Influence of Type and Amount of Recycled Material to Mechanical Properties of PC

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Abstract— The articles describe analyses influence of type and amount of recycled material on the mechanical properties of material. Polycarbonate was inspected material. Specimens were prepared by the mostly used technology for production products, which is injection molding. Several recycled materials were made, all from original material. Samples with different percentage amount and a type of recycled material were subsequently tested by mechanical testing. Included tests were tensile tests and Charpy impact test. Testing was conducted at different temperatures; at reduced, ambient and increased temperatures. The results of these tests were to determine appropriate technology preparation and optimum percentage of recycled content in tested materials. After the first recycling there was a change of mechanical properties; improvement in notch toughness and a small change in ultimate strength and modulus.

Keywords—polycarbonate, injection molding, preparation of recycled material, mechanical properties testing.

I. Introduction

CURRENT trends in production allow mass production of polymer products at affordable prices, which strengthened their role among other construction materials. With regard to the pressure of the general public and experts on environmental aspects of production, the recycling area gains more importance. Some types of polymers can be classed as easily recyclable but manufacturing companies are not capable of producing polymer with exactly the same properties as the original product. Therefore, recycled polymer is in the manufacture added only in a certain ratio. Thus, it is possible to process discarded products and waste from production. Generally speaking, during manufacture of the stressed products can be added very little or no share of recycled material. In cases where it is not needed to meet these requirements, product with a higher proportion of recycled material can be produced. In practice it is common that some non-structural visual parts are made entirely from recycled materials. [1]

One of the reasons leading plastics processors and manufacturers of machinery for the preparatory process for recycling is currently relatively high price of plastic. Modern states strive to lead companies to recycling by legislation and therefore seek to provide benefits for processors of recycled material. Today, there is already many machines and devices on the market that are designed specifically for processing waste into regenerated material. [2]

The impact of man-made polymers on the environment is a problem of high priority in most industrialized countries. Mainly due to a build-up of disposed waste in landfills, and due to campaigns in the press about mistakes made in the management of waste treatment, public opinion is focusing on this problem. The fact that the corresponding percentage by volume is higher, due to the low packing density of wastes, makes the problem more visible.

Although plastics constitute not even ten weight percentage of the total amount of wastes, both residential and industrial, public attention to them is increasing. A possible explanation of such a reaction suggests that there is a lack of compatibility of plastics with the environment, despite the fact that the majority of products used in present daily life are made of materials which have also been manufactured by a chemical process.

The plastic waste in landfills consists of about two-thirds polyolefines, and only approximately fifteen percent of styrene polymers, approximately ten percent of polyvinyl chloride, and less than ten percent of all other polymers.

The general concerns about environmental protection and resource conservation have led to the development of a variety of solid waste management techniques to reduce both the environmental impact of the different types of waste and the depletion of natural resources. Management of plastic wastes cannot be treated as an individual problem; it must be considered as an integral part of the global waste management system. Current

This paper is supported by the internal grant of TBU in Zlin No. IGA/FT/2013/020 funded from the resources of specific university research and by the European Regional Development Fund under the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089.

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waste management is based on a four-level hierarchical approach:

- mechanical (material) recycling,
- alternative (chemical depolymerization, gasification, thermal decomposition, tatalytic cracking and reforming, hydrogenation).

Mechanical or material recycling of plastics involves a number of treatments and operations: separation of plastics by resin, washing to remove dirt and contaminants, grinding and crushing to reduce the plastic particle size, extrusion by heat and reprocessing into new plastic goods. Because thermosets cannot be remoulded by the effect of heat, this type of recycling is mainly restricted to thermoplastics.

Mechanical recycling is limited by the compatibility between the different types of polymers when mixed, as well as by the fact that the presence of small amounts of a given polymer dispersed in a matrix of a second polymer may dramatically change the properties of the latter, hindering its possible use in conventional applications. Another difficulty with mechanical recycling is the presence in plastic wastes of products made of the same resin but with different colours, which usually impart an undesirable grey colour to the recycled plastic.

