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habilitation

RECYCLED PET IN ARCHITECTURE

Researching Additive Manufacturing Method

Praha 2021

VOLUME

ABSTRACT

0. INTRODUCTION

1.RESEARCH METHODOLOGY

Creative research
Applied research - crowd searching
Fundamental research - Material research

2. PRINTING RECYCLED PET

Short history of 3D printing
PETMAT research group
First experiment: test of B-PET with students - applied research
Settings A-F
Conclusion on the study of 3D printing recycled PET

3.CASE STUDY: SMALL OBJECTS - RECOLUMNS

Task
Designs of the columns
3D printer data
Stress tests
Lessons learned from the case study
Recolumns

4. BIGGER OBJECTS

Design 1 - Hymn
Model division
3D printed construction
Lessons learned from Hymn
Column

5. EVEN BIGGER OBJECTS: USE CASE N.1

Crowd printing
Lessons learned from crowd printing

6. DEVELOPMENT OF CZECH RECYCLED FILAMENT

The Czech made filament research goal
Proof of concept MB46: Velexa joints - feasibility
Proof of concept MB25: Tokyo bar
Lessons learned from development of rPET

7. EVEN MORE BIGGER OBJECTS: USE CASE N. 2:

Crowd-searching - user experience - PETangels
Findings from the volunteers
Issues in the printing technology
Lessons learned from project Angels

8. LAB TESTS ON RECYCLED CZECH FILAMENT

Tensile strength
Strength in pressure
Flexural strength
Lessons learned from the strength test

