

Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
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ULTRAVIOLET STABILITY OF MIXED WASTE PLASTIC COMPOSITES

Examiner(s): Professor Timo Kärki
D. Sc. Marko Hyvärinen

ABSTRACT

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Plastic waste disposal is one of the most challenging problem of the current era. It is non-degradable, causes soil and water pollution and thus have a dangerous impact on nature and mankind alike. Until 2018, most of the plastic waste from developed countries were sold or sent to China for further treatment; however, since then, China has imposed an import ban on many types of plastic waste coming from abroad. This directly led to an influx in plastics waste in various sorting centers across many waste exporting nations. Additionally, Waste Framework Directive set up by EU is compelling EU members to find new ways to recycle municipal solid waste (MSW). These political changes opened a big field for different research works to find efficient ways of how waste could be recycled. It has been well documented that increase in plastic waste is directly related to world's population growth, which in turn leads to more plastics production for consumers to use every year. The main issue is to separate different plastic grades from each other. One solution can be blending a mixture of different plastics grades thus saving energy, time and resources.

In order to protect the color and structure of the plastic material in outdoor applications, it is important to use ultraviolet (UV) stabilizers. Tinuvin 770 DF HALS and Chimassorb 81 UVA light stabilizers were added to the plastic blends. CIELAB spectrophotometer test was applied after accelerated weathering with a xenon lamp, where Chimassorb 81 stabilizer showed better results. The tensile test showed that the addition of UV stabilizers also affects the mechanical properties of the samples after accelerated weathering tests. Tensile modulus results of the samples with UV stabilizers display higher value compared to samples without UV stabilizers. Overall mixed plastic waste showcases a good level of mechanical properties similar to LDPE pure plastic grade. Hence there is good potential for recycling mixed plastic waste.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARS	Automobile Shredder Residue
CDW	Construction and Demolition Waste
EPR	Extended Producer Responsibility
HALS	Hindered Amin Light Stabilizer
MSW	Municipal Solid Waste
MPW	Mixed Plastic Waste
MFR	Melt Flow Rate
NIR	Near Infra-Red
PRO	Producer Responsibility Organization
WEEE	Electric Electronic Equipment
WPC	Wood Plastic Composite
UV	Ultra Violet
UVA	Ultra Violet Absorber

1 INTRODUCTION

According to World Bank Group about 1.3 billion tons of solid waste were produced in 2012, and it could rise up to 2.2 billion tons by 2025 (World Bank Group, 2015). Waste and waste disposal are the greatest challenge faced by mankind in the 21st century. It has severe detrimental impact on both mankind and nature alike. Additionally, waste disposal methods such as landfill or dumps can make the surrounding land infected and odorful; and if leaked into a water source or stream, can make it contaminated for both human consumption and aquatic life. Burning of waste material causes concern related to emission of harmful gases in the atmosphere, which has a direct impact on the health of the nearby habitants. Waste also had negative influence on the economic situation of the region. Foul sight and smell of waste in the landfill closer to cities can affect tourism, nearby agriculture and fishing industry can also be severely affected by the contaminated waste Proper recycling of waste can help in minimizing some harmful effects of waste and is a less costlier methods than compared to managing waste disposal afterwards. (UNEP, 2016)

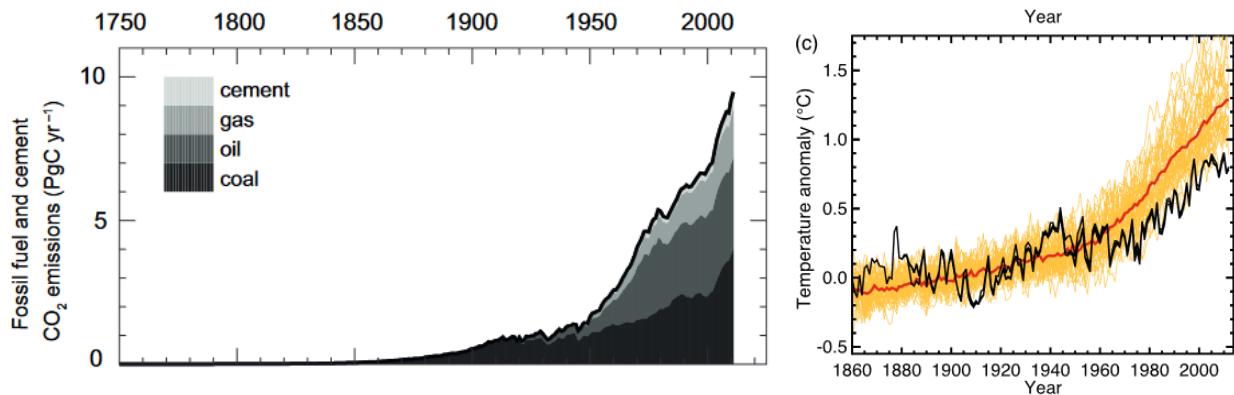


Figure 1 CO₂ emissions grow over the years compared with the mean surface temperature of the Earth. (IPCC, 2013)

Another major concern is global warming which is caused by burning of fossil fuels in industry and transportation sector and emissions coming from landfill and open-air incineration. Due to global warming, the atmospheric and ocean temperature has risen up drastically (as shown in Fig.1), which leads to ice melting and increase in sea level. Since 1901 the mean sea level has risen almost 0,2 m. Melting of ice effects the global water cycle

and climate. By using proper waste management, greenhouse effect can be reduced by 15%-20% .(IPCC, 2013)

Table 1. Global warming potential emissions. (World Bank Group, 2015)

CONTAMINANT	LIFETIME	GLOBAL WARMING POTENTIAL (GWP) TIME		
		20 years	100 years	500 years
Carbon Dioxide	long	1	1	1
Methane	12.4 years	86	34	8
Black Carbon (BC)	3-11 days	1200-3200	300-1000	100-400
Nitrous Oxide	121 years	270	300	150

In table 1, four main emission gases are shown with their relation to the global warming effect. It's obvious that black carbon mostly influencing global warming. Black carbon is produced during uncontrolled waste burning and waste transportation. Methane emission is coming from waste landfills and dumping sites and nitrous oxide from composting and waste-to-energy plants. (World Bank Group, 2015)

Fig.2 shows the different emission from different sources and also describes ways to avoid emissions. However, the emissions from open dumping, landfills, and burning of waste is impossible to prevent. In order, to reduce the effect of global warming, more and more waste should be recycled thus resulting in fewer emissions. (World Bank Group, 2015)

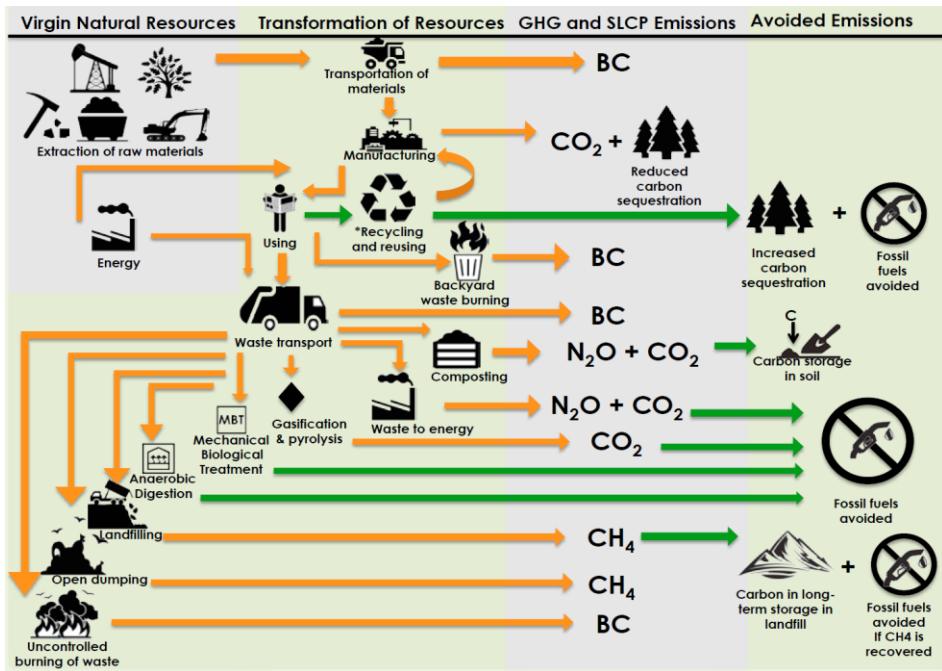


Figure 2. Emissions coming from waste management (World Bank Group, 2015).

Transportation of waste is also increasing the amount of black carbon to the atmosphere. According to a recent investigation, transportation creates almost 23% of all CO₂ emissions globally. (Chauhan, Kärki and Varis, 2019)

1.1 Waste management legislation

Today in the world every human produces on average 0.74 kg of waste in a day. The amount of waste varies from 0.1 to 4.5 kg per capita. In developed countries, the quantity of waste per capita is much higher than in developing countries. However, the level of waste management in most developed countries is very high and efficient, however, in developing countries more than 90% of waste is dumped. In developed countries, the government is implementing main waste management layout, laws and responsibilities for the local municipalities to follow. However, in developing countries the situation is different as shown in Table 2. Some common issues come from lack of support from the government with unclear laws, lack of financial resources, bad planning, and management. Additionally, some African countries are in the initial state of developing their waste management systems. The waste treatment methods differ from country to country and even inside a country, these methods can differ amongst various local governments. However some common logic could be seen in many countries by classifying the waste into different streams like solid waste,

medical waste, and hazardous waste and trying to manage them differently. (World Bank Group, 2015)

Table 2. National Waste Management Systems (World Bank Group, 2015).

Income group	Total Number of countries	Defined waste management guidelines	Not defined waste management guidelines	No information available	Share in percent.
High income	78	75	2	1	96%
Upper-middle income	56	47	4	5	84%
Lower-middle income	53	47	1	5	89%
Low income	30	18	1	11	60%
All	217	187	8	22	86%

A quite common practice for many countries is to organize special departments that are responsible for controlling and pushing the laws related to waste management. One of their goals is to centralize waste operation on a national level to have more efficient waste management processes and control. Waste management departments could be found in 148 countries. (World Bank Group, 2015)

There are some examples of how legislation can impact the situation of waste management. In San Francisco city was launched a program in 2002 to achieve zero waste to landfills until 2020. That strategy was supported by strict legislation, public and political support, financial investments. The city banned the use of plastic bags at shops, set the law for recycling the construction waste and even prohibited to use plastic water bottles. San Francisco was collecting actively bio-waste and distributed it between local farmers. In 2012 the city recycled or turned into energy almost 80 % of whole waste, which is the highest record in the United States. (World Bank Group, 2015)

One of the best examples of waste management could be seen in Japan. In this country, National and local governments are in strong cooperation with waste treatment. Local government is responsible to collect the data, create a reasonable waste management plan for the next 10 years and share it with the national government. Also, all municipalities are

following nation laws including water and air pollution controls. The national government also support municipalities with 60 % of waste management costs. This close cooperation gave a result that recently only 1 % of solid waste is landfilled in Japan. (World Bank Group, 2015)

EU has set up a Directive 2008/98/EC on waste so-called Waste Framework Directive. This directive enforces some basic waste management principles to treat the waste without harming habitants, environment, animals, and plants. Also, it pointing out the main target which should be achieved in 2020- 50% recycling of Municipal Solid Waste (MSW) and 70% of Construction and Demolition Waste (CDW). (European Commission, 2019) Fig.3 explains that initially it is necessary to prevent possibly incoming of waste, since some of waste can be reuse or recycle. While, recovery and disposal is the most unlike treatment of waste.