In addition, most polymers suffer certain degradation during their use due to the effect of a number of factors such as temperature, ultraviolet radiation, oxygen and ozone. This degradation leads to a progressive reduction in length and to a partial oxidation of the polymer chains.

Therefore, recycled polymers usually exhibit lower properties and performance than the virgin material, and are useful only for undemanding applications. A higher quality of recycled plastics is achieved when separation by resin is carried out prior to the remoulding step. However, even in this case, recycled plastics cannot be used in food containers, unless direct content with the food can be avoided.

An alternative developed in recent years for promoting the use of recycled plastics has been the preparation of containers with a three-layer wall. The middle layer is the thickest and is made of recycled polymer, whereas the thinner external and internal layers are made of virgin material. With this approach direct contact between the recycled polymer and both the consumer and the product in the container is avoided. [4]

II. Experiment

This paper deals with analysis of influence of type and amount of recycled material on the mechanical properties of material. The goal is to perform an experiment in which the products of the studied polymer will be crushed to crushed material (recycled material) and then reprocessed into new products. These are then subjected to mechanical testing.

Specimens were prepared by the most common technology for production of plastic products, which is injection molding.

Testing was conducted at different temperatures; at reduced, ambient and increased temperatures.

A. The specimens

The first task was to produce products by injection molding technologies. Thus these parts were used to receive recycled material. Injection was carried out on the injection molding machine made by Arburg. Specifically, it is an injection molding machine Arburg 470 C with a hydraulic clamping unit.

Table I Process parameters

Melt temperature	300 °C
Mold temperature	100 °C
Ejection temperature	130 °C
Injection speed / pressure	60 mm.s^{-1} / 60 MPa
Holding pressure time / pressure	30 s / 35 MPa
Cycle time	55 s

B. Material

Tested polymer was polycarbonate Makrolon 2205. This polymer belongs to a group of thermoplastics. It is a linear polycarbonate based on bisphenol A. It has a low molecular weight and very easy flowing. Makrolon 2205 is characterized by a lower level of toughness, but this is still adequate for a large number of applications. The material also displays excellent flow-ability. Their thermal and electrical properties are largely identical to those of the higher-molecular grades; however, the higher-molecular grades offer greater toughness and resilience and better stress cracking behaviour. [3]

C. Preparation of specimens

1) Grinding

Grinding polycarbonate products conducted on the knife mill type GK 2218 from producer Maskain AB Rapid. The output of the knife mill was mixed crushed material containing many particles of various sizes up to a fine powder. It is the dust and very fine particles, which presents a certain risk for further processing.

2) Sieving

Grinding of material was immediately followed by sieving. The purpose of the sieving was to eliminate the above mentioned very fine particles and dust. Sieving was carried out on laboratory sieve shakers AS 200 Basic figure.

Sieve mesh of size 2 mm was used for sieving, which caught the particles larger than 2 mm. This material is further called sieved crushed material. The size of mesh was chosen to achieve the size of recycled material to be as close as possible to the original material. The bowl was placed to the bottom to capture smaller particles than 2 mm and dust.

Non-sieved crushed material then contain particles of all sizes and is very diverse.

Difference between recycled sieved material (particles size larger than 2mm) and dust (particle size smaller than 2 mm) is shows in Fig. 1 and Fig. 2.

Fig. 1 Sieved material (particles size larger than 2mm)

Fig. 2 Dust (particle size smaller than 2 mm)

After the crushed was made, preparation for the injection of new specimens made from this material began. Several recycled materials were made, all from original material. Samples with different percentage amount and a type of recycled material were subsequently tested. For injection molding the following mixtures of these materials were used:

- virgin polycarbonate,
- sieved crushed material,
- non-sieved crushed material.

