to other wastes which may contain much higher proportions of plastics (Panda et al. 2010). The majority of the plastic wastes generated are disposed (Kikuchi, et al. 2008). However, the continuous growth of worldwide plastic consumption due to its short life cycle compared to other products; roughly 40% have duration of life cycle smaller than 1 month, and the legislations of many countries concerned with minimizing landfills content and incinerators have led to a necessity of recovering plastic waste instead of disposing (Kikuchi, et al. 2008) & (Panda et al. 2010). Incineration and land filling alternatives were rejected by several countries due to their potential danger to the environment either by polluting air or land; which results in not closing the loop of Cradle to Cradle and therefore depleting natural resources. As a consequence, the tendency towards recycling has increased (Jayaraman and Bhattacharyya 2004). Some attempts for plastic recovery resulted during 2004 in a recovery of almost 8.25 million tons (39% of total amount of plastics consumed) in Western Europe; 35,000 tons (13.48% of total imported virgin plastics) in New Zealand (Adhikary, et al. 2008). While in 2005, the United States recycled around 5.7% of the total plastics generated (USEPA 2006). On the other hand, some states in the US like Michigan have a recycling rate that is close to 100% (Beg and Pickering 2008). In Brazil, some potential in recycling have been raised where around 15% of all plastics consumed are recycled and returned to industry (Beg and Pickering 2008).

Therefore, the tendency towards recycling plastic instead of other options made it better for the sake of WPC production increase in the future. On the other hand, wood waste has a significant contribution to the total amount of waste especially that it comes from various commercial, industrial, and residential activities; which could include scrap lumbers, pallets, sawdust, tree stumps, branches, twigs, wooden crates and pallets, building construction and demolition, furniture manufacturing, and many others. In addition, it is one of the main environmental concerns stated by many countries. In the United States, a report that was written in 1995 by CIWMB (California Integrated Waste Management Board) tells that severe problems concerned with landfill disposing were revealed (CIWMB 1995). It tells that the construction and demolition of buildings; which are mainly wood waste, generates almost twelve percent of all solid waste in California. Furthermore, the average fee for disposing of a ton of waste in a California landfill is about $30 to $35, but disposing of a ton of wood at a wood processing facility may only cost $10. In addition, the amount of wasted wood disposed in landfills in some regions in California reaches 90 percent of the total wood waste (CIWMB 1995). Adhikary, et al. 2008, stated that a large amount of wood waste is generated from wood industry at different stages of the processing of wood; which is disposed mostly in landfills; Besides, the hazardous content of the wood waste are numerous and takes time to decompose (Adhikary, et al. 2008). The Department of Environmental Quality (DEQ) in the United States reported that the other alternative; that used to be used, to get rid of wood wastes instead of disposing was burning (DEQ 2009). Wood burners were used at first and as a result of their environmental hazards; represented in huge amount of smoke & ash generated directly to the atmosphere polluting air and ambient, were shut down and prohibited from being used (DEQ 2009). Currently, a tremendous shift is done in the area of wood burning especially with the developed ideas of avoiding the environmental hazards. Therefore, the use of wood waste in WPC helps to overcome disposal and burning hazards and costs (Adhikary, et al. 2008).

4.3 Virgin or recycled (non-virgin) material in WPC production

The issue of producing WPC using virgin or recycled (non-virgin) material is been controversial. When searching in literature, various opinions were found regarding the practicality of usage, mechanical properties, physical properties, and even final product look or appearance.

Various comparisons were done between virgin and recycled materials using many conditions have shown agreements of authors with the use of recycled material and other times disagreements. However, studies based on recycled products are very limited (Adhikary, et al. 2008) and almost all producers of the commercial scale WPC are using virgin materials (Klyosov 2007). This tendency could be due to the fear of obtaining a product with non controllable properties resulted from impurities as justified by Yeh, et al. 2009, on research scale (Yeh, et al. 2009). Conversely, Adhikary, et al. 2008, used in their study post-consumer HDPE which was collected from plastics' recycling plant and sawdust was obtained from a local sawmill. They have shown in their study the feasibility of making composite panels from recycled HDPE using hot-press molding technique. They added that the obtained product has proven superior dimensional stability when compared to virgin HDPE and equivalent tensile and flexural properties of the composites. On the other hand, Yeh, et al. 2009, showed that wood with recycled ABS resulted in poor and variable mechanical properties as compared to the relevant virgin ABS. They added that unlikable odor is obtained from recycled material which could be avoided by adding a thin layer of virgin polymer (Yeh, et al. 2009).