Figure 3. EU waste management framework (European Commission, 2019).

In the EU almost the 25 years working a waste management scheme called extended producer responsibility (EPR), where producers are in charge of their product life cycle see Table 3. EU set up special directive and guidelines for the members about different waste streams, who has still flexibility to decide their way how to follow them. Also, outsource companies like producer responsibility organizations (PROs) exist on the market to help companies with legislation aspects of the product life cycle. EPR implementation since it

covers the costs of the product future lifecycle. Also, it creates competition among PRO companies, which leads to more efficient and technological waste management. (World Bank Group, 2015)

Table 3. EU member implementing EPR (World Bank Group, 2015).

Legal framework	EPR scheme	Member state number
Covered by Special European Union directives	Electrical and electronic equipment	28
	Batteries	28
	Packaging	26
	End-of-life vehicles	24
Not covered by Special European Union directives	Tires	20
	Graphic paper	11
	Oils	10
	Medical waste	10
	Agricultural waste	8

EPR implementation since it covers the costs of the product future lifecycle. Also, it creates competition among PRO companies, which leads to more efficient and technological waste management. (World Bank Group, 2015)

An interesting approach was introduced in South Korea, where the government created a digital system of waste management control. The system can collect data from waste production place, transportation, and utilization. It tracks licenses and documentation, creates all waste treatment transparent and eliminates uncontrolled waste dumping. Also, the system is programmed to take a waste fee from each habitant based on the weight he is produced, which leads to a result of a 20 % decrease in food waste in Seoul. (World Bank Group, 2015)

1.2 Waste Market Analyze

The main waste products on the secondary material markets are glass, wood waste, metals, paper and board, plastic and textiles. Around 800 million tons of a different kind of waste was recycled in 2010. Recently recycling covers nearly 15% of whole waste generated, without construction and demolition waste. (UNEP, 2016)

Also, valuable carbon and glass fibers are difficult to recycle from their respective waste composite and if recycled carefully can be much more profitable than manufacturing composites using virgin fibers. (Karuppannan Gopalraj and Kärki, 2020)

Fig.4 showing the average amount of waste produced in the world regions. East Asia and Pacific are most populated region in the world, therefor the most of waste is produced there.

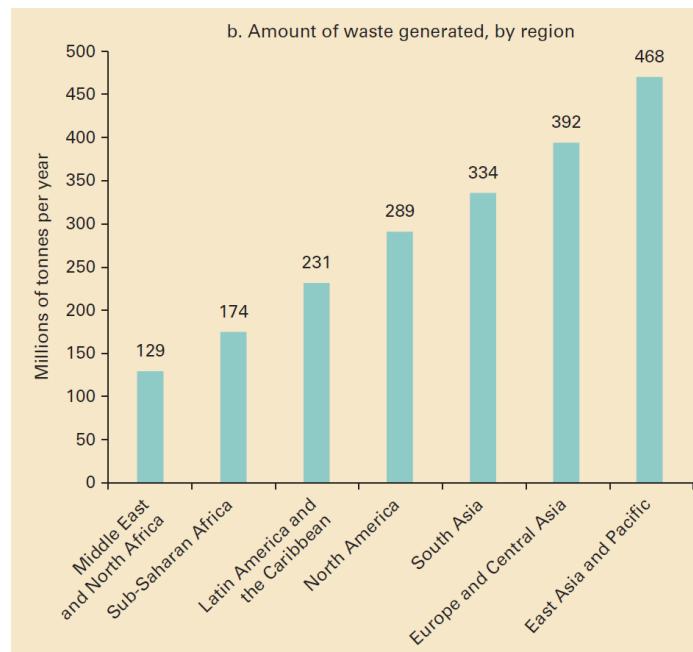


Figure 4. Global solid waste production (World Bank Group, 2015).

Asian countries represent the most important market for secondary materials. Many years developing countries of Asia importing recycling materials from developed countries. This strategy creates a valuable economy grow in developing countries, like India, China and Turkey. (UNEP, 2016)

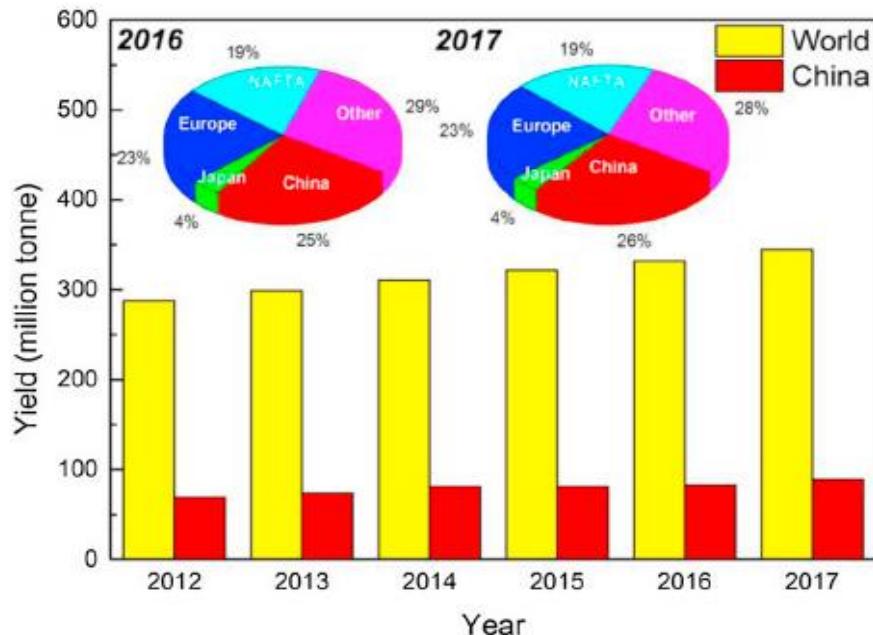


Figure 5. Statistic data of plastic production (Wang, Zhang and Wang, 2019).

Recently the trade of plastic waste is about 15 million tones, which is only 5% of the amount of plastic produced in the world. The market for waste plastic was dominated by China. It was importing globally around 56% of secondary plastic material (UNEP, 2016). However, in 2017, the government of China forbids to import waste plastic and many other types of solid waste, to help protect habitants health and environment. (Zhang, Morse and Ma, 2019)

1.2.1 MPW streams

MPW can be found from different sources. On Fig.6 shown 4 main streams from where most of the MPW is coming: automobile shredder residue (ARS); CDW; MSW and electric and electronic equipment (WEEE). (Wang, Zhang and Wang, 2019)

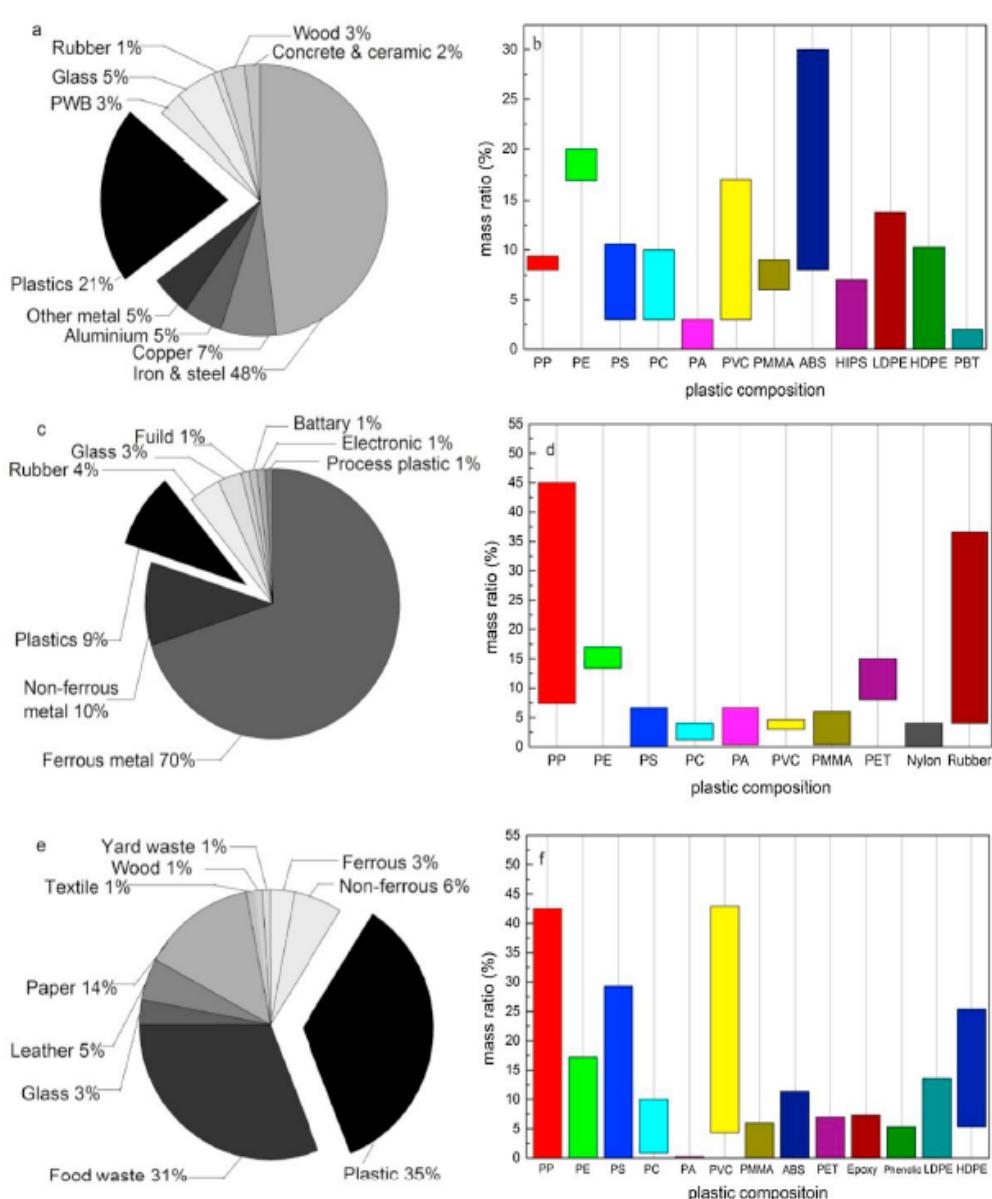


Figure 6. Estimated proportions of the plastic grades in a) WEEE, c)ASR and e)MSW (Wang, Zhang and Wang, 2019).

