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Short communication

# The effect of primary sludge on the mechanical performance of high-density polyethylene composites

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ABSTRACT

Effective reutilization of by-product material is an important goal which should be aimed at globally. The effects of primary sludge instead of wood on the mechanical performance of composites are examined in this study. The studied composites were made from high-density polyethylene (HDPE), anhydride-grafted-polyethylene (MAPE), lubricant, and either wood flour or primary sludge from forest industry production. The HDPE –composites were compounded in a conical twin-screw extruder. The mechanical properties of the composites were characterized by tensile, flexural, hardness, and impact testing. The primary sludge as a component in the structure of the composite resulted in an improvement of mechanical performance in some of the tests, e.g. the properties of hardness and impact strength increased over 40 per cents, and weakened results were not noticeable in a larger scale.

## 1. Introduction

Waste reduction is a global goal that contributes to technological innovation related to the re-use and recycling of material, for example as a raw material in the structure of composite. A composite is a combination of two or more materials that results in more favorable performance than that of the individual components used on their own. It consists of a continuous phase matrix and a reinforcing phase, such as a fiber or a particulate. In this study, some properties of the wood-plastic composite (WPC) are compared to a composite where the wood material has been replaced by sludge from the forest industry.

Sludge is a by-product of the pulp and paper industry, which is often utilized by burning in the energy process with other wood material. Sometimes, the nature of the sludge may be uneconomic for burning and then it must be composted, which may cause problems with odor and runoff water (Ojanen 2001). The burning of sludge may have a negative effect, for example nitrate-rich sludge includes components which generate greenhouse gases (Soucy et al., 2014). Additionally, according to the national Waste act (646/2011), waste must be first and foremost re-used or recycled rather used as energy. The same principle is also described in the area of the European Union (Official Journal of the European Union, 2008).

The forest industry produces two kinds of sludge, primary sludge from waste water treatment plant and secondary sludge from biological treatment. According to Stoica et al. (2009), primary sludge should be dealt with separately from secondary sludge, because it is more suitable for material recovery than energy recovery. Soucy et al. (2014) note that primary sludge has a reinforcing effect in composite applications due to the fibers it contains. The secondary sludge content must be low if deterioration in strength is to be avoided (Edalatmanesh et al., 2011). It has been estimated that the total production of paper mill sludge is about 35–45 kg per ton of paper (Girones et al., 2010). The total amount of produced effluent has reduced significantly during the last decades. In 2015, Finnish forest industries produced 31 kg of effluents per ton of production (Metsäteollisuus, 2016). The effect of paper sludge on the composite structure has been studied, and it has been found that the elasticity and water absorption have increased with the increasing sludge content, while tensile strength and elongation at break have decreased (Ismail and Salmah Bakar, 2005).

The objective of this study is to assess the influence of primary sludge as a raw material of a composite instead of wood particles, on the mechanical properties of the composite. The properties are assessed by the results of impact strength, hardness, and tensile and flexural strength tests.

## 2. Experimental

### 2.1. Materials

High-density polyethylene (HDPE), RecyPE HDPE 8 blue (L&T

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Muoviportti), density ~0.960 g/cm$^3$ and melt mass-flow rate 8 g/10 min (190 °C/2.16 kg), was used in the experiments. The tensile strength and tensile modulus of the used HDPE polymer were 28.1 (MPa) and 1.21 (GPa), respectively. The coupling agent was maleic anhydride-grafted-polyethylene (MAPE), Fusabond E226 (DuPont). Struktol TPW 113 (Struktol) was used as the lubricant. The primary sludge (PrSl) was delivered by UPM Finland, whose production process is as follows. A wastewater treatment plant (WWTP) treats the waste-waters coming from the paper mill, pulp mill and wood handling. The WWTP performs primary clarification, from which the primary sludge is directed to a mixing tank. The primary sludge for the present study was collected before mixing with the secondary sludge. The solid content of untreated primary sludge is typically about 2–4%. In this case the original solid matter was 4.3%. First, the bigger particles and flocs were screened and then the screened primary sludge was thickened with a laboratory membrane filter (Outotec Larox MFP 0.3), equipped with polypropylene filter (ASKO T50), press to the solid content of 42.7%. The primary sludge contained 25% of inorganic matter. The wood flour was prepared from spruce (*Picea abies*) and it was produced in the laboratory from dried lumber by hammermilling and sieving (20-mesh). The components amounts are follows: HDPE 50%, MAPE 3%, lubricant 3%, and 44% either wood flour (Reference) or primary sludge (PrSl-HDPE).

### 2.2. Processing

The composite material was prepared to a profile by direct extrusion with a conical counter-rotating twin-screw type extrusion machine, CE 7.2 FE (Hans Weber Maschinenfabrik Gmbh). The gravimetric feeding system included a main feeder connected with side feeders for each individual component. All components were fed into the extruder through the main feeder. The temperatures and other processing parameters are presented in Table 1.