9. BIG BEAUTIFUL OBJECTS: USE CASE N. 3 CROWD-SEARCHING - DIGITAL FACTORY

Print settings
Lessons learned form the digital factory

10. CONCLUSION

11. FUTURE WORK

12. REFERENCES

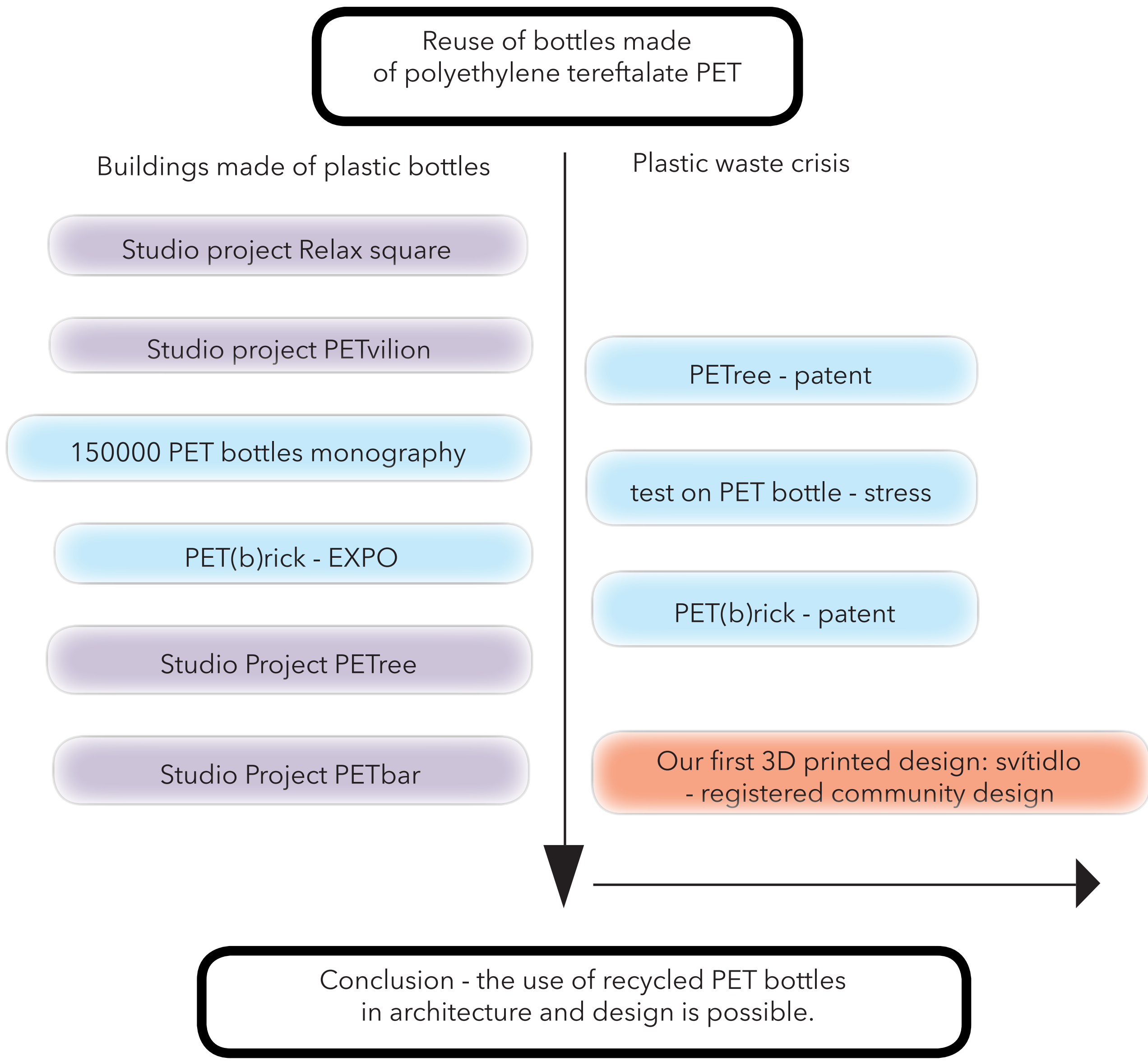
ABSTRACT

It is possible to use recycled polyethylene tereftalate in architecture: architectural interior, detail, designing and education.

This research concluded, that one of the best applicable ways of this waste material in architecture and design is its industrial transformation into filament which can be transformed into various products. The problem is, that the outputs are limited by size of the additive manufacturing (3D printing) machine and time of facilitation. Solution to both limitations will be presented through use cases, experimental studio designs and research projects. The 5 years lasting research has proven where and to which extend can recycled polyethylene tereftalate be used in architecture and where it touches the thin border between architecture, interior architecture and architectural detail.

Last but not least, a motivation to apply this material in architecture and design touching ecology and environment will be briefly discussed, hoping in the possible worldwide impact of making recycled polyethylene tereftalate a regular and accepted material to be used in architecture, interiors and architectural details.

preliminary research timeline 2013 – 2016



Reuse of bottles transformed into filament for 3D printing

Our first 3D printed design: svítidlo - registered community design

Building a 3D printer Průša MK2

PET(s)culpt - Czech record for biggest statue 3D printed out of 100%recycled PET - B-PET

Studio project: Veletiskárna made of recycled PET B-PET

Development of own Czech recycled filament

Studio project - columns

laboratory tests

Studio project - hymn

Project COLUMN

test of columns - stress

Project PETAngels

test of printer settings

crowdsearching platform

Project Digital factory

current research time line 2017 - 2021

We made the use of the recycled PET possible through helping the development of filament for 3D printers made of recycled PET

0. INTRODUCTION

The research of the use of recycled materials in architecture started at FA CTU Prague in 2009 by founding the Experimental design studio Achten - Nováková focused on garbage reuse. The idea was to give waste material value by design. As we wanted to deliver test results in 1:1 model within one semester, we focused on architectural interior design and architectural details or product designs. Among all possible kinds of garbage we focused on the issues of plastic pollution. This topic was further developed by studying at ETH Zurich, where our lecture with students had the topic of building a 20meter high tower from 150 000 PET bottles produced in Zurich city (Nováková, 2014). This brought us to implementation of parametric designing and actually researching the best design methods when working with students with garbage. The research led us to publishing a book about architecture built from PET bottles also in Czech language with multiple examples of its use around the world (Nováková, 2015). We experimented with the use of regular plastic bottles within the years 2011 to 2014 in our Experimental Design studio at FA CTU having publicly exhibited installations such as Relax Square or PETvilion, PETbar and PETree.