Table II Mixtures

Set of samples	Mixture
1	100 % virgin polycarbonate
2	75 % virgin polycarbonate + 25 % sieved crushed material
3	50 % virgin polycarbonate + 50 % sieved crushed material
4	100 % sieved crushed material
5	75 % virgin polycarbonate + 25 % non-sieved crushed material
6	50 % virgin polycarbonate + 50 % non-sieved crushed material
7	100 % non-sieved crushed material

3) Drying

The injected material is very hygroscopic and should be dried before processing. The material should not contain more than 0.02% residual water for injection molding. Moisture would lead to surface defects in material and could even result in reduction of the molecular weight.

Polycarbonate was dried in a drier directly connected with the hopper of injection molding machine. It is a convenient way of solving, because the transport between the dryer and hopper could lead to undesirable wetting of the material. Thermolift made by Arburg was used for drying of the material. The material was dried for 3 hours at 120 ° C. Thus dried material already contained the optimal amount of water (less than 0.02%).

D. Testing

All described set of samples were subject to different mechanical tests. Those were a tensile tests, Charpy impact test and hardness test Shore D.

1) Tensile test

Tensile test was performed on a tensile testing machine from company Zwick/Roel type W91255. The machine is equipped with temperature control chambers, which enables testing at different temperatures. Testing was performed at various temperatures. Used temperatures were: lower temperature -24° C, room temperature 23° C and increased temperature 100° C. Even measuring at 145° C was done, which is close to the glass transmission temperature. The temperature this high was used to find out if recycled material has any bigger effect in mixture. The test was performed according to ISO 527.

2) Charpy impact test

The second mechanical test in order was notch toughness test alias Charpy impact test. Testing was performed on the

Resil Impact Junior testing machine from company CEAST. The tests were carried out according to ISO 179. Preparation of individual samples proceeded before each testing. It consisted of making of notch in specimens. Notch was shaped into V-shape with depth of 2 mm.

3) Hardness test

Shore D hardness test was performed on the hardness tester from the OMAG company with type marking ART 13. The test surface of specimens must be cleaned before test. Testing was performed according to EN ISO 868. First, the sample was placed in a rack of hardness tester and then indenter started pressing to the surface of the test specimen. After the time interval of 5 seconds display shows the value of hardness Shore D. Hardness Shore D is determined by the depth of penetration of the indenter and the size of the scale is then 0-100 Shore. The samples were subjected to measurements only at room temperature (23 ° C).

III. Results and Discussion

A. Tensile test

1) Ultimate tensile strength

In the graph the ultimate tensile strength (Fig. 3) at -24° C are the most dispersed values at 100 % non-sieved crushed material. The highest value shows a mixture of PC + 50 % sieved crushed material, but it is higher only by the order of magnitude of standard deviation. The lowest strength then gained PC + 50 % non-sieved crushed material.

At ambient temperature 23° C, it is clear that the values have approximately the same variance. The difference between the highest value at 100 % non-sieved crushed material, and the smallest value of PC + 25 % sieved crushed material are minimal. Values are fairly evenly balanced and thus there is no change when added to the original PC recycled material in all mixtures.

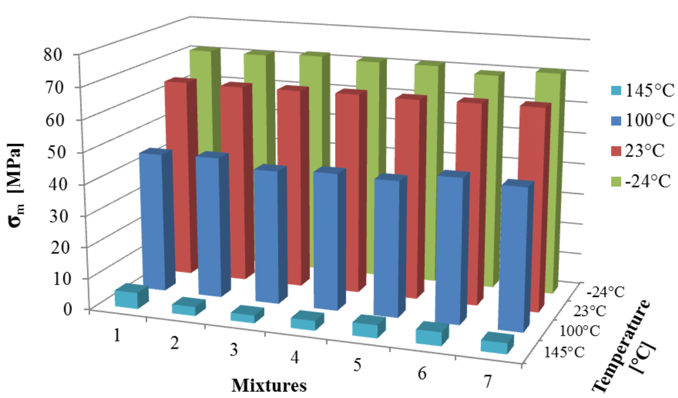

Fig. 3 Ultimate tensile strength

Furthermore, in this graph at 100° C difference between values is more apparent than in the previous case. The highest maximum strength takes PC + 50 % non-sieved crushed material and smallest maximum strength is at PC + 50 % sieved crushed material. The differences are in the order of magnitude of 3 MPa.