Regarding physical properties, Adhikary, et al. 2008, showed that the panels gave very low water absorption and thickness swelling thus the products was considered stable in humid environment (Adhikary, et al. 2008). In contrast, Najafi, et al. 2007, have tested water absorption and thickness swelling of WPC obtained from sawdust and recycled and virgin plastic; HDPE and PP. The test consisted of 2 hr and 24 hr submersion tests.

The results showed that recycled WPC absorbed more than virgin, PP absorbs water more than HDPE, and the mix of recycled HDPE and PP absorbed the maximum (Najafi, et al. 2007).

Yeh, et al. 2009, and Adhikary, et al. 2008, have found variable performance of their final product. It was justified by Adhikary, et al. 2008, by the different grades and colors of waste stream used and the material contaminants. They said also that the impact is still not fully understood which calls for further investigations and opens a new area of research (Adhikary, et al. 2008). Moreover, the problem was addressed by Yeh, et al. 2009, as the reuse of polymers obtained from post-consumer application caused unpleasant outcomes many times. They justified by basing their claim on the impurities contained within the material; which led to decrease the mechanical and thermal behavior. The authors added that; based on their findings, impurities would affect the product impact strength and ductility negatively to the extent even if it was of 1 % of amount. Another problem accompanied with impurities in polymers is that the cost of its disposal will be more than using virgin material (Yeh, et al. 2009). Therefore, it could be concluded that the main problem lies in the variable performance or different outcomes of the same material settings when tested. This issue was also discovered in findings of the new proposed technology in this chapter as the main cause of variability was due to impurities and contaminants agreeing with authors; as mentioned above. However, the environmental savings from using non-virgin material, availability, high properties, and almost no-cost should be the stimuli behind using recycled material instead of virgin.

4.4 Additives

Additives should be added to the mix because the majority of the WPC physical and mechanical properties are depending mostly on the interaction developed between wood and the plastic which is increased by additives (Wechslera and Hiziroglu 2009). Generally, the additives enhance the compatibility between hydrophilic wood and hydrophobic plastic allowing the formation of single-phase composite (Wechslera and Hiziroglu 2009). The two main families of additives which are used with WPC are mineral additives and coupling agents. The most famous coupling agent utilized in literature by many researchers is the maleated polypropylene (MAPP); on the other hand, the most famous mineral additive utilized is the talc and calcium carbonate (Klyosov 2007), (Adhikary, et al. 2008), and (Fabiyi, et al. 2008). Maleated polyolefins, organosilanes, and acrylic-modified polytetrafluoroethylene (PTFE) are the most famous family of coupling agents which are added to the composite with minimal percentages; typically less than 5% (Klyosov 2007), (Adhikary, et al. 2008), (Bengtsson and Oksman 2006), and (Fabiyi, et al. 2008). Typically, coupling agents act to provide better flowability of the molten composite, therefore better compatibility obtained, and strength enhanced (Klyosov 2007). However, many arguments were raised mentioning that coupling agents do not provide strong adhesion between fiber and plastic; which is the main intended function (Klyosov 2007). The main mineral additives adopted in literature are talc ($Mg_3Si_4O_{10}(OH)_2$), calcium carbonate, silica, glass fiber, kaoline clay (Al_2O_3, $2SiO_2$, $2H_2O$), wollastonite ($CaSiO_3$) (Klyosov 2007). Talc and calcium carbonate are most common additives used in WPC production due to their good outcome in enhancing mechanical properties, availability, and cheap cost (Klyosov 2007). Additionally, talc is the most additive used in literature due its good absorption of water; to minimize the wood moisture, its natural similarity to oil in addition to its distinct platy shape (non uniform layered composition) making it a good filler for hydrophobic plastic (Klyosov 2007). In addition, talc was utilized by many researchers because it has proven that it enhances WPC mechanical properties (Fabiyi, et al. 2008, Klyosov 2007).