1.2.2 MPW sorting issues

The bigger the stream the more challenging it is to separate different types of plastic. Exist several methods to separate different types of plastics:

- Electrostatic separation. Different plastic blends have unique electrical properties, based on that they could be separated by going through the electromagnetic field.
- Density separation. The difference in plastic density is from 0.1g/cm^3 to 2g/cm^3 . By adding liquid into the mixed plastic different density types of plastics are separated.
- Spectroscopic separation. By scanning different plastic compounds with specific light frequency, the spectrum of the absorbed light will tell the grade type of plastic.
- Flotation Separation. Plastic compounds have different wettability, which could be regulated by having special pretreatment or using wetting agents. In the end, plastic is separated by floating on a different level. (Wang, Zhang and Wang, 2019)

Separating of plastic is still requires energy sources and can be costly. In this study, mixed plastic waste (MPW) will be not separated. Instead, the mixed plastic will be extruded as a blend. Still, it is important to understand which grades of plastic are used in a mixture. For this near-infrared (NIR) spectroscopy will be applied.

1.2.3 Construction and demolition waste

Whenever there is new construction, renovation or demolition happened the construction and demolition waste is needed to be managed. This type of waste could come from buildings, roads or tunnels constructing sides. On Fig.6 showed that CDW taking the biggest part in hole waste production. (UNEP, 2016)

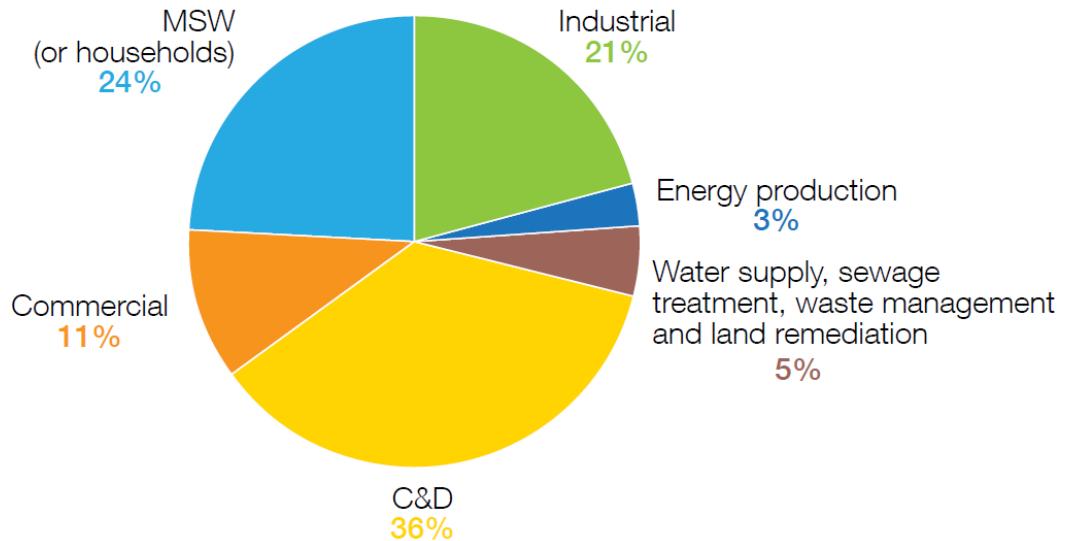


Figure 7. Quantities of waste from different sources (UNEP, 2016).

CDW could be divided into inert waste, which usually consists of cement materials and non-inert compound of metallic, glass, plastic and gypsum waste. Table 4 shows that about 341 Mt of CDW was generated in Europe in 2012. About 1.5 Mt is plastic and 5.5 Mt is wood. (European Commission 2017)

Table 4. CDW managed in Europe in 2012 (European Commission, 2017).

Waste types	Generated CDW (Mt)	Baseline scenario		Optimized scenario	
		% recycled	Mtonnes recycled	% recycled	Mtonnes recycled
Inert waste	315	50%	158	80%	252
Noninert waste					
Metallic waste	15,6	80%	12,5	95%	14,82
Glass waste	1,56	6%	0,093	50%	0,78
Plastic waste	1,56	25%	0,39	50%	0,78
Wood waste	5,46	30%	1,64	50%	2,73
Gypsum waste	2,34	10%	0,23	20%	0,468

Of course, depending on the region from where CDW comes from the composition of the materials could be different. It also depends on is it construction waste or demolition waste composition.

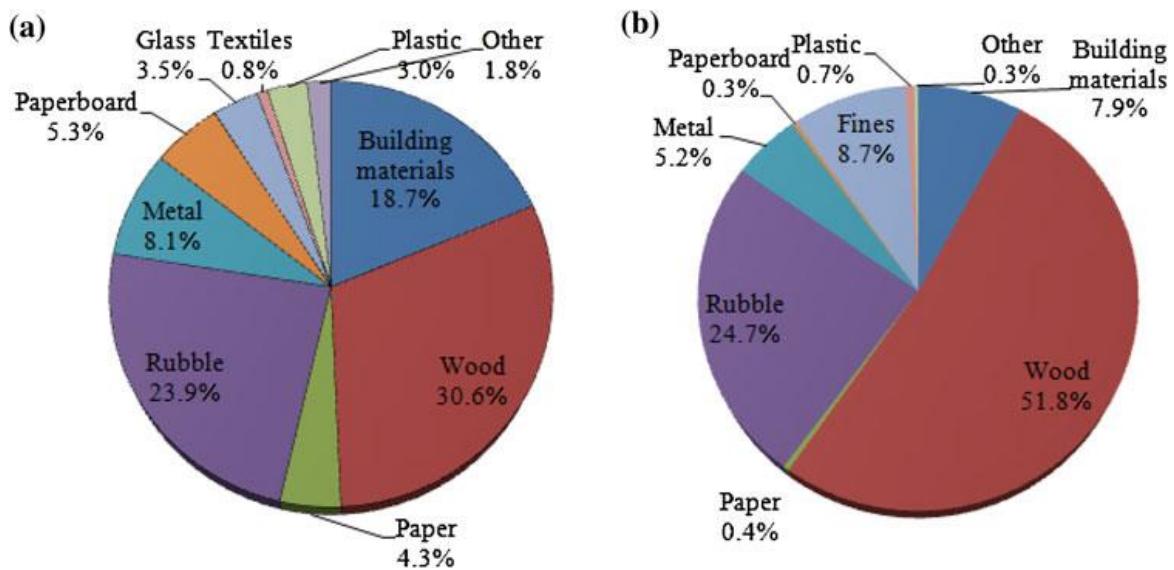


Figure. 8 CDW a) Construction waste b) Demolition waste (Yeheyis 2012).

The amount of plastic is less in demolition waste since some demolished buildings are built in a time when the plastic materials were not used as much as recently Fig.8.

Depend on the region where CDW has collected the composition of materials may vary. For example, the case study made in Finland where several samples were taken from the waste management center showed quite a different mixture of the materials compare to the EU average.

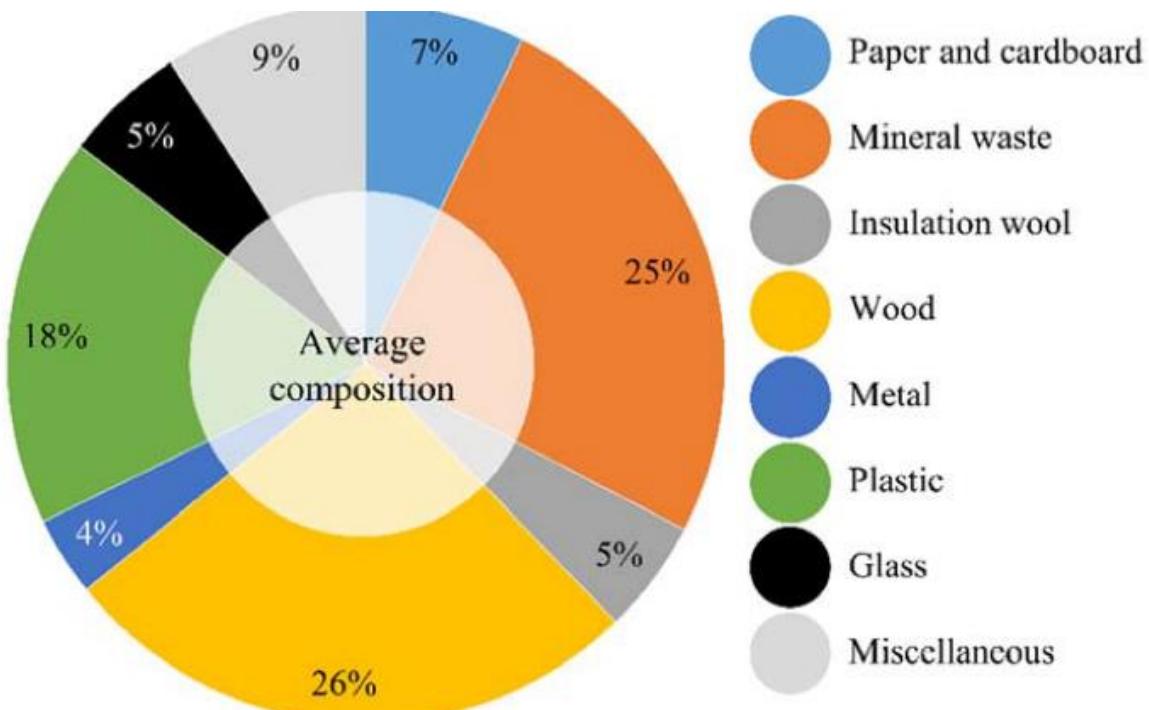


Figure 9. A mixture of materials from CDW (Liikanen *et al.*, 2019).