### 2.3. Testing

The samples for the mechanical tests were prepared by cutting from the extruded profile. The dimensions of the samples were according to standards. The tests were performed with a testing apparatus, Zwick Z020 (Zwick Roell group). The hardness, tensile, and flexural strengths were measured according to standards EN 1534, EN ISO 527, EN 310, respectively. The impact strength was determined with a Zwick 5102 Model impact tester, according to standard EN 179-1. Some of the tested impact strength specimens were examined with a scanning electron microscope (SEM), Hitachi SU3500.

## 3. Results and discussion

### 3.1. Composite manufacturing

The share of HDPE is one half in the composite structure, which enhances adhesion at the interface. Lu et al. (2005a) have found that the amount of thermoplastics should be equal or larger than that of fiber for the adhesion to be sufficient. Huang et al. (2012) have found that paper mill sludge as a filler has a similar effect on the extrusion process as wood fiber, if the HDPE matrix is maintained at the commonly used level. In addition to the main raw materials, additives (lubricant and coupling agents) are utilized in composite production to assist in manufacturing and improve the properties. For example, various coupling agents have a significant effect on the mechanical properties of composites, but too high a content decreases the effectiveness of coupling (Lu et al., 2005b; Khademieslam and Kalagar, 2016). Also, the higher level of lubricant decreases the strength of the composite (Bettini et al., 2013). Yemele et al. (2013) report that the addition of lubricant and a coupling agent improved the flexural and tensile strength properties in some HDPE composites, but toughness and strain were reduced.

The processing parameters are listed in Table 1. It can be seen that primary sludge as a part of the composite requires higher temperature in the manufacturing. A lower melt temperature reduces energy use and the need for cooling, which is an important benefit. Also, reduced melt temperatures decrease the change of degradation (Rauwendaal 2010).

SEM pictures of the tested surfaces are shown in Fig. 1(a) to (d). Fig. 1(a & b) are "Reference" specimens, and Fig. 1(c & d) are "PrSl-HDPE" specimens. Wood particles are detectable in the reference specimens, which can be proved by bordered pits, which are pointed at by black arrows. Small circular cavities are detectable in PrSl-HDPE pointed at by white arrows. The cavities indicate that the materials react slightly in the manufacturing phase, and therefore the bonding may not be optimal (Turku and Kärki 2014). A previous study has shown that paper mill sludge contributes to the adhesion and dispersion of the filler in the matrix (Khademieslam and Kalagar, 2016), and Fig. 1 supports this assertion. The small size of the filler enhances the interfacial interaction between the filler and the matrix further (Ismail and Salmah Bakar, 2005).

### 3.2. Mechanical properties

The mechanical properties (tensile, flexural and impact strength and hardness) of the composites were tested, and numerical values of the results are presented in Table 2. Generally, the PrSl-HDPE composites had slightly better mechanical properties than the reference composites, which may have been due to their lower lignin content. According to Bouafif et al. (2008), a lower lignin concentration contributes to the ability to form ester bonds with MAPE.

### 3.3. Tensile properties

Tensile test provides information about stiffness, strength, toughness and ductility of a material (Eftekhari and Fatemi, 2016). The reference and PS-HDPE composites had almost congruent tensile strength and tensile modulus and there were no remarkable differences in the standard deviations in the results. However, the tensile strengths decreased and modulus increased compared to the values of neat polymer. It has been noted that the lubricant used (Struktol TPW 113) reduces tensile strength if its level is too high in the composite, which might be due to the interacting effect with the compatibilizer (Bettini et al., 2013). The lubricant facilitates the extrusion, but on the other hand, it deteriorates rigidity and strength (Santi et al., 2009). Girones et al. (2010) have found that the increasing content of sludge in composites resulted in materials with lower deformation at break. However, 44% of primary sludge instead of wood flour as a reinforcing phase showed a significant increase in deformation of the composites. Addition of coupling agent increase to deformation capabilities of the composites because it enabled a more effective stress transfer (Girones et al., 2010). Elongation at break is higher as impact strength is improved, in agreement with previous study (Bertin and Robin, 2002).

**Table 1**
Processing parameters of the composites. (± *italic* values below the results indicate standard deviations).

| Composite | Temperature (°C) barrel[a] | tool | Melt temperature (°C) | Melt pressure (MPa) | Feeding rate (kg/h) | Screw speed (rpm) |
|---|---|---|---|---|---|---|
| Reference | 139 ± 6.1 | 140 | 140 | 2.3 | 20 | 13 |
| PrSl-HDPE | 171 ± 9.2 | 176 | 174 | 4.0 | 20 | 14 |

[a] Average temperature in the mixing zone (total of 7 measurements).