5. Manufacturing

5.1 WPC manufacturing techniques

Various techniques were adopted in literature to manufacture WPC, however; the two main adopted techniques are extrusion and injection molding.

Typically, the extrusion process produces continuous linear profiles via forcing a melted thermoplastic through a die; on the other hand, the injection molding process produces three-dimensional items with minimizing the stages of post-manufacturing (Migneault, et al. 2009).

The manufacturing techniques adopted by Bengtsson and Oksman 2006, were based on drying wood flour at 100 C to reach a moisture content of 0.3%. The dried wood and plastic granules were then fed to the cororating twin-screw extruder at temperatures varying from 165 to 200 C. A rectangular die was used at the extruder end and the extrudates were then cooled at ambient temperature. Silane was added during extrusion to enhance the product properties. Bengtsson and Oksman 2006, showed that adding silane resulted in superior increase in toughness, impact strength and creep properties in comparison to those without silane; However, The flexural modulus was lower (Bengtsson and Oksman 2006). Yeh, et al. 2009, divided the WPC manufacturing process into two main parts. The first part consisted of compounding the material; using a twin-screw extruder. The second part was to obtain profiles via single-screw extruder or use injection molding to obtain a product resembling to wood in look and properties (Yeh, et al. 2009). Bouafif, et al. 2009, produced WPC in a two-stage process. In the first stage, a co-rotating twin-screw extruder was used to compound wood particles with HDPE into pellets at temperatures from 180 C to 190 C. In the second stage, a reciprocating screw injection molding machine was used to inject WPC test specimens (Bouafif, et al. 2009). Soury, et al. 2009, manufactured WPC pallets by firstly producing profiles; utilizing counter-rotating twin screw extruder, and then assembling them by using nails, rivets and screws. The authors found an advantage of adopting extrusion instead of injection molding represented in the high challenge of producing one piece pallet in injection molding which could make the wood; in the composite, burn. This is due to the high shear rate in the rapid injection speed and therefore excessive heat generated causing burn to the product. On the hand, extrusion generates much less shear and therefore heat; in addition, it is more flexible in terms of adoption of various die designs (Soury, et al. 2009). Migneault, et al. 2009, conducted a comparison between extrusion and injection molding for producing WPC, common steps found in both include melting, shaping, and cooling; in addition, they both use screws to convey, pump, and blend the mixed component. However, they added that process parameters such as residence time, temperature, pressure, shear rate, shear stress, and cooling rate are different. Moreover, they concluded that pressure and shearing in injection molding are higher than en extrusion regardless the process parameters mentioned (Migneault, et al. 2009). Stark, et al. 2004, compared WPC samples; composed from 50% wood flour and HDPE, obtained from extrusion and injection molding and found that they gave the same flexural modulus; however, the flexural strength and density of injected parts were higher. The authors justified that this could be resulted from the better interfacial contact in injection molding

between wood and polymer; totally encapsulated wood particles within polymer matrix, resulting in higher density and therefore more strength (Stark, et al. 2004).
However, Bledzki and Faruk 2004, have shown that WPC made from 30% hardwood particles and polyethylene resulted in similar specific bending modulus of elasticity and density for both injection molding and extrusion techniques. Conversely, injection molded WPC have shown higher specific tensile strength (Bledzki and Faruk 2004).
Concerning physical properties, Clemons and Ibach conducted sorption behavior comparison for WPC; composed from 50% of 40-mesh pine flour and HDPE, and concluded that water-soaked extruded samples absorbed and swelled more water than injection molded samples (Clemons and Ibach 2004).

5.2 WPC reprocessing

Another important point that should be addressed is the reprocessing of the wood plastic composite itself. Although literature did not emphasize much on this point, however; Beg and Pickering, 2008, have shown that mechanical properties of WPC samples composed from 50% fiber; reprocessed two times, increased respectively by 13.5% and 33% for tensile strength and yield modulus. In addition, after the second reprocessing time, the properties decreased till reaching the 8th reprocessing when tensile strength and yield modulus; of a WPC with 40% fiber, was reduced to 25% and 16% respectively (Beg and Pickering 2008).