Fig. 1.1 PETree and Relax square

During this research we found out what has the biggest impact in order to beat plastic catastrophe by means of architecture. We concluded that public must be addressed by building pavilions and architectural installations in order to behave sustainable. We found out, that it makes sense to produce relatively big, photogenic, shining or provocative and informative objects, that promote the need for sustainability and recycling. We anticipate that biggest impact is made by pedagogy and promo objects for institutions, companies and state.

Together with this realisation we kept designing and researching within education involving our students. Inspired by Swiss and Taiwan research we designed and patented a special plastic bottle called PET(b)rick. (Nováková, 2017) This prototype financed by Mattoni 1897 found its place in interior design and objects, in theatre performances, at public exhibitions and conferences promoting the idea of reuse and recycling. Despite the success we observed that the objects showed up to be too weak and flammable to be used directly in building industry and architecture and therefore we turned into next technology of reuse: reforming the bottles into filament for 3D printing.

There are many areas where 3D printing really is creating significant change, particularly in architectural designing and prototyping new products, in the arts, and in visualizing abstract concepts. (Horvath, 2014) Architecture is a relevant human activity, the architects are designing new buildings, their equipment and architectural details, which they want to place in interior. They want to see exact physical model or prototype. Models are important in architecture. In 1980, the subtraction technology was accompanied with so called additive type of manufacturing: polymerization, fusion deposition and bio printing. (A. Savini and G.G. Savini, 2015) Material used in 3D printing technology are usually polymers made of virgin plastics. In order to act ecologically in this sense, the focus was directed to using and, if needed, developing recycled filament for 3D printers made of collected waste, bio-polymers or recycled polyethylene tereftalate material: PET. The PET material was chosen for its non-toxicity, almost never-ending ability to be recycled and beauty.

Also manpower at the building sites is limited, with increasing level of life, less workers is willing to travel and work manually in bad unhealthy conditions. The price of energy for a robot gradually goes below the price of human labour. Cheap fuel, affordable prices of robots and easier distribution of technology pushes further the aim of using new machines in building industry plus new materials are developed for realisation of architects' visions. Additive manufacturing penetrated also the area of real scale architecture and companies producing building materials such as cement, wood and clay composites, plastic and chemicals invested in development of the printable mixtures for 3D printed buildings. We can see, that 3D printing is possible with many unusual materials like salt, sugar, coffee, tea or vine, sawdust, mud or bio-plastic some of which seem not really relevant for architecture, but it proves, that this technology become increasingly applicable for generating 3D objects in any scale (Rael, 2018). One of the aims of this study is to research, how can be recycled PET filament together with additive manufacturing technology used in architecture.

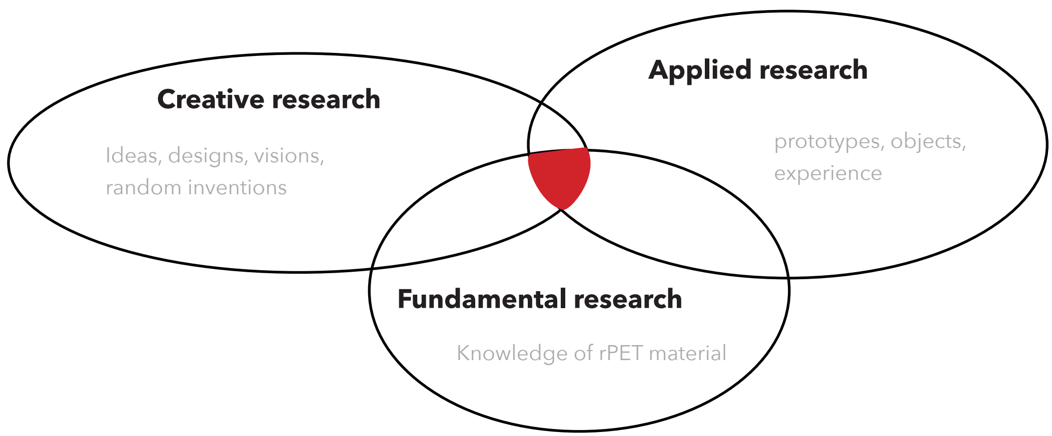
There is strong push to implement innovation in all branches of human activity. The use of innovative technologies in architecture is facing many obstacles. Architecture is based on proven technologies and approved knowledge, materials we thoroughly know. This knowledge was passed over from architect to architect (school to school) since ever. The question is our architectural attitude to new materials, plastics, which were introduced in 1940, and what's more, their recycled version, which is even younger. How can we even think about implementing material created first around 1990? We need to start testing, designing, researching as soon as possible. Just because the production of plastics, specially PET grows steadily [1] and it became one of the most important plastic matters during the last two decades (Navarro, 2015). Although it can be advantageously recycled in many ways (Al-Sabagh, 2016), untreated plastics is causing environmental problems.