Table III Ultimate tensile strength

Ultimate tensile strength - σ_m [MPa]				
Mixtures	Temperature [°C]			
	-24°C	23°C	100°C	145°C
	Arithmetic mean	Arithmetic mean	Arithmetic mean	Arithmetic mean
	Standard deviation	Standard deviation	Standard deviation	Standard deviation
1	71.1	64.1	44.7	5.2
	0.9	0.2	0.7	0.2
2	71	63.9	45.2	2.9
	0.7	0.2	0.7	0.1
3	71.8	64.1	42.7	2.5
	0.9	0.2	0.8	0.4
4	71.1	64.3	43.6	3.1
	1	0.1	0.6	1
5	71.1	64	43.1	4.1
	1.4	0.2	1	0.9
6	69.3	64.2	45.8	4.3
	1.2	0.1	0.7	2.1
7	71.2	64.4	44.7	3.4
	1.7	0.2	0.9	1.7

At a temperature of 145° C, the highest tensile strength is in virgin PC. In this case, other materials show much lower values, sometimes down to half value. It should be taken into account that the temperature of 145° C is close to the glass transition temperature and therefore influence of recycled material have bigger impact to this values.

From the graph is visible, that the values are again very balanced. Some differences can notice up at 145° C, virgin PC material has the best maximum strength and mixtures of PC + non-sieved crushed material have the worst values.

2) Elastic tensile modulus

From table (Tab. IV) at -24 ° C it is evident, that at least are dispersed values of virgin PC and PC + 25 % non-sieved crushed material. Values are the most dispersed in mixture after adding non-sieved crushed material, these mixtures have a lower modulus value. Virgin PC also has the highest value of the elastic modulus. This value is about 100 MPa higher than other values. The lowest value is in mixtures with non-sieved crushed material.

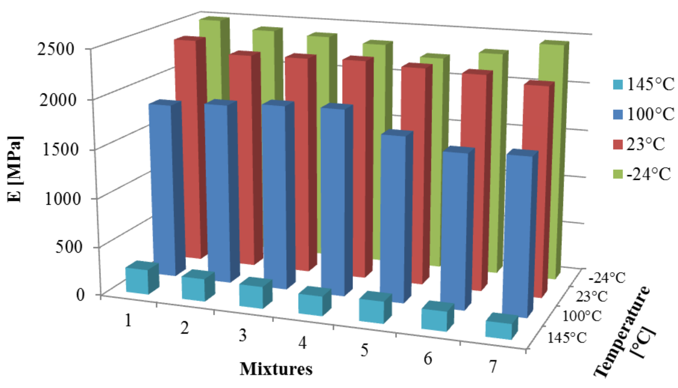

Fig. 4 Elastic modulus

At 23° C, the modulus still has the highest elastic modulus virgin PC see (Tab. IV). The lowest value is in the mixture of 100 % non-sieved crushed material, which has also the most dispersed deviation. Size of elastic modulus of other mixtures is in ranges from about 2200 MPa to 2300 MPa.