6. WPC new manufacturing technology

6.1 Experimental stages

Most of the WPC techniques mentioned in the literature are very expensive and require high technology which called for developing a simple, reliable, cheap technique to produce WPC. A new suggested technology in this section utilizes extrusion technique which was decided based on a local market survey that was performed. The technology was applied at The American University in Cairo (AUC) Technology and Innovation Labs. It showed high availability of extrusion technologies; manufactured locally, and relative cheap cost. Conversely, injection molding machines mainly are less available and more expensive than extruders. Therefore, the decision was made to use the extrusion method. In addition, Special procedures were presented to manufacture WPC that showed satisfying outcomes. All the processes have gone through several **pilot, prerequisite, stage 1, 2, and 3** experimentations till reaching the required manufacturing processes which will be explained in details within this section.

Pilot experimentations

These experiments are called the pilot or baseline experiments (Elsayed, 2009). It is consisting of running initial experiments to get more experience and knowledge about the factors included, determine the important ones to be investigated further, and exclude the unimportant i.e. getting the feeling of interconnected components. In addition, its outcomes give the necessary data to set bounds and constraints on factors involved. As well, it is the key which gives the guidelines for the necessary manufacturing techniques; as it was shown in this work. Moreover; based on results obtained from pilot experiments, sequential modifications were done leading to the final adopted manufacturing technology. These experiments were run in random patterns to estimate the general behavior of factors; however, extreme settings of factors should be experimented to be able to add boundaries and restrictions.

Prerequisite stage

This stage consisted of making assumptions to start the experiments with. It was based on literature review and a local market survey. The first experimental settings were built based on this stage; where literature was the first key giving the way for a manufacturing technology. Two methods for the manufacturing of wood plastic composites were suggested: injection molding method and extrusion and compression molding method (Klyosov, 2007). Then, a local market survey was conducted to check the availability of machines needed for these two technologies. It showed high availability of single extrusion technologies; manufactured locally, and relative cheap cost. Conversely, injection molding machines and twin extruders are not manufactured locally, less available and more expensive than extruders. Therefore, the decision was made to use the extrusion method.

Stage 1

The main target of this stage was to check the adequacy of the chosen technology via its applicability using virgin plastic and wood waste. Virgin plastic was used to block any effect that could be accompanied with plastic waste. As a result, the three manufacturing steps; extrusion, heating, and compression have proven efficiency and gave a feasible product.

Stage 2

Plastic waste was utilized within WPC instead of virgin within experimentations. Several problems appeared in this stage regarding wood and plastic wastes. As a consequence, the product which was obtained suffered in many cases from a non homogenous grains' distribution in the final product i.e. plastic and wood weren't distributed evenly in the product. Therefore; it was suspected to obtain non consistent properties if large WPC sheets were decided to be produced. This problem was avoided in stage 3 when meshing and shredding process were added. The main problem accompanied with plastic waste was the formation of volatile organic compounds which affected the product negatively and called for adding bounds and constraints for this factor. On the other hand, wood waste has caused problems concerning the formation of water bubbles; due to its hydrophilic nature, and the uneven grain distribution within the product which allowed the formation of water bubbles and voids within the wood plastic matrix.

Stage 3

Stage 3 included many modifications that started by the introduction of shredding and meshing operations to avoid non homogenous products obtained in stage 2. Eight different sizes of sieves were adopted ranging from 400 to 1300 Micrometers to mesh the wood; where only 2 sizes; 500 and 1180 Micrometers, were decided to be used in the final experimental processes as they gave the highest flexural strength and modulus properties. The 500 Micrometers' sieve was selected from a range of sizes that is commonly used in literature for the production of WPC; ranging from 50 to 700 Micrometers (Klyosov, 2007), and the 1180's one was selected based on a claim that increasing in particle size would ameliorate properties (Klyosov, 2007). The second important modification was the need to do something concerning the wood humidity and tendency to absorb water; hydrophilic nature. Drying wood before usage was the first step to minimize wood water content and adding talc was the second. On the other hand, decisions concerned with process variables (furnaces' temperatures and extruder's temperatures and speed) were taken in this stage also. Mainly, the limits' selection of all these variables was based on the product obtained; whereas, burned products will call for decreasing temperature; for example. Typically, it was required to obtain a well cooked product yet not burned with the minimum possible time. Therefore, Furnaces' temperature; used for wood drying and forming the paste, were set based on these main criteria. Extruder's temperature was decided to be set at a specific degree to avoid solidification or overheating of the product. Extruder's speed was set at 19 RPM; because when the speed was higher than 20 RPM, the product obtained wasn't coherent and well mixed. In other words, the time wasn't sufficient to merge plastic and wood where the plastic wasn't well heated. In contrast, when the speed was less than 18 RPM the product obtained was overheated; therefore the plastic liquidified and stuck within the extruder. Based on the previous justifications, levels of process variables were decided not to be included within the final experimental processes.