1. RESEARCH METHODOLOGY

We implemented three types of research methods in this study of the use of recycled PET in architecture. Firstly, we were inviting students into research process giving them opportunity, material and space for creativity (creative research method). Secondly, we developed and applied 3D printing technology to the creation of prototypes of varying sizes and complexity (applied research). Thirdly, within fundamental research, we made material tests in a laboratory in order to compare the features of recycled material with the virgin one (fundamental research). The three types of research methods are all driven by developments through a design process. Thus we can say that all three types contribute to an understanding of PET in architecture through research by design.

Nowadays we perceive that the profession demands working with digital tools and machines, which should make processes faster, cheaper and more ecological. Students need to acquire different ability and knowledge

RESEARCH BY DESIGN



than their teachers had learned to hand over. Schools are limited in offering lectures on the innovative technologies. Students are sometimes more familiar with the digital technology than teachers. One of the possible solutions of creative research is to invite students into the research process offering them the tools to play with (3D printer and Rhino Grasshopper). Here, the students came up with own designs, which took advantage from additive manufacturing method. Together with the technology, the student also needed a topic, which provoked them to self reflection. We offered them the chance to save the world from plastic disaster. The creative research was driven by the student's need to investigate unconventional material that require novel design methods and applications. Results from Experimental studio are presented, where students were invited to participate in the research. The students task was not only the actual design task, but also implementing the use of machines in model production. The part of the studio was also discussion about the advantages and disadvantages of robot-made architecture models in terms of aesthetics, arts and beauty.

The creative research with the students is quite similar to what Helen Kara (Kara, 2015) calls arts-based research, where she notes a tight coupling between the artistic work, methods, and context of the research. For example, we apply technology in research for gathering data about printing the designs from the 3D printers for the quantitative research (such as printing time and volume of material consumed.) Through this, students learn how to operate the machine, overcome unexpected situations, and learn more than the minimum they originally needed. Furthermore, observing the behaviour of the machine can influence their design concept. Kara also talks about generating visual stories in order not only topresent the research but also to formulate it and improve the outputsthrough writing about it or verbally describing it. This is accommodated through the continuous process of presentations in various stages of designing. As teachers, we engage in instant peer reviewing process through instant messaging opportunities - again using innovative communication technology. Mixed research design is comonly used and well described research method (Creswell, 2017), which usually combines qualitative with quantitative form. In our research we apply both these strategies: We not only collect data from the machines, compare models with the reality and post questionnaires, but also we also look at the quality of the outputs, while collecting feedback from participants, their thoughts and suggestions.

We "employ" students untouched minds and encourage them to deliver new ideas.

APPLIED RESEARCH - CROWD SEARCHING

In our applied research, we mainly looked at the realisation of full-scale prototypes, and in particular objects that are much larger than the printing scope of regular 3D printers. On the other hand, small home 3D printers are cheap and thus very common in the society and no special skills or education is needed in order to operate them. Anyway, the printing area of such printers is limited to approximately to 8dm 3 space. We present the combination of methods of crowd-searching (Ambrogi, 2014) and crowd-printing method to achieve large objects in order to reach relevant research outcomes. In order to motivate the participants we designed a big piece of art, where people could participate and add a piece of their own. Through involving public volunteers into this action we managed not only to decrease production time but also to gather data of print-ability of the recycled PET on multiple (30) types of printers.