1.3 WPC's (long version)

WPC material consists of wood in a form of fiber or flour, plastic material, and other special additives. A common application of WPC could be found in building and furniture production. WPC is a good candidate to substitute the wood materials but with better mechanical properties. Usual polymer materials used in WPC are PE-polyethylene, PP-polypropylene, and PVC- polyvinyl chloride. Plastic amount in WPC varies from 30-70% of total mass (Yáñez-Pacíos and Martín-Martínez, 2018). Most commonly production of WPC requires extrusion and injection molding processes. For better adhesion and homogeneity between wood and thermoplastic components, special coupling agents are used. (Liikanen *et al.*, 2019)

1.4 UV stabilizers

Ultraviolet has a negative effect on the plastic and WPC materials. It destroys the cap layer of material and creates photodegradation. This leads to a wearing of the compound, and weakening the mechanical properties. To protect polymers from UV radiation Ultraviolet

absorbers (UVA) and hindered amine light stabilizers (HALS) are mainly. (Jin, Stark and Matuana, 2013)

The working principle of UV absorbers is to transform UV radiation into heat. Absorption will depend also on the thickness of the tested sample. The thicker the protection layer of the sample the better is absorption. Chimassorb 81 presented in Fig.10 is UVA stabilizer which will be used in this study

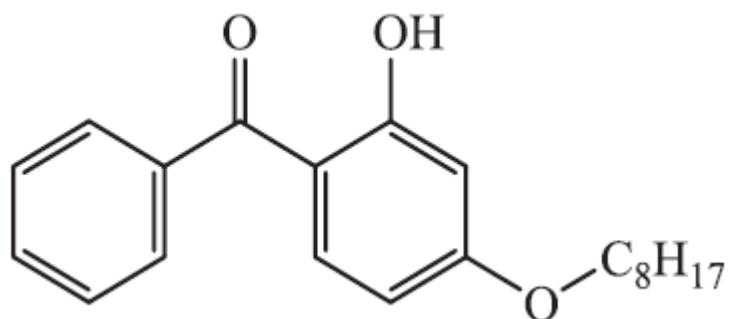


Figure 10. Chemical structure of Chimassorb 81 (Marzec *et al.*, 2017).

The working principle of HALS is different, instead of absorbing energy the process of quenching of the material and radical scavenging is taking the action. Therefore, the effect of UV protection does not rely on the thickness. HALS are likely used in the protection of thin films, fibers and sheets. (Wilén and Pfaendner, 2013)

Tinuvin 770 showed on Fig.11 is one of HALS which prevents polymer degradation. (Valera and Bode, 2014). Tinuvin 770 behaves as a material with a surfactant structure, consisting of the hydrophilic head with a hydrophobic chain.

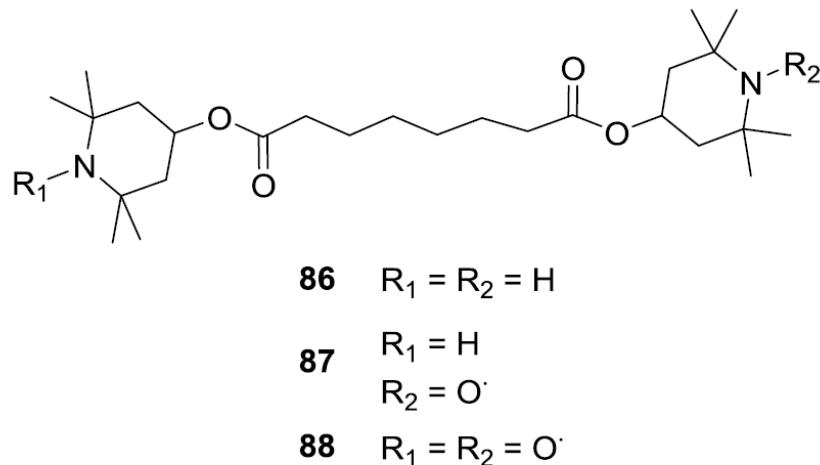


Figure 11. Chemical structure of Tinuvin 770 (Valera and Bode, 2014).

1.5 Objective

The objective of this study is to analyze the grades of the plastics coming from MSW and investigate the mechanical properties of the polymer blend made from MPW. The suitable UV need to be investigated, which will protect the mechanical properties of the material. Samples will be measured before and after applying the UV weathering test. Finally, through the tensile test, the mechanical properties of the mixed plastic will be obtained and compared with references.

1.6 Research problem and questions

1. What type of UV protection to use in MPW blends?
2. How perspective is the utilization of the recycled MPW material?

2 MATERIAL AND METHODS

Mixed plastic waste was taken from two different Municipal solid waste disposal sites. 5 kg of plastic waste was taken from “P” source and 5 kg from “F source”. Source “P” consisted mostly of packaging material waste after that plastic was separated into different grade groups using NIR. Microphazir Analyzer Fig.12 was used as a tool for NIR measurement. This device can scan solid, powder, liquid surfaces or any material which can reflect the light. (Thermofisher, 2020)

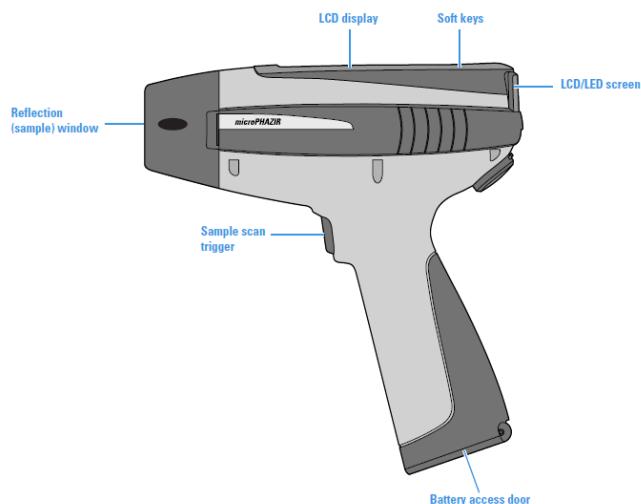


Figure 12. microPHAZIR Analyzer components (Thermofisher, 2020).

Every piece of plastic waste was placed on the reflection screen of the analyzer and after the trigger is pressed in a short period the plastic grade was shown on the LCD display. Some food packages blended from a few different plastic grades were not possible to identify. Also, usually it is not possible to identify dark surfaces materials, where the reflection of light is low. Mixed plastic waste also consisted of non-plastic members, which were excluded from the MPW, see Fig.13.



Figure 13. Non-plastic waste found in source “P” left and source “F” right.

The non-plastic waste found from the sources was carbon, wool, aluminum foil, rubber materials, and soil particles.

Table 4. Types of materials from two different sources.

Plastic grade	Waste “F” kg	Waste “P” kg
PE	2,04	4,18
PET	0,82	0,06
PP	0,54	0,24
PVC	0,11	0,05
PS	0,69	0,01
Not Defined	0,8	0,16
Waste	0,13	0,36
ABS	0,04	
PE/PET	0,11	
Total:	5,28	5,06

After all, materials were defined Table4. On the Fig.14 showed that source “F” -household waste plastic consists of more types of plastic grades compare to source “P”-packaging plastic waste was most of the waste were LDPE films.

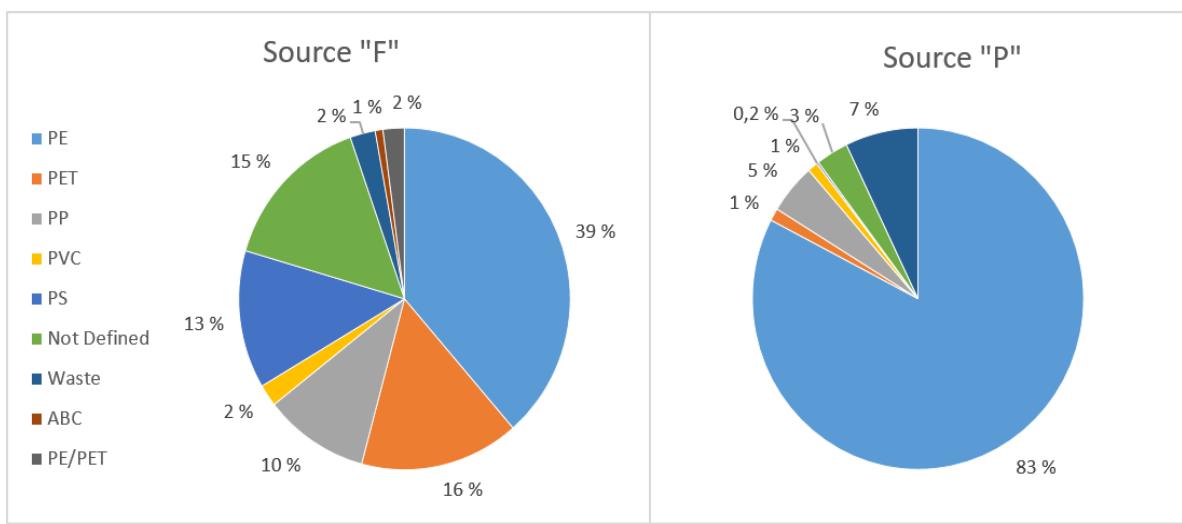


Figure 14. Types of materials from two different sources in percent.

2.1 Bulk material preparation

After NIR measurements each group of plastic was granulated in low-speed granulator SHINI SG-1635N Fig.15. Efficient blades of this granulator cutting material to Ø4-Ø12 size particles (Shini, 2020). Depends on the size of the particle suitable screens were used.



Figure 15. Low-speed granulator SHINNI SG-16235N (Shini, 2020).

Two of 1.5 kg bulk material was prepared by mixing crushed plastic grades according to the proportion on Fig.16 the bulk material density for source “F” was 127 kg/m³ and “P”- 100 kg/m³.

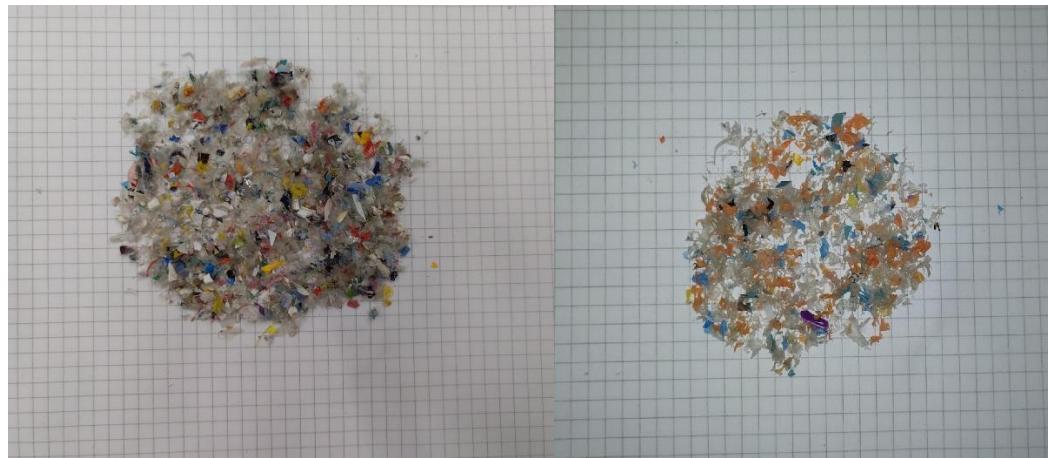


Figure 16. Granulated bulk material. Left “F” right “P”

2.2 Preparation of samples

The next step after bulk material was prepared is to make extrusion molding of testing samples. For this purpose, the extrusion machine BOY 30 was used. For each “F” and ”P” material types were made 36 six samples.