6.2 Factors affecting WPC

Four factors (ingredients) were used to produce WPC: plastic, talc, and wood waste with size of up to 1.18mm and 0.5mm. The wood waste utilized is formed from sawdust with fine particle sizes. This type of wood waste generally is a by-product of wood sawing which ranges from 20 to 5000 µm (Klyosov 2007). Based on literature, the common adopted sizes of wood utilized for the production of WPC range from 50 to 700 Micrometers; where increasing particle size results in better flow of molten composite, lower mold shrinkage, and higher flexural modulus (Klyosov 2007). In other words, better properties are obtained when the size approaches the 700 Micrometers. Based on this claim, it was decided; during pilot experimentations, to test 8 different sieves ranging from 300 to 1300 Micrometers for the sake of obtaining the best possible accepted product. Increasing the size more than 700 Micrometers intended to experiment the claim mentioned above of "the increase in size would ameliorate properties". As a result, two sieves were decided to be used with sizes of 500 Micrometers (0.5mm) and 1180 Micrometers (1.18mm) as they gave higher flexural strength and modulus in comparison with the other 6. Moreover, it was decided to use various mixtures of these two sizes during main experiments; as it was suspected that a mixture of two sizes may ameliorate properties. For illustration, these factors will be described as X1, X2, X3, and X4 respectively. Table 1 presents all the bounds and constraints in this technique. Bounds were the upper and lower limits of each factor that was adopted in this work.

	Upper and lower bounds	*Constraints*
X1 = Plastic	$40 \leq X1 \leq 70$	$15 \leq X3+X4 \leq 50$
X2 = Talc	$0 \leq X2 \leq 35$	
X3 = Wood (1.18mm)	$0 \leq X3 \leq 50$	$X1-X3-X4 \geq 0$
X4 = Wood (0.5mm)	$0 \leq X4 \geq 50$	

Table 1. Upper, lower bounds, and constraints of factors

All percentages, bounds, and constraints were based on pilot experimentations that showed these adopted percentages to be most appropriate using this technology.

X1 Factor

X1 is the percentage of plastic within the mix. It is a mix of HDPE and LDPE with ratios of 25% and 75% respectively. It is a waste product obtained from municipal waste and no virgin materials were used. It is composed of shredded plastic waste obtained mainly from garbage plastic bags which are highly contaminated. The utilization of this type of plastic would save the environment as these bags are non biodegradable materials which are mostly thrown away in a dumpsite; therefore, it is a costless unutilized resource calling for investment. In addition, the highest percentage of WPC produced commercially worldwide is based on Polyethylene (Klyosov, 2007). X1 was utilized in this work with percentages varying from 40% to 70% (table 1). The higher bound of X1 was decided based on pilot experimentations. When the percentage exceeded 75% then, volatile organic compounds; resulted from melted plastic, were produced during extrusion in addition to unknown gases which could be resulted from the contaminations in plastic (bearing in mind it is a product obtained from black plastic bags used for garbage collection). The production of these gases caused a continuous blowing of the extruder; which called for shutting down several experiments for safety reasons and to avoid possible hazard. Therefore, it was decided afterwards not to exceed the amount of plastic more than 70%. On the other hand, the adoption of the lower bound was based on the non-coherent burned product obtained when the percentage of plastic was 35% or less during pilot experimentations. This could be due to the high wood (filler) amount not meeting enough plastic to be merged in a matrix.