One of the possible solution to produce bigger object out of recycled PET with the method of 3D printing with small printers is the division of the object into smaller printable pieces and distribution of the work among many printers, owned by different people. 3D printing is time demanding and by distribution of the work among many participants results can be reached sooner. We made this possible by developing a sharing web [31] platform, which invited lay people to take part in the project. The point was in offering the participants possibility to choose and preview each piece for printing online through a json

3D model on the web page and automatically sending them stl file of their selected piece right after the login. Next, the participants sliced them with their own slicer programmes and generated g-codes for their own printers following our basic setting recommendation. The setting recommendations were necessary, because each printer behaves differently. The crowd-searching method helped to develop printing settings for various printing machines, so that the filament could be widely used and industrially produced. A questionnaire was prepared for the public participants of the crowd-printing projects, where the settings for various types of printers were posted. The filling of the questionnaire was voluntary. We printed architectural self standing interior and exterior decorations and promo objects in large scale up to 2 meters height. In order to be able to use recycled PET in ecological manner, we had to not only research and distribute filament from Argentina, but also we helped developing filament made of this material which fits into 3D printers in Czech republic. A private rPET production company was involved [2].

FUNDAMENTAL RESEARCH - MATERIAL RESEARCH

Fundamental research in architecture is not common, but may be relevant at the faculty of architecture at CTU in Prague (Novotný, Prokopcová, Bošová 2018) Material reuse in terms of thermo - mechanical recycling such as filament extrusion was declared as one of the feasible and most harmless solutions (Ávila, 2003) to the plastic waste increase. A chapter of this study will be devoted to authors' experiments with technology and materials in the lab. We chose material tests, which were found to be relevant to use in architecture with the 3D printing method and tested recycled PET in the universal lab at Faculty of Civil Engineering, CTU Prague. We chose stress, tensile and flexural force tests, which are the basic tests for a new material. We compared the results with the virgin PETG material approved for 3D printing. We also compared the results with standard material used in architecture such as concrete.

In this research we used quantitative measuring with a universal test machine FP100 and ZD100 according to ČSN EN 12390-5 and in the stress test machine according to ČSN EN 12390-3.

2. PRINTING RECYCLED PET

Application of recycled polyethyleneee tereftalate (PET) [3] in architecture, architectural design and education was tested.

There are several known attitudes for the use of recycled polyethyleneee tereftalate in architecture. A company called Via Alta [27] has build a machine in Okříšky, where they invented a POLYBET [4] machine. It mixes PET with other rest plastic together with sand and produces small architectural particles like tiles, cubes or kerbs by rolling machine. This company supported research on VUT in Brno and together they invented a mixture of polymer and concrete [5] which is in general a mix of various waste polymers and up to 4mm fragmented sand or waste glass. This mixture can be deposited into products with additive manufacturing technology, which allows more innovative geometry. Examples such as 3D printed Christmas trees by lamaquina.io [6] or furniture by Nagami design [7] can be found, but there is no closer specification of the plastic material being 3D printed and although it is closer to our research, we can not be sure what material is used. On the other hand 3Dees company declares they can print recycled PET in the biggest 3D printer in Europe. [8] In Dubai a pavilion was produced by MEAN, which claims to be made of recycled plastic bottles. [9]

Companies so far implement 3D printing objects from mixed plastic waste in order to increase public awareness of the problematic topic. Netherlands NGO Clear Rivers [10] 3D prints furniture out of collected mixed plastic waste, mainly HDPE. The New raw company [11] prints furniture out of polypropylene, polyethylene and HDPE successfully, but according to them, PET can be printed with problems due to its natural features of shrinkage when there is bigger mass heated. Here we found potential research opportunity. Although we found it is possible to print (Zander, 2018), all examples found do not use clear recycled PET in 3D printed design.