The first 12 samples were made as a reference without the addition of UV stabilizers. The next 12 samples were made with the addition of 3 % and 5% UV stabilizer Tinuvin 770 DF respectively. And the last 12 with the addition of 3 % and 5% UV stabilizer Chimassorb 81 respectively. The naming algorithm is shown in Table 5.

Table 5. The naming of the samples.

Source “P”	Name	Source “F”	Name
No UV stabilizers	1...6Pin	No UV stabilizers	1...6Fin
No UV stabilizers	1...6PinX	No UV stabilizers	1...6PinX
3% Tinuvin	1...6P3T	3% Chimassorb	1...6F3C
5% Tinuvin	1...6P5T	5% Chimassorb	1...6F5C
3% Chimassorb	1...6P3C	3% Tinuvin	1...6F3T
5% Chimassorb	1...6P5C	5% Tinuvin	1...6F5T

In Pin samples, no UV stabilizers were used as well they were not going for accelerated weathering. In samples, PinX was no addition of stabilizers but they were treated in xenon chamber. Pin and PinX were made as a reference to compare them with samples where UV stabilizers were used.

2.3 Injection molding of samples

Granulated plastic waste was mixed with UV stabilizers and the injection molding process started. To extrude samples single screw BOY 30 injection machine was used. The material was added to the hoper see Fig. 17.

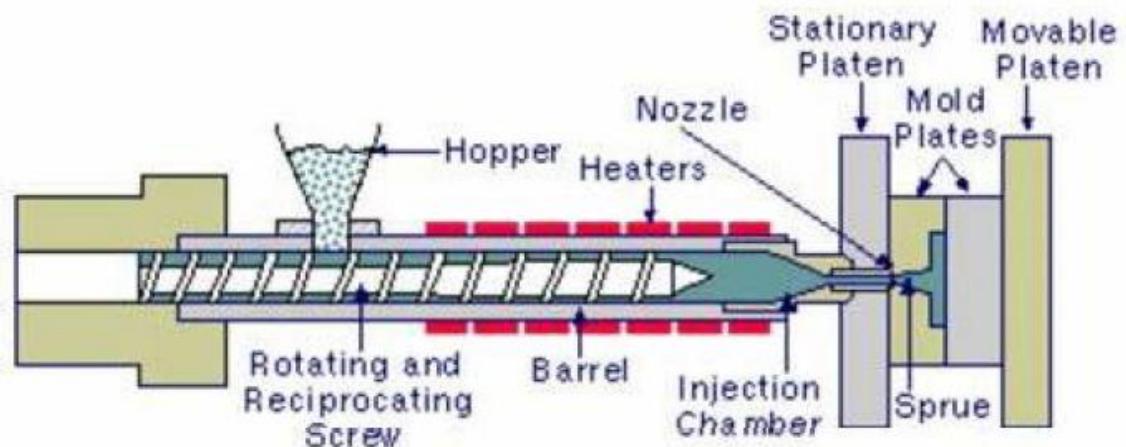


Figure 17. Single screw injection molding machine. (Srebrenkoska, Gaceva and Dimeski, 2009)

The material was processed on a temperature between 170°-190° C. The specific shape of testing sample was designed to be able to make spectrophotometry and tensile strength measurements. Dimensions of the testing piece are shown in Fig.18.

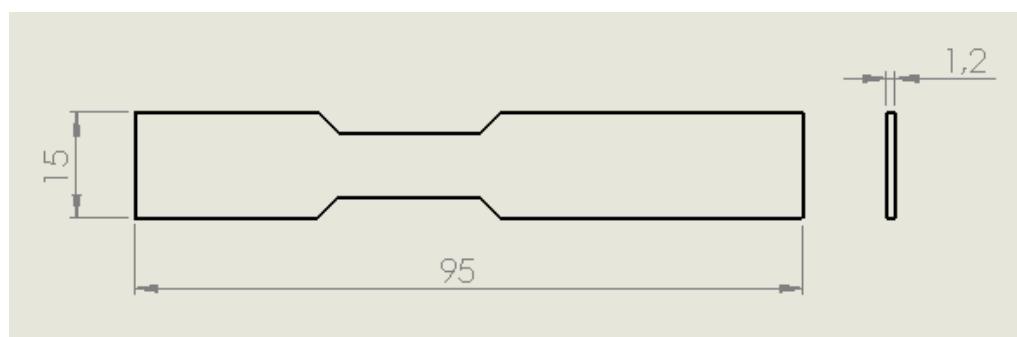


Figure 18. Dimensions of testing sample.

Since the sample was made from two sources the color of them was different. The sample from source “P” became dark green and from source “F” – grey color Fig. 19.



Figure 19. Samples from source “P” (green) and source “F” (gray).

2.4 Accelerated weathering

In this test, plastic samples are going to the Q-SUN xenon test chamber where the accelerated weathering will be applied under the ISO 4892-1.Q-Sun xenon test chamber recreate the distraction caused by sunlight and rain Fig. 20 (Q-SUN, 2020).

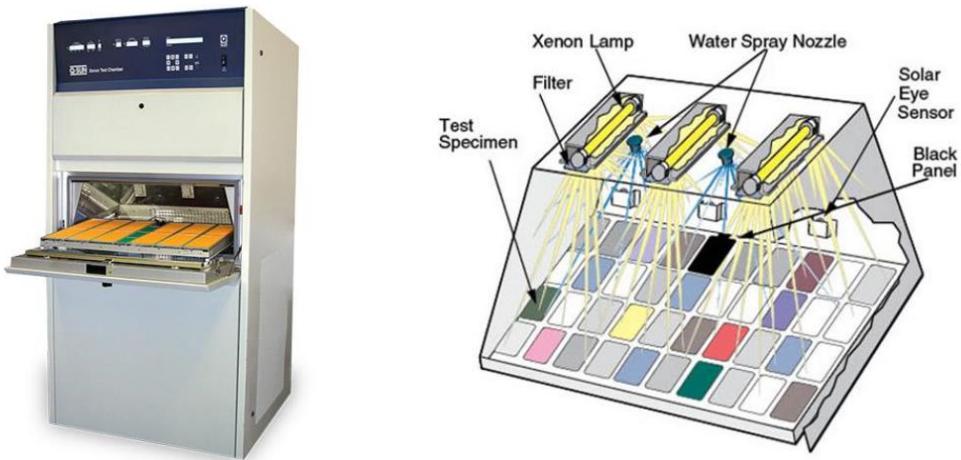


Figure 20. Q-SUN xenon test chamber (Q-SUN, 2020).

All samples are shown on Fig. 21 which are going to the xenon chamber were nailed to the pallet and mark according to the composition. 6 samples with code Fin and with code Pin, were removed from the experiment to make a comparison with weathered samples. The xenon chamber is programmed of a total of 500h of accelerated weathering. On a defined time intervals samples are taken out from the chamber measured with spectrophotometer CM-2600d to define the color change.



Figure 21. Pallet with testing samples for accelerated weathering test

2.5 Color measurement

For this experiment CIELAB color measuring system was used. With this approach, any color could be presented in three-dimensional space. This method is used often in industries as a standard for experiments with color (Hyvärinen, 2014).

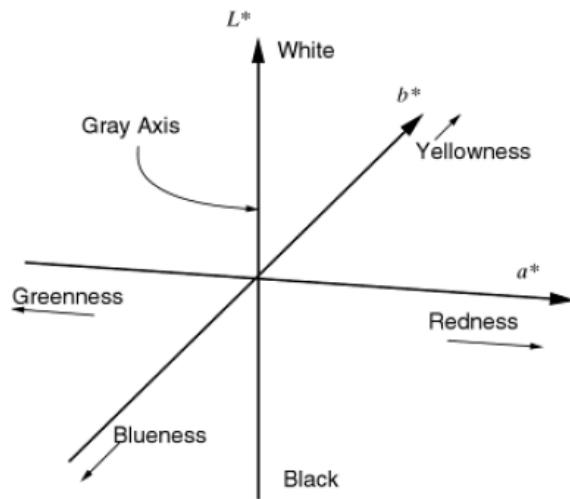


Figure 22. CIELAB three-axis color representation (Hyvärinen, 2014).

Fig.23 showing Spectrophotometer, CM-2600d used in this study. This device is well designed to use for specimens from small to large scale with a smooth surface. It is used to measure color, gloss and UV properties of the tested object (CM-2600d, 2020).



Figure 23. CM-2600d Spectrophotometer (CM-2600d, 2020).

Before measuring device need to be calibrated to define absolute dark zero, which should be made in a dark room. Absolute white zero value is set by a special white sample. Every testing specimen was placed under the screen of a spectrophotometer and after several seconds the result was shown.

The measuring intervals were 0, 25, 50, 75, 152, 296, 410 and 500 hours. Spectrophotometer gives 3 values: “L” – lightness from 0 to 100, “a” from green (-) to red (+) and “b” from blue (-) to yellow (+) according to CIELAB color space. One measurement gives 3 values L, a and b SCI (specular component included) and SCE (specular component excluded). For the measurements, SCE values will be used. The color change of each sample will be identified by the formula:

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2} \quad (1)$$

Finally, for all 6 samples from one category, the mean ΔE value is calculated for each period.

2.6 Melt Flow Rate testing.

Melt flow rate (MFR) test was made from Dynisco LMI 5000 melt flow indexer Fig.24. Samples Pin, P5C, P5F, Fin, F5C, F5T before accelerated weathering were taken for the test. The experiment was done according to the ISO 1133-1.



Figure 24. DYNISCO melt indexer LMI 5000 (*DYNISCO*, 2020).

The material for MFR test was made by granulating already extruded testing samples. The temperature used during the experiment was 230° and load 5kg. Each extrusion was performed in a specific time scale and specimens were measured on weight to determine MFR, Melt Volume Rate (MVR) and density. For each sample type, two measurements were done and the average value calculated.

2.7 Tensile strength test

The tensile test was provided on the machine Zwick/Roell Z020 Fig.25. All output parameters were performed based on a standard DIN EN ISO 527-1. All tested samples were placed on the machine jaws. The software which handles the measurement process was necessary to define the cross-section of the sample manually. The tensile test was provided for all samples after accelerated weathering treatment and for samples that were excluded from the xenon chamber as a later reference.