X2 Factor

X2 is the percentage of talc ($Mg_3Si_4O_{10}(OH)_2$) within the mix. It is a part of the phyllosilicate minerals which is used as a mineral additive to this mix. It is characterized with its ability to absorb water; therefore, minimize the humidity of wood; which is characterized with its hydrophilic nature, as a consequence enhancing mechanical properties of WPC (Sun-Young Lee, et al. 2008). In addition, talc has a natural affinity to oil; therefore, it works as good filler for hydrophobic plastic (Klyosov, 2007). Also, talc is available with very low cost in Egypt and elsewhere. Before using talc; within pilot experimentations, water formation within the product was a major problem especially with mixtures containing high filler content; 45% or more. These products failed easily with minor load application when tested; flexural strength was 2 MPa or less and the modulus didn't exceed 250 MPa. However, results after using talc were far higher and the effectiveness of its usage was proven in this technique. The upper bound was based on literature recommendations; where talc gave highest flexural strength modulus at 27% talc (Noel and Clark, 2005) & (Klyosov, 2007). Therefore, it was decided to use an upper bound of 35%.

X3 and X4 Factors

X3 and **X4** are the percentage of meshed wood waste with size of up to 1.18mm and 0.5mm. X3 and X4 are sawdust wastes obtained from wood workshops; which are typically thrown away in dumpsites. The main problem of wood waste lies in its hydrophilic nature; unlike the contamination issue of plastic where wood is obtained from wood workshops. It absorbs water and humidity in an immense way. Two actions were taken to solve this problem; drying wood and adding talc. The upper bound of X3 and X4 was decided not to exceed 50% as the plastic should be at least 40% to produce coherent product and 10% would be considered as a basic percentage of talc to get rid of wood water content. However, runs with zero talc percentage were also conducted to measure its effect.

The first constraint tells that the total wood wastes percentage shouldn't be less than 15% and more than 50%. The lower bound was needed because there should be a minimum amount of wood waste in the product to give the desired WPC properties which was obtained at a minimum of 15% wood waste content. The upper bound was added to make the total wood wastes acting less than or equal 50% in all cases to avoid burned products and get the desired properties. The second constraint says that the plastic percentage should be more than the total wood wastes percentage. It is an assurance condition for avoiding a case such as 40% plastic, 50% wood, 10% talc; where non-coherent product was suspected in this mix (containing high filler content).

6.3 Processes experimental settings

The processes start as shown in figure 1 by meshing the wood waste into 2 predetermined grades using sieves of sizes giving wood waste particles up to 0.5 mm and 1.18 mm to obtain a homogenous saw dust material. Based on pilot experimentations, these two sizes were used as they gave highest flexural properties (strength and modulus) of the final product in comparison with several sieves of different sizes utilized during trials. The meshed wood waste is then taken to be dried in a furnace for 4 hours to eliminate the moisture within wood waste particles up to almost 100%. The furnace temperature is set at 115 C. This temperature was decided not to be increased more than 115 C due to safety reasons as to avoid wood waste burning. After drying takes place, the wood waste is then mixed with plastic and talc (if any) in a jar (container) using a mixer and then the mix are fed into the single screw extruder. The talc is added as a mineral additive to enhance the properties of the final product. Two electric heaters are used at the beginning and end of the extruder. Temperatures were set at 120 C for the first and 150 C for the second heater. The resulted extrudates are left to be cooled at room temperature then taken to the shredder to form small particles with identical dimensions which will make the paste formed from the last process more homogenous. Then, the shredded particles are fed into the furnace to form a paste which is formed after about 15 min. Therefore, it is taken to the hydraulic compression molding machine to be pressed. A die with specific dimensions is used to satisfy the required application. Finally, trimming and cutting processes into the exact specified dimensions are done to make the product ready for testing in accordance with the requirements of the testing standards.