Table IV Elastic modulus

Elastic modulus - E [MPa]				
Mixtures	Temperature [°C]			
	-24°C	23°C	100°C	145°C
	Arithmetic mean	Arithmetic mean	Arithmetic mean	Arithmetic mean
	Standard deviation	Standard deviation	Standard deviation	Standard deviation
1	2488	2372	1811	257
	133	79	73	33
2	2411	2253	1858	233
	95	57	129	36
3	2384	2263	1898	225
	147	54	198	25
4	2339	2278	1911	201
	203	83	141	48
5	2235	2245	1694	224
	213	67	409	32
6	2319	2221	1578	200
	246	99	179	64
7	2448	2152	1601	156
	184	184	278	61

From the graph (Fig. 4) it is clear, that the measured values at 100° C are very different from previous cases. A large variance between the values was observed. Virgin PC and mixtures with sieved crushed material have similar behavior when the differences are minimal, even a slight improvement with the percentage of filling of recycled material. But mixtures with the recycled non-sieved crushed material show deteriorated values. Reduction of the modulus is up to 10% lower in comparison with virgin PC.

At 145° C the values are the most dispersed in the mixture of PC + 50% non-sieved crushed material. The highest value of modulus of elasticity has the virgin PC. Mixtures of sieved crushed material have a more balanced course of values than non-sieved crushed material. The lowest value is 100% non-sieved crushed material.

After examination of graph (Fig. 4) it can be seen, that the best value of modulus of elasticity reached virgin PC at all temperatures except 100° C. In contrast, the mixtures of non-sieved crushed material reach worse values at all temperatures.

B. Charpy impact test

1) Charpy notch toughness

Charpy notch toughness with standard deviation at -24° C is comparable in all mixtures against virgin material.

Graf of notch toughness at 23° C shows, how individual materials behave when tested. As it can be seen in the picture (Fig. 5), the highest values of toughness are reached with mixtures of PC + 25% and 50% non-sieved crushed material. Mixtures with non-sieved crushed material behave very similarly to the original material.

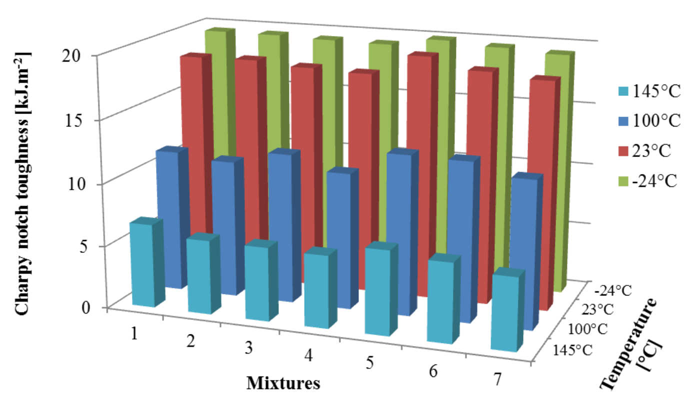

Fig. 5 Charpy notch toughness

This graph also shows the impact toughness of materials at 100° C. At first look, it is apparent that the values are similar as in the previous case. Spacing of notch toughness of materials is the same analogy. The biggest dispersions it possible to see in mixtures where it was used as non-sieved crushed material.

Table V Charpy notch toughness

Charpy notch toughness [kJ.m^{-2}]				
Mixtures	Temperature [°C]			
	-24°C	23°C	100°C	145°C
	Arithmetic mean	Arithmetic mean	Arithmetic mean	Arithmetic mean
	Standard deviation	Standard deviation	Standard deviation	Standard deviation
1	19.53	18.17	11.36	6.7
	1.7	0.85	1.14	0.43
2	19.51	18.23	10.96	5.91
	0.74	0.72	1.37	0.38
3	19.37	17.92	11.97	5.87
	0.63	0.61	0.87	0.57
4	19.3	17.76	10.88	5.76
	0.83	0.83	1.76	0.5
5	19.91	19.43	12.76	6.69
	0.84	1.25	1.79	0.61
6	19.6	18.56	12.67	6.27
	0.7	0.91	1.61	0.49
7	19.33	18.18	11.71	5.7
	0.82	0.63	1.24	0.38

Charpy impact toughness at temperature 145° C is also relatively equable and dispersions in the order of magnitude of 2 kJ.m^{-2}. The highest impact toughness of mixtures of PC + 25% non-sieved crushed material is a better then virgin PC again.