SHORT HISTORY OF 3D PRINTING

3D printing technology is processed in the way that 3D model designed eg. in CAD software is converted to STL format, which converts the object into triangular mesh. When the model is ready, the STL format is sliced into 2D profile layers where each "2D" layer is printed separately like on a regular printer. It is also the reason, why this manufacturing gained its name "printing". The history of the technology called Additive manufacturing, Fused Deposition Modelling, or originally Rapid Prototyping comes to year 1892, when an inventor Joseph E. Blanther patented 3D typographic maps with the use of layering [12]. Today, we still follow his idea of "layering" - generating landscape model with the use of laser-cutter. In 1980 the method was almost patented by dr. Hideo Kodama in Japan. He had the idea of photo-polymerizing material in order to quickly stabilise material with the use of UV rays and called it Rapid prototyping. He has not finished the specification of the patent though. [13]This happened 6 years later in the year 1986, when Charles Chuck Hull realised this idea and patented the Stereolitography (SLA) [14] technology. The liquid consisting of photo-sensitive polymers was layer by layer stabilised-hardened in predefined places with UV rays of various lengths. In 1987 Carl Deckard from Texas university alternated the layering method and switched liquid for solid powder. His method called Selective Laser Sinthering (SLS) [15] was not commercialy implemented until 2006 though due to its complexity and the use of laser. Fused Deposition Modelling (FDM) inspired by glue pistol was presented by S.Scott and his wife in 1989. Firstly, plastic fibre was manufactured and secondly melted polymer filament was deposited layer by layer on each other. This technology is connected with Stratasys company, which gained patent in 1992 [16] and has produced 3D printers until nowadays.

The method of binder jetting [17] was developed by Ely Sachs and Mike Cima at the Massachusetts Institute of Technology in 1993 and Z Corporation obtained an exclusive license for the process in 1995. The method is described as covering a table with metal, ceramic or sand powder, the printing head distributes gluing substance. The advantage of this method is the possibility to fabricate fast quite large products and colour variations. On the other hand, worse mechanical resistance deserves post-production and thus this method is limited in application. As for geometry usages this one is popular among architects and designers as it has almost no limits. The Z-printer [18], as it is now called, has become one of the most popular 3d printers available.

10 years later 3D printing started to be used in medicine in terms of printing live cells the same way as SLA method with the difference of materials and with the use of biodegradable cast. [19]

Another possible method of 3D printing is Laminated object manufacturing (LOM) (Park, 2000), where layers of plastic or paper are fused (laminated) together using heat and pressure and cut into desired shape with computer controlled laser or blade. It is one of the fastest and most affordable way how to create prototypes. This method is not frequently used in the Czech Republic.

In 2004 dr. Bovyer introduced his idea of an open-source technology called Rep-Rap: a self replicating machine (Kentzer, 2004). From this point on, the price of small 3D printers started to decrease and this technology started to be available to lay people, where producers, mainly on US market achieved to sell 3D printers for 300 dollars or less as DIY home-kits.

Last method mentioned is Directed Energy Deposition (DED) [20], which covers a range of terminology: Laser engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding (Xu, 2018). It is a more complex printing process commonly used to repair or add new material to existing components (Gibson et al., 2010). This method must be researched in special laboratory as 3D printing metal is demanding on equipment. (Sames, 2016)

In 2015 International standardisation organisation (ISO) introduced ISO/ASTM 52900:2015 [21], where main terms definitions in additive manufacturing domain were set reacting on the fact, that AM technology has overgrown into daily life. Additive manufacturing is defined as a method that applies the additive shaping principle

n	Method	Year	Inventor	material
0	Layering	1892		Paper
7	SLA - strereolitography	1986		UV rays in polymer liquid
5	SLS - selective laser sintering	1987		Laser beams and powder
3	FDM . Fused deposition modelling	1989		various materials, polymers, concrete
6	LOM - laminated object manufacturing	1990	Michael Freying	
1	Binder jetting: binder and powder	1993	Ely Sachs and Mike Cima	Metals, ceramic, sand
4	BOM - ballistic Particle manufacturing	1995	William Masters	
2	DED - Direct energy deposition	1984	Deckard and Beaman	steel

Tab 1.1 Table of 3D printing methods

and thereby builds physical 3D geometries by successive addition of material. Also main additive manufacturing process categories were named as follows.