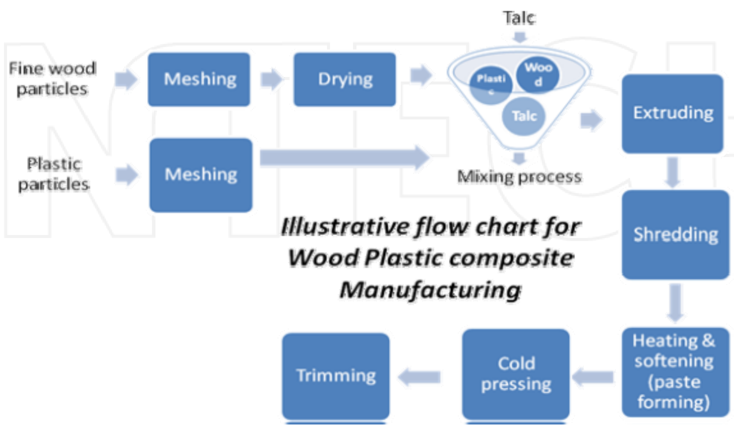

Fig. 1. Illustrative process flow chart of WPC manufacturing

6.4 Experimental processes

Wood waste meshing

The wood waste utilized is formed from sawdust with fine particle sizes. This type of wood waste generally is a by-product of wood sawing which ranges from 20 to 5000 µm (Klyosov, 2007). Based on literature, the common adopted sizes of wood utilized for the production of WPC range from 50 to 700 Micrometers; where increasing particle size results in better flow of molten composite, lower mold shrinkage, and higher flexural modulus (Klyosov, 2007). In other words, better properties are obtained when the size approaches the 700 Micrometers. Based on this claim, it was decided; during pilot experimentations, to test 8 different sieves ranging from 300 to 1300 Micrometers for the sake of obtaining the best possible accepted product. Increasing the size more than 700 Micrometers intended to experiment the claim mentioned above of "the increase in size would ameliorate properties". As a result, two sieves were decided to be used with sizes of 500 Micrometers (0.5mm) and 1180 Micrometers (1.18mm) as they gave higher flexural strength and modulus in comparison with the other 6. Moreover, it was decided to use various mixtures of these two sizes during main experiments; as it was suspected that a mixture of two sizes may ameliorate properties.

Wood waste drying

The dryer used was set at 115 C to avoid wood waste burning. The meshed wood waste is left for 4 hours in the dryer to get rid of the moisture (see figure 2). It was assured that the moisture was totally eliminated through a test that was done. The test consisted of taking two samples of wood waste; sizes of up to 0.5mm and 1.18mm, utilized within experiments and weighs it through a calibrated scale. Then, it was left in the dyer for 2 hours then weighed. Each hour after the second hour, it was weighed. At the 5th and 6th hour the weight was not changed for the two types. Therefore, it was concluded that 4 hours was sufficient to dry the meshed wood waste. The experiment was repeated 3 times to guarantee the results.

Fig. 2. Oven used to dry waste wood

Extruding

Before feeding the extruder (single screw extruder), the plastic is mixed; using a mixer, with wood waste and talc (if any). The plastic used; which is composed of a mix of HDPE and LDPE with 25 % and 75 % respectively, has the shape of small particles. This mix is composed of shredded plastic waste obtained mainly from garbage plastic bags which are highly contaminated. The talc is used as a mineral additive; to enhance mechanical properties, with percentages varying from 0 to 35 percent by weight of the total. The mix is then being fed into the hopper of the extruder and the process starts as shown in figure 3.

Fig. 3. Feeding the extruder with the mixture

Setting the two heaters at 120 C; for the first one, and 150 C; for the second, the extrudates are produced and the sample is accomplished and extrudates obtained within about 17 min for a 1.5 kg used (see figure 4 and 5). Intuitively, a warm up period for the heaters of about an hour was a prerequisite. The temperatures' settings were dependent mainly on the plastic utilized as it has major effects on the process and therefore the final product obtained. These effects were discovered during pilot experimentations; which were reflected when the temperature range of the extruder was increased to 135 C (1st one) and 165 C (2nd one), the melt was overheated, liquidified, then stuck around the screw as it turned with its rotation without flowing. This caused the process to stop as it prevented the flow to continue and jammed the whole process. In other instances, when the temperature was dropped to 105 C (1st one) and 135 C (2nd one), the melt was solidified causing the blockage of the flow. Therefore the settings of 120 C ± 5 and 150 C ± 5 were applied to obtain a well cooked product yet not burned with the minimum possible time. The difference in temperature is due to start with a primary heating then increase it to the final one as not to cause a sudden increase in temperature within the mix and therefore caused an incremental pressure resulted in exploding the mix from extruder outlet rather than flowing.