Graph comparing the impact toughness at all temperatures can be seen in the graph (Fig. 5). The graph shows that the highest value of impact toughness occurs at a temperature of - 24° C (approximately 19.5 kJ.m^{-2}). At 23° C it is possible to observe a loss of toughness on average 18 kJ.m^{-2}. Decline is relatively small. Another decline is visible at a temperature of 100° C when the drop to approximately 12 kJ.m^{-2}. When evaluating this graphs it can be concluded that the highest average values of toughness becomes a mixture of PC + 25% non-sieved crushed material. The increase is visible at all temperatures.

2) Charpy breaking force

After the first sight at the graph (Fig. 6) it is clear, that the dispersion is relatively small. The highest force for breaking of the specimen has to be applied in mixtures of PC + 25% non-sieved crushed material. Other values are held in the range of 20 N.

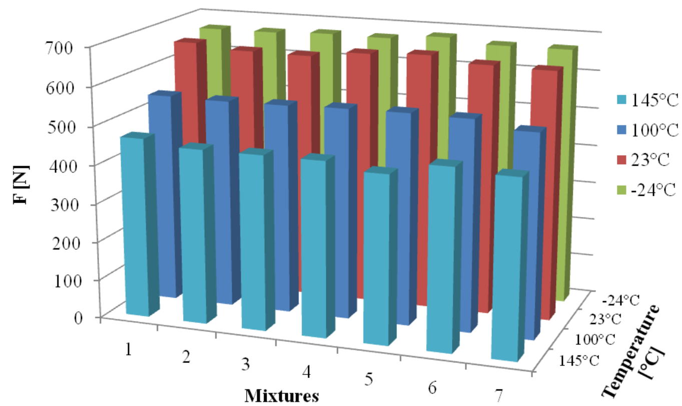

Fig. 6 Breaking force F_m

Graf of force required for breaking the sample at 23 ° C shows that the size of the forces for each material. Values vary in a small range. Smaller standard deviation values come off mixtures of sieved crushed material, and therefore values at this temperature are more uniform.

Table VI Impact breaking force F_m

Force F_m [N]				
Mixtures	Temperature [°C]			
	-24°C	23°C	100°C	145°C
	Arithmetic mean	Arithmetic mean	Arithmetic mean	Arithmetic mean
	Standard deviation	Standard deviation	Standard deviation	Standard deviation
1	666.74	655.4	543.6	467.1
	8.92	22.18	37.75	35.47
2	667.12	642.92	541.42	452.14
	20.97	17.18	21.52	36.4
3	672.28	640.9	542.72	451.72
	16.49	16.7	23.51	26.62
4	670.65	656.5	546.21	451.09
	13.15	11.21	33.39	35.47
5	681.99	662.96	547.38	432.18
	18.13	22.19	38.5	48.47
6	669.26	647.84	544.99	464.07
	16.64	20.17	37.24	59.91
7	669.51	644.18	524.6	453.49
	16.7	20.83	34.72	57.07

At a temperature of 100 ° C, the measured values are more dispersed than in the case of a temperature of 23 ° C. Force ranges up to 70 N. Such high dispersion values are visible with all of the material mixtures. In this case, the temperature influences the heterogeneity of the material. With focus on the value of arithmetic mean values, values are in same level for all materials and maximum difference is in range of 20 N.

As in previous cases, it can also be seen that the force values have relatively large variance. It reaches nearly 90 N. The highest force is necessary for breaking the virgin PC. For all mixtures reduction of the force needed to break is 3% on an average. Only for mixture PC + 25 % non-sieved crushed material the required force is further decreased by another 3%. The largest dispersion of values is clearly evident in a mixture of non-sieved crushed material.