1. Binder jetting (e.g., 3D printers that utilize binder and powder)
2.Directed energy deposition (e.g., laser cladding)
3.Material extrusion (e.g. fused deposition modelling)
4.Material jetting (e.g., Polyjet)
5.Powder bed fusion (e.g., selective laser sintering)
6.Sheet lamination (e.g., sheet forming)
7.Vat polymerization (e.g., stereolithography)

	PLA	ABS	PETG
Fumes	None	Karcinogenous	Strong
Moisture absorption	YES	YES	YES
Flexibility module (GPa)	4	2,2	1,9
Bending strength (MPa)	80	65	64
Strenght/weight ratio (kN*m/kg)	40	31-80	42
Tension strength (MPa)	110	37-110	53
Kick durability (J/m)	-	70-370	77
Hardness Rockwell R	-	94	108
Deformations (°C)	65	100	70
Melting temp. (°C)	160	-	140
Heat leading (W/m*K)	0,13	0,17	0,29

Tab 1.2 Table of material characteristics

Our research was influenced by the Rep-Rap open-source technology and that is was the direction, where we wanted to go with our idea of recycling polyethylenee tereftalate into filament for home 3D printers, which are available for everybody.

	PLA	ABS	PET-G
Nozzle temperature	180 - 230 °C	210 - 250 °C	220 - 260 °C
Bed temperature	20 - 60 °C	80 - 110 °C	60 - 90 °C
Print bed	Unneeded	Compulsory	Recommended
Print chamber	Unneeded	Recommended	voluntary
First layer behaviour	Sticky	Problems	Various - good

Table 1.3 Generic printing behaviour of PLA, ABS and PETG at home printers of small dimensions

PETMAT RESEARCH GROUP

Petmat research group was established on the Faculty of architecture in 2016 in order to find the employment of post-consumer plastic bottles in architecture. After having researched the use of post-consumer PET bottles in architecture and developed a bottle-brick (Nováková, 2017) the research focused on better transformation of the recycled material into architectural shapes. We found out, that it is better to transform the plastic bottles into form-able material in form of PET flakes, granules and finally fibre and use the method of additive manufacturing in order to produce the shapes we design. In our research and also education we focused on the method of FDM, where usually polymer materials are used and thus recycled plastic bottles could be transformed into architectural objects. Poly-actic acid (PLA), acrylo-nitril butadien styren (ABS) and polyethylenee tereftalate with glycol (PETg) are most commonly used materials for 3D printing. Although all of these three materials are acknowledged as approved materials, none of them is ideal.

PLA

Synthetic PLA (Ren, 2010) [26] was invented in 1932 and it was used mainly in medicine in form of fibres. Poly-actic acid (PLA) is generated from corps starch through enzymatic hydrolysis. via glucose. The PLA fibre is almost non-flammable. It is stable against UV rays and acids. On the other hand alcalics can damage them. Plus technically it is rather fragile material, which is non-stable in bending, pressure and tension. (stress = 32 – 36 cN/tex, tension 30-40 %, specific weight 1,25 g / cm3, moisture capacity 0,4-0,6 %, melting point 120-175 °C)

ABS

Acrylo-nitril butadiene styrene [22] is a light thermoplastic polymer with greater flexibility than PLA. It is mechanically durable, also against high and low temperatures and absorbed minimum amount of moisture. It iOS inert material against acids and hydroxides, oils and fats. (specific weight 1,045 g / cm3, moisture capacity less than PLA, melting point 210 - 250 °C) this pure plastic material is used for production of furniture and LEGO pieces. The biggest problem of this polymer is shrinkage. Although water bottles are sometimes produced, ABS is slightly carcinogenic and therefore not recommended for the use in food industry.