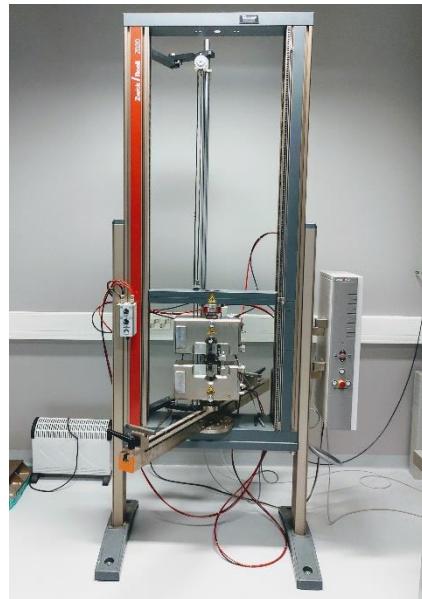


Figure 25. Zwick/Roell Z020 Tensile strength test machine.

The valuable parameters were obtained such as tensile strength, elongation at break and elastic modulus.

3 RESULTS

Fig.26 shows that the UV stabilizers affecting differently on the color change ΔE after the weathering test.

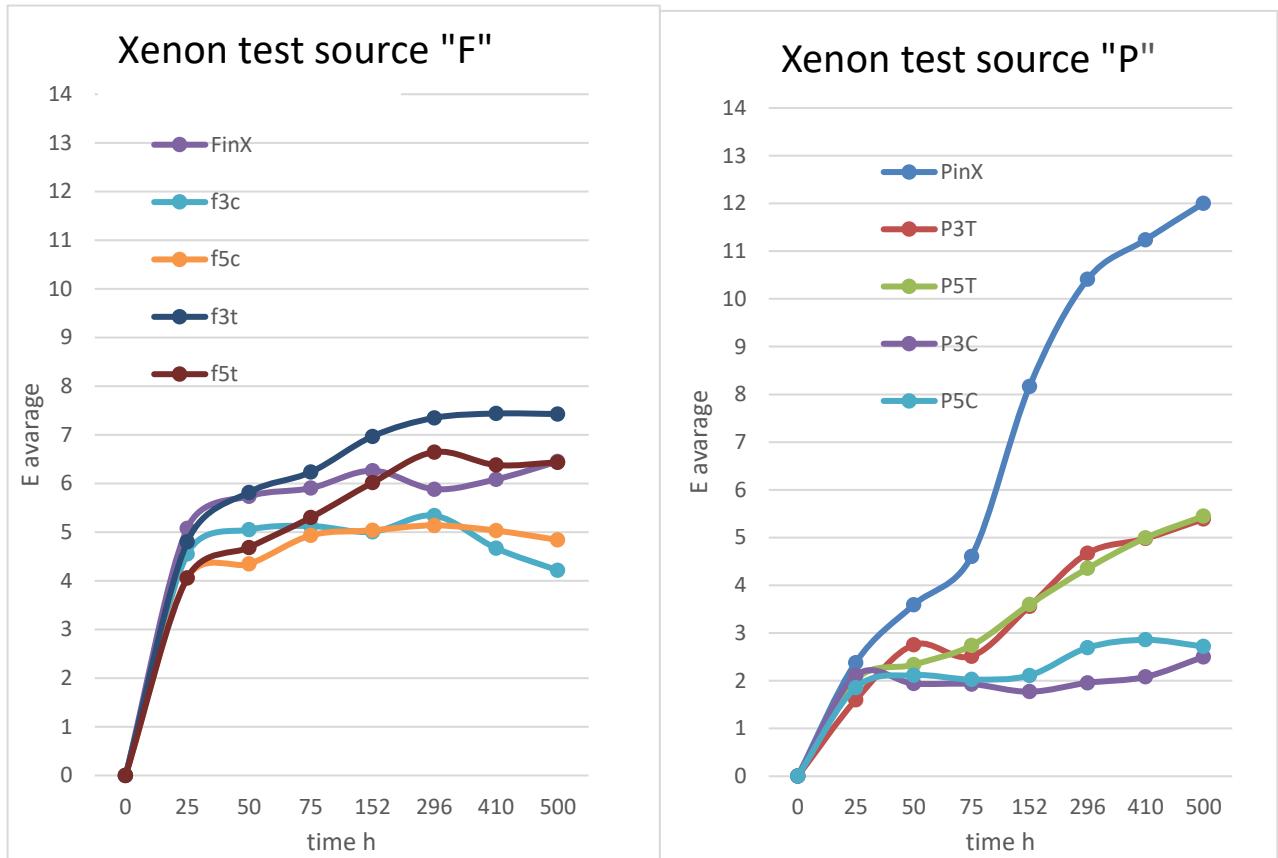


Figure 26. Accelerated weathering test results.

In general, samples, where UV stabilizers were added from the source “P”, showed slightly better results in color change compare to source “F”. After 500h of accelerated weathering samples from “P” source where Chimassord 81 was added showed ΔE between 2 and 3, whereas similar samples from “F” had ΔE between 4 and 5. “F” Samples with Tinuvin 770 stabilizer showed ΔE lying between 5 and 6 and “P” samples showing ΔE between 6 and 7. The color change on the reference samples from source “P” was the highest. Even it was expected that samples with stabilizers should show lower color change, the results from “F” source showed that samples F3T went above the Fin and F5T sample got almost the same result after 500 h. From Fig.26 it is possible to conclude that Chimassorb 81 showing less

color change and could be considered as a better UV stabilizer for mixed plastic blends. The biggest color change happened after samples being tested for 50h.

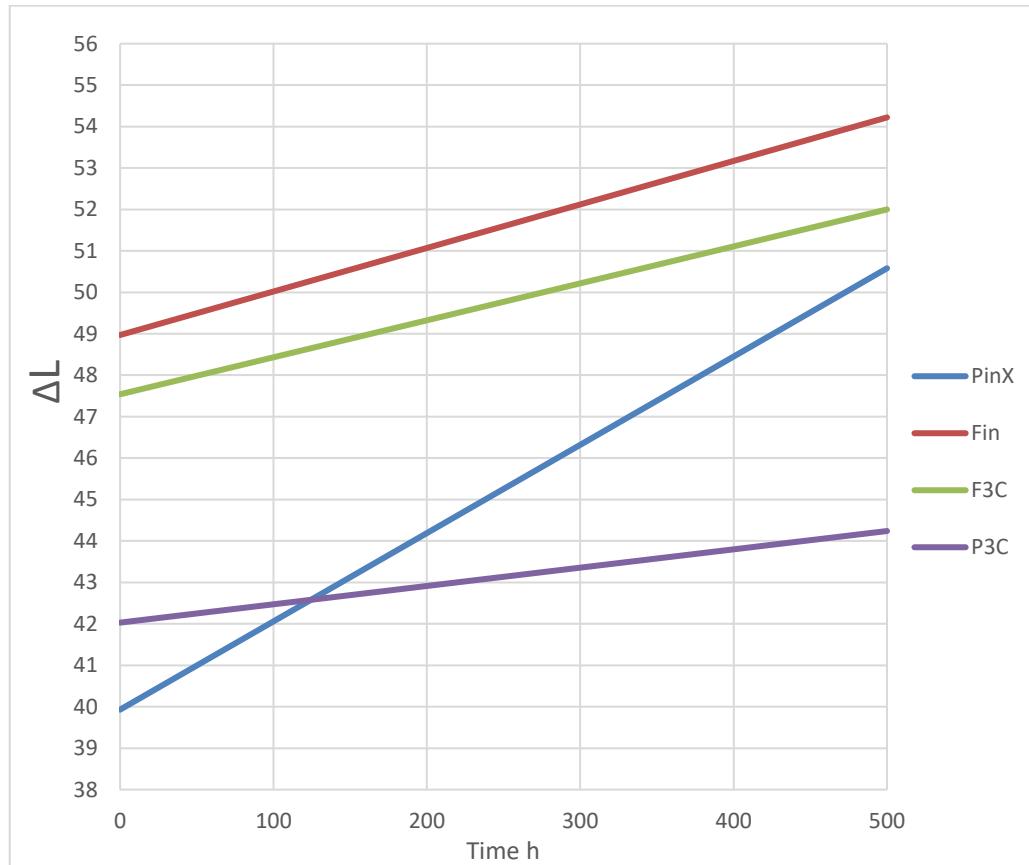


Figure 27. Lightness change results from the samples Pin, Fin, F3C and P3C.

Fig.27 shows the actual lightness change of the material. Samples P3C had initial lightness $L = 40$ and $\Delta L = 2,2$, whereas sample F3C initial $L = 47,5$ and $\Delta L = 4,5$. From both Fig.26 and Fig.27 PinX sample, where no UV stabilizer was added showing the most degraded by UV light sample. The $\Delta L = 10,5$ for PinX sample whereas for FinX it was 4,2.

Small cracks were observed on the surface of the treated samples, mostly on samples where no UV stabilizers were used. This effect was most visible on samples without UV stabilizers.

3.1 Melt Flow Rate measurement

The main plastic components of the mixed plastic blends were LDPE, PET, PS, and PP plastic grades. The results showing the density of the mixed plastic materials made from source "P" where LDPE material was dominant showing lower density compared to the virgin LDPE. The average density of plastic blend from source "F" was 1,05 g/cm³ which is higher than the range density of LDPE plastic grade and less than the density of PET. Looking at the proportion of the material of source "F" from Fig.14 It can be seen that the density result for the blend is reasonable according to the density range of virgin material.

Table 6. The result from MFR test

Sample	Temp(°C)/mass	Density (g/cm3)	MFR (g/10min)
Pin	230 °C, Load 5,00 kg	0,726	3,8 (0,15)
P5C	230 °C, Load 5,00 kg	0,728	5,18 (0,13)
P5T	230 °C, Load 5,00 kg	0,74	5,46 (0,14)
Fin	230 °C, Load 5,00 kg	1,341	4,88 (0,05)
F5C	230 °C, Load 5,00 kg	0,988	5,01 (0,3)
F5T	230 °C, Load 5,00 kg	0,823	6,4 (1,22)
LDPE		0,910-0,980	0,16-16
PET		1,16-1,58	3,00-80,00
PS		0,017-2,14	0,2-137
PP		0,886 - 1,04	0,3-130

The average density from the source according to MFR measurements "P" is 0,731 g/cm³ and the source "F" is 1,05 g/cm³. So the average difference between them is 23, 3%. The The density of bulk material for sources "P" and "F" was 100 kg/m³ and 127kg/m³ respectively. So the difference in bulk material was 27%. Therefore, the density of the material from two sources after MFR test showing almost the same average density difference compared to the bulk material. Test results showing that the MFR of source "P" is varying from 3,8 till 5,46 and from 4,88 till 6,4 of source "F". Pin and Fin sample showing lower MFR value compare to the samples with UV stabilizers. Overall MFR results of all specimens laying in a range of virgin plastic grade from which they made (MatWeb, 2020).