From this graph in the figure (Fig. 6) it can be safely stated, that increasing the temperature decreases the force required for breaking the test specimens. At a temperature of - 24 ° C, the force is about 660 N. The temperature increase to 23 ° C caused a decrease in force of about 10 N. At a temperature of 100 ° C decreased of force is 110 N and other a further 100N at temperature 145 ° C. Furthermore, looking at the graph it is clear, that the deviations against virgin PC are minimal, except at temperature 145 ° C, with which there is bigger decrease for all mixtures.

C. Hardness test

The samples were subjected to measurements only at one temperature, which is room temperature.

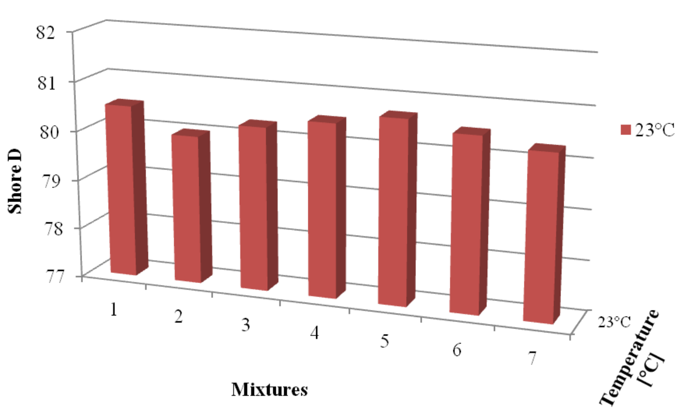

Fig. 7 Charpy notch toughness

The last test was a test of hardness Shore D. From measured hardness it is possible to conclude, that added recycled material has little effect on the diversity of hardness values in the case of this experiment.

Table VII Hardness Shore D

Shore D	
Mixtures	Temperature [°C]
	23°C
	Arithmetic mean
	Standard deviation
1	80.5
	0.3
2	80
	0.5
3	80.3
	0.4
4	80.5
	0.5
5	80.7
	0.7
6	80.5
	0.7
7	80.3
	0.8

It can also be seen, that in the case of virgin PC without recycled material, standard deviation of measured value is small. The other way around, adding non-sieved crushed material in varying proportions leads to higher standard deviations. For mixtures of PC and sieved crushed material standard deviation are smaller. This suggests that the addition non-sieved crushed material results in more varied material in terms of hardness.

IV. Conclusion

The goal of this work was to determine the effect of the type and amount of recycled plastic on the properties of a product.

The subjects of testing were material mixtures composed of virgin PC, sieved crushed material and non-sieved crushed material that had to be made first. Testing was carried out using mechanical tests (tensile test, Charpy impact test) and it was conducted at a different temperatures - 24° C, 23° C, 100° C and 145° C.

From results of the mechanical tests emerged that influence of the type and amount of recycled material (in this case polycarbonate) is small. Ultimate tensile strength and elastic modulus are quite similar in all values, but with increasing temperature, the standard deviation is slightly increased.

Change appeared at the temperature of 145° C where are relatively large deviations of values.

Effect of preparation on the mixture prepared by sieving is that they have a smaller variance standard deviation. So, these mixtures show better stability behavior in strength and elasticity in comparison with non-sieved crushed material. Notch toughness was generally a few percent better in mixtures with non-sieved crushed material. Mixtures with sieved crushed material came off practically identical when compared to the virgin material.

Everything indicates that this result is due to a single recycling process of tested polycarbonate. It can be assumed that if the material was recycled repeatedly, there would be a gradual change in mechanical properties.

In cases, where is not big emphasis on the requested mechanical properties, usage of recycled materials should be matter of course the in practice. The main aspect is the economy of recycling, when the company is able to process its own technological waste from production. Recycling also reduces the industrial production of new polymers and raw material consumption associated with it. This helps to reduce the overall impact on the environment.

Acknowledgment

This paper is supported by the internal grant of TBU in Zlin No. IGA/FT/2013/020 funded from the resources of specific university research and by the European Regional Development Fund under the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089.

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