Fig. 4. The hot extrudates coming out of the extruder

Shredding

The extrudates (see figure 5) are crushed in the shredder (see figure 6) forming small particles with identical sizes to be fed into the furnace. The shredding operation was important as it avoided bad distribution of the mix during furnace heating within experimentation. As this process at first; during the pilot trials, was done without shredding which resulted in several cases of non homogenous final product. The main reason behind this that the extrudates have different sizes and the material's concentration within each extrudate wasn't distributed the same. Therefore, it was decided to use a shredder.

Fig. 5. The final shape of the extrudate

Fig. 6. The shredder adopted in crushing the extrudates

Drying

The furnace works for about 15 min at 140 C to form a paste which is then taken to be pressed (see figure 7). The temperature was decided based on pilot trials aimed at forming a homogenous paste without burning.

Fig. 7. The furnace used for heating the shredded particles to form a paste

Compression molding

The hydraulic compression molding machine used consists of a hydraulic press with parallel platens which apply the pressure of high amount (see figure 9). A pressure of 40 bars is applied. The steel die used is a custom made one with dimensions of 42 * 12 * 12 cm (see figure 8) to accommodate the size required for the ASTM D 4761 test of flexural test. A sample obtained after pressing is show in figure 10.

Fig. 8. The custom made die

The required thickness is obtained via right weight selection for the mix and adjusted using thickness cutter.

Fig. 9. The hydraulic press used

Fig. 10. The sample obtained after pressing

Trimming and adjusting thickness

A trimming process is done for the sample giving final dimensions of 40 * 10 cm to be ready for the testing in accordance with the ASTM D 4761 requirements. The thickness is corrected via cutting the sample obtained to the 1 cm thickness required by the ASTM D 4761.

7. Conclusion

Plastic and wood wastes have been a major environmental concern because of high amount of waste generated which affect the sustainability of natural resources. Wood Plastic Composites (WPC) made out of wood waste and plastic waste has been a fast growing research area because of its wide range of applications such as fences, siding, park benches, landscaping timbers, windows and door frames, ponds, indoor furniture, pellets and many others. The fact that WPC ingredients are manly composed from wood and plastic wastes has led to the rapid increase of its production due to the high availability of non-utilized plastic and wood wastes. WPC will close the loop for conserving the natural resources, according to cradle-to-cradle concept. The use of plastic waste and wood waste in WPC helps to overcome disposal (through landfill) and burning hazardous material through incinerators and reduce the cost of environmental degradation as well as depleting the natural resources and the indirect cost of health hazardous material.

Various techniques were adapted in the literature to manufacture WPC, however, the two main adapted techniques were extrusion and injection moulding. This chapter provide a new technique based on moulding technology which is cheaper than extrusion & injection moulding and provide WPC with any dimensions and shapes according to the dimension and shapes of moulds.

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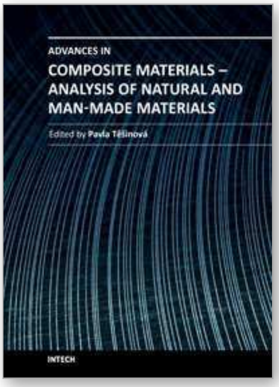

Advances in Composite Materials - Analysis of Natural and Man-Made Materials

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Composites are made up of constituent materials with high engineering potential. This potential is wide as wide is the variation of materials and structure constructions when new updates are invented every day. Technological advances in composite field are included in the equipment surrounding us daily; our lives are becoming safer, hand in hand with economical and ecological advantages. This book collects original studies concerning composite materials, their properties and testing from various points of view. Chapters are divided into groups according to their main aim. Material properties are described in innovative way either for standard components as glass, epoxy, carbon, etc. or biomaterials and natural sources materials as ramie, bone, wood, etc. Manufacturing processes are represented by moulding methods; lamination process includes monitoring during process. Innovative testing procedures are described in electrochemistry, pulse velocity, fracture toughness in macro-micro mechanical behaviour and more.