3.2 Tensile test measurement

For both “P” and “F” there was 12 reference sample were made for the testing. During the xenon test, 6 reference samples were going to be tested together with other samples and the naming for them was PinX and FinX. Left 6 samples Pin and Fin were used to compare the tensile test of material not being used in the Xenon test. As it is seen from the table the Pin and Fin have higher tensile test results compare to the FinX and PinX. This result explains that extreme weathering damaging the structure of plastic blends and weakens its mechanical and color properties.

Table 7. The tensile test of the specimens.

Sample	E_t Gpa	σ_m MPa	ε %
Pin	0,59	26,87 (0,9)	27,80 (0,95)
PinX	0,68	19,51 (0,9)	15,19 (1,07)
P3T	0,62	27,50 (0,5)	29,28 (1)
P5T	0,55	27,82 (1,3)	38,16 (1,73)
P3C	0,55	19,23 (1,1)	20,82 (1,93)
P5C	0,49	20,15 (0,8)	30,94 (2,49)
Fin	1,00	23,88 (1,6)	6,90 (0,87)
FinX	1,17	19,34 (2,4)	2,28 (0,37)
F3T	1,15	25,27 (2,7)	3,89 (0,82)
F5T	1,06	19,17 (2,7)	3,15 (0,50)
F3C	1,15	20,57 (2,3)	2,11 (0,25)
F5C	1,07	20,40 (3,8)	2,70 (0,66)
LDPE	0,110-0,449	2,80-56,5	13,5-800
PET	1,48-12,0	42,4-108	2,00-200
PS	0,065-24,1	10,3-200	0,5-800
PP	0,75-3,5	5,5-320	1,8-600

The interesting observation came by analyzing P3T and P5T where samples despite weathering wear have shown better tensile strength compared to Pin. Also, elongation at break was showing higher numbers for these samples. The same effect observed from another source where F3T sample also showed improvement in tensile strength. However, sample F5T had the lowest tensile strength result from its group. UV stabilizers showed a positive effect on the mechanical properties on the plastic blends. Based on results stabilizer Tinuvin 770 DF had better tensile strength and an increase of elongation break value

compare to Chimassorb 81 absorber. This effect is seen in specimens made from “P” source. Specimens P3T and P5T showed a better tensile strength test result than Pin. Specimen F3T had the best tensile test result, nevertheless, F5T showed the lowest result from the samples made from source “F”. Elongation at brake of the samples from source “P” was significantly higher compared to the samples from source “F”. The reason for that is the content of LDPE material, which has one of the highest elongations at brake properties compare to other polymer materials. Elastic modulus and other discussed properties of tested mixed plastic coincide with the range properties of virgin materials.

4 DISCUSSION

Analyze of mixed plastic waste showed that both “P” and “F” sources consisted of non-plastic waste like carbon, soil dust, and rubber materials. The MPW from packaging materials showed 2% and from MSW 7%. This non-plastic waste was excluded from the mixture of bulk material before the grinding process, however, it may have some influence on the extruded material properties if it wouldn't be ignored. The reason for the presence of other material in MPW may be in the not efficient separation methods on the waste sorting facilities. There are some possible solutions to be done considering the no- plastic waste: to have more efficient techniques for solid waste separation on the waste facilities; to have a post-separation stage before grinding the plastic to the bulk material or to include the alien material found in MPW. Of course, the inclusion of other materials will affect the resulting properties. Nevertheless, in the case is the MPW will be used in wood-plastic composites materials, the negative effect on WPCs material properties would be less compared to MPW blends material properties. Non-plastic waste material, in this case, could be treated as an additional filer material of WPCs.

Unidentified material is also one aspect that makes it difficult to predict the mechanical properties and behavior of the MPW material. Source “F” had 15% and source “P”-3% of unidentified material. Based on the Master Thesis of Nepal Suman from Composite material lab at LUT, where the MPW composition was analyzed, the amount of unidentified waste was even higher- 47,67%. Some plastic blends taken from household waste may consist of several polymer grades. Like it could be seen in Fig.14, source “F” had a 10% of PE/PET mixed plastic blend. This material could not be identified by MIR measurement, only based on the plastic grade symbols on the package it could be to separate. Also, some plastic materials marked with the number “7”-other plastics.

So, it seems that even there is an efficient way method to separate MPW on different polymer grades, still, there will be some material consisting already several different plastic grades, which will make separation of them quite challenging.

After the extrusion molding process, the samples from source “F” were bright grey colored whereas samples from souse “P”- dark green colored. Based on research made by (Attwood

et al., 2006), and (G. Iannuzzi, 2013), the color of the polymer have a straight impact on the color degradation of plastic under weathering. More dark-colored material had a less ΔE color change compared to brighter colored materials. Material from the first reference was almost similar to material from source “P”-MPW where the amount of LDPE material was more than 60%. One sample of reference was black colored, another blue colored. Material from the second reference was ABS plastic blend, one sample transparent and another grey colored. All samples were acceleratory weathered during 500h. Samples F3C and P3C were chosen for comparison since they showed the best results of color change among others.

The observation made by analyzing the results and references is that the initial brightness of the color is affecting the final ΔE change after weathering. The darker color will result in less color change compare to more bright material.

However, the addition of UV stabilizers has a more significant influence to protect the color. The biggest color change was observed in the samples PinX. Source “F” was blended from household waste and the number of different plastics varies more compare to source “P” which has more packaging material. Different materials inside MPW can already consist of a certain amount of UV stabilizers and other unknown additives (Turku *et al.* 2018). This may be an explanation for the reason why the FinX sample had less color difference after the xenon test compares to PinX. Also looking to Fig.26 it is notable that all of the curves beside PinX have a more or less similar shape. They have a rapid rise from 0 to 50h but then sliding smoothly up horizontally or even downwards. Whereas in the case of PinX the curve has a sudden jump from 0 to 50h and from 75 to 296 h. Source “P” consisted of 83% LDPE plastic grade mostly in the form of thin packaging films. Most of the material was transparent and probably no UV stabilizers were used during the production. That could be a reason how the PinX sample has shown such dramatic color change compare to other samples.

Samples P3C and sample Ref1B consisted of almost the same materials with major consistent of LDPE material. After the same procedure of accelerated weathering both samples showing almost the same results of color change.

The spectrophotometry test showed that Chimassorb 81-UVA UV stabilizer showing better protection from UV compare to Tinuvin 770 DF-HALS. The reason for that may be in the

different working principals of these two stabilizers. As it was mentioned in chapter 1.5, the UVA stabilizers showing better protection with thick materials, where HALS are more used in cap layers or thin-film protection. In this research, the thickness of the samples was 1,2 mm which can be considered more like thick material compare to thin films. Therefore, the usage of UVA Chimassorb absorber is more reasonable and gives better results.

Since some of the plastic waste can already consist of UV stabilizers, it's difficult to estimate what should be the reasonable amount of UV stabilizer added to the MPW blend. The results from Fig.26 showing that samples P3T and P5T were showing almost the same color change after 500h of weathering. The same behavior is observed with samples P3C and P5C. PinX samples showed significantly high color change. Having no initial addition of UV stabilizer could lead to the result of why the PinX sample had so notable ΔE difference from other samples.

The different behavior of samples observed from the source "F" CIELAB results. Curve FinX ending at the same point with curve F5T, and F3T sample showing the most extensive color change from all samples of source "F". This phenomenon could be explained that source "F" consisted of household waste, mostly food packaging plastic. The initial amount of UV absorbers used in the plastic blend in samples FinX may be enough for color stabilizing. Also, the type of absorbers that were used in household waste could be better than Tinuin 770. This could be the reason why the FinX sample, where no addition UV stabilizer was used showing the same color with samples F5T where stabilizers were added. Still, the differences between two stabilizers in color protection from UV are quite insignificant.

Melt properties test result was made only for 3 samples from each source. The results found from Nepal Suman master thesis work were sample was made from the MPW taken from the municipal solid waste sectors showing higher MFR equal to 16 g/10min. And the composition of different plastic grades was the same as in samples from source "F". Whereas P5T and F5T showed 5,46 g/10min and 5,1 g/10min respectively.

Samples with the addition of UV stabilizers showed a higher melt flow range, but since they're only two measurements of each group were done, it difficult to be statistically proved

does the addition of UV stabilizers will affect MFR. The test results made by (Kaci *et al.*, 2003) showing that the addition of UV stabilizers does not increase or decrease the MFR of LDPE. However, after gamma irradiation melt flow rate of samples without the addition of UV stabilizers showing a faster increase of MFR. Results from reference having almost 3 times higher MFR index. The used material in this reference was mostly made from LDPE thin films, which has a high MFR index. Nevertheless, all results not outstanding from the range of the properties given by virgin polymers.

Similar data found from Nepal Suman master thesis and (Turku *et al.*, 2018) research with plastic samples where no xenon degradation process applied, therefore it was reasonable to compare them with samples Pin and Fin. The results of the tensile strength of mixed plastic waste are near to the pure PE plastic. The proportion of PE material in sample Pin and the second reference was almost the same around 80%. These samples showing the closest result to virgin PE tensile strength value taken from the references. The consistent of different plastic grades coming from household waste is big. Therefore MPW blends are less homogenous and showing lover tensile test results. The result for from (Attwood *et al.*, 2006) was near 25 MPa and this was the average result for all samples tested in that research. The first reference showing less tensile strength, but still, this result is not far from others. The material used in this reference were less homogeneous and consisted of thin plastic films. Sample from the second reference, which consisted mostly of packaging materials showed tensile strength equal to near 17 MPa.

After comparison one reference showed results above 20 MPa and two others below 20 MPa. Based on this it's possible to assume that tensile strength of the mixed plastic waste blends varying approximately from 17 to 27 MPa. Samples from packaging material source having better tensile strength results compare to household waste. Tensile test of pure material showing higher results compares to MPW blends. The more different material existing in a mixture the less adhesion between molecules of polymers is going to happen which results in purer mechanical properties. (Turku *et al.*, 2017)

Samples PinX and FinX were no UV stabilizers were used showing a dramatic loss in the tensile strength compared to Pin and Fin samples that were not treated in a xenon chamber.

Accelerated weathering not only affecting the color change of the polymer material but also has a straight impact on its mechanical properties.

In both “P” and “F” sources Tinuin 770 showed not only protection from a decrease of mechanical properties but also an increase of tensile strength compare to the Fin and pin samples. P5T showed almost the same result as a pure PE material mentioned in reference2. There was no tensile test made for samples with UV stabilizers on which no accelerated weathering was performed. But looking to the research from (Attwood *et al.*, 2006) it seems that samples with UV stabilizers could have higher tensile strength after being aged-in-field compared to untreated samples. Therefore, having UV stabilizers in a mixed plastic blend will have two positive effects: protection of color and improving the tensile strength of a sample.

Chimassorb 81 UVA stabilizer has shown a less positive effect on the mechanical properties of samples but better on the color stabilization. Samples F5T and P3C have shown almost the same result as PrefX and FrefX. So, it could be assumed that there may be a case when stabilizer material is not well mixed with bulk material, and it's not taking an action during weathering. Similar behavior of stabilizers was observed in research work (Nikafshar *et al.*, 2017) where Tinuin 770 showed better results against polymer degradation compare to Chimassorb.

The research work of (Cheloufi *et al.*, 2014) was found a relation between the mechanical properties of plastic samples and the crystallinity rate. Depending on the number of stabilizers used and UV radiation during accelerated weathering the rate of the crystallinity rises and therefore tensile strength could show better results after weathering compare with unweathered samples. During degradation stabilizers with UV radiation having a kind of quenching effect on the plastic blend.

The content of the UV stabilizers used in mixed plastic blends were 5% and 3%. From the color protection perspective having 3% of UV stabilizers showing less color change in case of using Chimassorb 81. Source “F“ showed that having 5% of Tinuin 770 gives better protection from degradation compares to %3. However, material from source “F“ may have initially some of the UV stabilizers included. Results from source “P“ showing that both 5%

and 3% have the same result after being treated for 500h. In the case of Tinuvin, 770 further increase of UV stabilizer may led to the higher degradation rate of a material. (Motyakin and Schlick, 2002)

Samples with 5% of both stabilizers having a slightly better tensile strength compared to 3% in the source “P”. Results from source “F” showed that F5T samples have less tensile strength compare to F3T and F5C and F3C have almost the same result.

Overall its looks like there is no major difference to adding 5% or 3% of UV stabilizers into the composition. In one case adding %3 has shown better tensile strength. Based on that it may be economically efficient to use only 3% of UV stabilizer in the composition with mixed plastic in further researches.

It is noticeable that material from source “P” has a much larger elongation at break value compare to source “F”. Similar result obtained in the reference2. Plastic coming from household waste has more different polymer grades, which is less homogenous and decreasing the elongation of the sample. From Table7 it is notable that elongation at break dramatically decreases after the weathering of non-stabilized samples. Samples with UV stabilizers having a larger ϵ % value. That behavior shows that after UV degradation material begins to behave more in a brittle way. (Attwood *et al.*, 2006)

5 CONCLUSION

The focus of the research was to analyze blends from mixed plastic waste coming from MSW facilities. The literature review showed a lack of information concerning the recycling of mixed plastic waste. However, few research works were carried out where a separated waste plastic grade was analyzed which gives a good basis for comparison analyzes.

Plastic grades that were found in waste and later used in the experiments were PE, PET, PP, PVC, PS and ABS. Some of the plastic was undefined – 15% from source “F” and 3% from source “P”. The non-plastic waste material found in a stream was 2% in source “F” and 7% in “P”. Granulation process of mixed plastic is a reasonable way to process waste into bulk material for extrusion. Extrusion molding didn’t show any issues in the process, both waste plastic mixtures were easily formable.

The main experiments which were made during this research work were accelerate weathering in the Xenon chamber and tensile tests. UV stabilizers Tinuvin 770 DF-HALS and Chimassorb-UVA were added to the bulk material to see which stabilizer has better protection against light degradation. After 500h hours of accelerated weathering CIELAB test results showed that for both “F” and “P” sources have less ΔE color change when Chimassorb-UVA is added. The use of UV stabilizers showed that the color of mixed plastic waste blends becomes more stable compared to samples where no UV stabilizers were used. Also, the appearance of small cracks on the sample surface is less.

Tensile test results showed that the MPW blends have a similar mechanical property compare to virgin LDPE material. The addition of UV stabilizers not only affected the color change of the sample but also increased their tensile strength. The addition of Tinuvin 770 DF-HALS had increased the tensile strength relatively more compared to blends with Chimassorb-UVA.

Results obtained from this research, as well as information, taken from literature shows that material created from mixed plastic waste could be a reasonable solution for the recycling of plastic waste. Mechanical properties and simple ways of preparation make this new type of material economically efficient. The areas of utilization could be found in a field where

LDPE plastics are commonly used e.g. packaging material. Wood-plastic composites are the materials where mixed plastic waste could be a reasonable filler material but further research is needed.

6 LIST OF REFERENCES

- Attwood, J. *et al.* (2006) ‘The effects of ageing by ultraviolet degradation of recycled polyolefin blends’, *Polymer Degradation and Stability*, 91(12), pp. 3407–3415. doi: 10.1016/j.polymdegradstab.2006.04.025.
- Chauhan, V., Kärki, T. and Varis, J. (2019) ‘Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques’, *Journal of Thermoplastic Composite Materials*. doi: 10.1177/0892705719889095.
- Cheloufi, T. *et al.* (2014) ‘Effet des additifs sur la structure cristalline du polyéthylène à basse densité (PEBD) irradiés par des rayonnements UV’, *MATEC Web of Conferences*, 11. doi: 10.1051/matecconf/20141101038.
- CM-2600d* (2020). Available at: <https://sensing.konicaminolta.us/products/cm-2600d-spectrophotometer/>.
- DYNISCO (2020). [Referred 12.2.2020]. Available at: www.dynisco.com
- European Commission (2017) *Resource Efficient Use of Mixed Wastes*. doi: 10.1017/CBO9781107415324.004.
- European Commission (2019) *Directive 2008/98/EC on waste*. Available at: <https://ec.europa.eu/environment/waste/framework/index.htm>.
- G. Iannuzzi, B. M. (2013) ‘Color Changes Due to Thermal Ageing and Artificial Weathering of Pigmented and Textured ABS’, *Polymer engineering and science*.
- Hyvärinen, M. (2014) *Ultraviolet Light Protection and Weathering Properties of Wood-Polypropylene Composites*. Doctoral thesis, Lappeenranta University of Technology, Lappeenranta, Finland. Available at: www.lutpub.lut.fi.
- IPCC (2013) *Climate change 2013*. [Referred 10.10.2019]. Available at: <https://www.ipcc.ch/report/ar5/wg1/>

Jin, S., Stark, N. M. and Matuana, L. M. (2013) ‘Influence of a stabilized cap layer on the photodegradation of coextruded high density polyethylene/wood-flour composites’, *Journal of Vinyl and Additive Technology*, 19(4), pp. 239–249. doi: 10.1002/vnl.21315.

Kaci, M. et al. (2003) ‘Study of the effects of gamma irradiation on the structure and physical properties of low density polyethylene films containing hindered amine stabilizers’, *Macromolecular Materials and Engineering*, 288(9), pp. 724–729. doi: 10.1002/mame.200300026.

Karuppannan Gopalraj, S. and Kärki, T. (2020) ‘A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: fibre recovery, properties and life-cycle analysis’, *SN Applied Sciences*. Springer International Publishing, 2(3), p. 433. doi: 10.1007/s42452-020-2195-4.

Liikanen, M. et al. (2019) ‘Construction and demolition waste as a raw material for wood polymer composites – Assessment of environmental impacts’, *Journal of Cleaner Production*, 225, pp. 716–727. doi: 10.1016/j.jclepro.2019.03.348.

Marzec, A. et al. (2017) ‘Effects of solar irradiation on the properties of ethylene-norbornene composites containing solvent dyes’, *Polymer Testing*. Elsevier Ltd, 62(October), pp. 392–401. doi: 10.1016/j.polymertesting.2017.07.029.

MatWeb (2020). [Referred 5.02.2020]. Available at: <http://www.matweb.com/>.

Motyakin, M. V. and Schlick, S. (2002) ‘Electron spin resonance imaging and ATR-FTIR study of poly(acrylonitrile-butadiene-styrene) containing a hindered amine stabilizer and thermally treated at 353 K’, *Macromolecules*, 35(10), pp. 3984–3992. doi: 10.1021/ma011919l.

Nikafshar, S. et al. (2017) ‘The effects of UV light on the chemical and mechanical properties of a transparent epoxy-diamine system in the presence of an organic UV absorber’, *Materials*, 10(2), pp. 1–19. doi: 10.3390/ma10020180.

Q-SUN (2020). [Referred 15.01.2020]. Available at: <https://www.q-lab.com/products/q-sun-xenon-arc-test-chambers/q-sun-xe-3>.

Shini(2020). [Referred 15.01.2019]. Available at: https://www.shini.com/en/products_i_Low-speed_Granulators-SG-16N-16D-20N.html.

Srebrenkoska, V., Gaceva, G. B. and Dimeski, D. (2009) ‘Preparation and Recycling of Polymer Eco-Composites’, *Macedonian Journal of Chemistry and Chemical Engineering*, pp. 99–109.

Thermofisher(2020). [Referred 10.10.2019]. Available at: <https://assets.thermofisher.com/TFS-Assets/CAD/Product-Guides/microPHAZIR-User-Manual.pdf>.

Turku, I. *et al.* (2017) ‘Characterization of plastic blends made from mixed plastics waste of different sources’, *Waste Management and Research*, 35(2), pp. 200–206. doi: 10.1177/0734242X16678066.

Turku, I., Kärki, T. and Puurtinen, A. (2018) ‘Durability of wood plastic composites manufactured from recycled plastic’, *Heliyon*, 4(3), pp. 1–20. doi: 10.1016/j.heliyon.2018.e00559.

UNEP (2016). [Referred 10.11.2019]. *Global Waste Management Outlook*. Available at: <https://www.unenvironment.org/resources/report/global-waste-management-outlook>

Valera, S. and Bode, B. E. (2014) ‘Strategies for the synthesis of yardsticks and abaci for nanometre distance measurements by pulsed EPR’, *Molecules*, 19(12), pp. 20227–20256. doi: 10.3390/molecules191220227.

Wang, H., Zhang, Y. and Wang, C. (2019) ‘Surface modification and selective flotation of waste plastics for effective recycling—a review’, *Separation and Purification Technology*. Elsevier, 226(October 2018), pp. 75–94. doi: 10.1016/j.seppur.2019.05.052.

Wilén, C.-E. and Pfaendner, R. (2013) ‘Improving weathering resistance of flame-retarded polymers’, *Journal of Applied Polymer Science*, 129(3), pp. 925–944. doi: 10.1002/app.38979.

World Bank Group (2015) *What a waste 2.0*. [Referred 05.10.2019]. Available at: <https://openknowledge.worldbank.org/handle/10986/30317>

Yáñez-Pacíos, A. J. and Martín-Martínez, J. M. (2018) ‘Surface modification and adhesion of wood-plastic composite (WPC) treated with UV/ozone’, *Composite Interfaces*. Taylor & Francis, 25(2), pp. 127–149. doi: 10.1080/09276440.2017.1340042.

Zhang, D., Morse, S. and Ma, Q. (2019) ‘Corporate social responsibility and sustainable development in China: Current status and future perspectives’, *Sustainability (Switzerland)*, 11(16). doi: 10.3390/su11164392.