PETG

Polyethylenee tereftalate is a compromise material for 3D printing between the two above. It is easy to work with and strong and flexible. G - means modified Glycol that is being added during the polymerisation. The most fancy feature of the PET is its basic transparency. (The specific weight 1,045 g / cm3, moisture capacity less than PLA, melting point 210 - 250 °C) Polyethylene tereftalate is more expensive than PLA, but also is not bio-degradable and thus durable in outer conditions. It has no influence on human health. [23]

Knowing the features of the three polymer based mate-

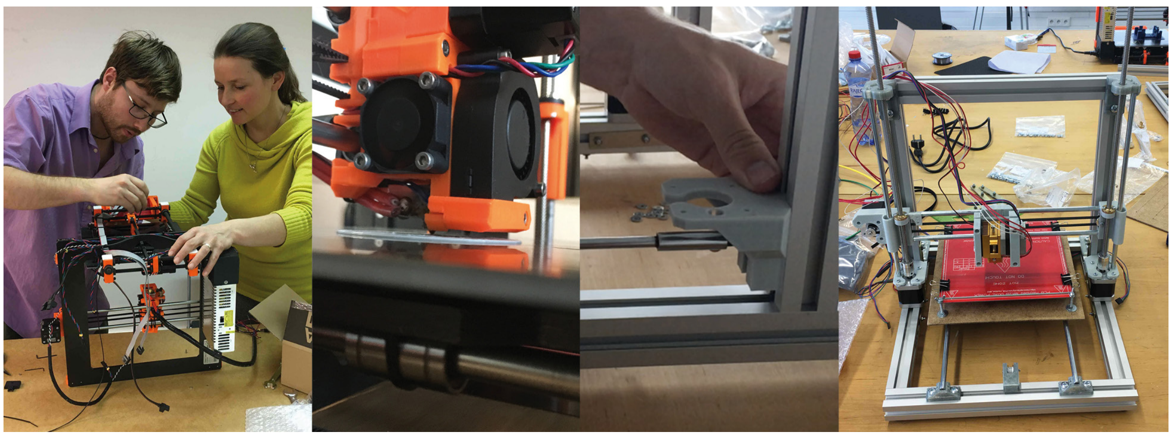


Fig. 2.1 Evolution of 3D printing machines: Rep-Rap style

rials we decided to continue in researching the recycling of PET for its amount of waste, strength and zero-toxicity. In 2016 there was no recycled filament on Czech market and therefore we found Netherlands and Argentina based products of recycled filament to test for the use in architecture. The tests of print-ability of these materials were started on the faculty of Architecture CTU in Prague, where first 3D printers were constructed through RepRap system in Experimental studio by master student Jiří Vele. We immediately started to test the print-ability of the recycled PET materials refill [24] and B-PET [25] in order to prove the relevancy of research of the use of recycled PET in architecture and design.

FIRST EXPERIMENT: TEST OF B-PET WITH STUDENTS - APPLIED RESEARCH

In the first experiment we had to test the print-ability of the Argentinian recyclet PET material. From the authors we knew nothing about the material apart of the proclamation, that it was made from recycled plastic bottles. Although we found two companies (FututeBetterFactory with 70% recycled PET and B-PET with 100% recycled PET), we decided to choose the material with 100% recycled material. We have not heard anybody in the Czech republic who tried to test it and this meant were the first researchers in the Czech Republic, who started testing print-ability of this material by using self constructed Průša 3D printer.

	nozzle temperature °C	speed %	infill type	infill %	fan speed %	bed temperature °C
Settings A	255	100	honeycomb	20	100	none
Settings B	260	50, 40, 10	triangular	40	100	none
Settings C	240	100	triangular	20,30	50, 60	90
Settings D	250	100	honeycomb	20	50	90
Settings E	245	100	honeycomb	20	100	90
Settings F	255	100	honeycomb	20	100	60

Table 1.4 Printing parameters settings

When printing plastic generally, many limits appear and a lot of conditions must be met. Firstly, size restrictions are there such as the printer bed dimensions, height of the possible product and diameter of the nozzle and thus thickness of the actual printed layer. Secondly, the characteristics of the PET (and other polymer) material does not allow for thick solid structures, because the tension between the printed layers can cause deformation of the whole product. Therefore we joined the project of Rep-Rap and started printing small functional pieces in order to construct a second printer. Not only we tested the print-ability of the material but also its usefulness in construction.

This influences the design of the final structure, which must be respected. Thirdly, the inclined walls of the printed product must appear under maximum 45°, or the layers don't stick together properly and the material drops down unless being additionally supported. This can be done, but removing the supports requires usually too much time of post-production and the model is usually damaged. Finally, the speed and system of printing matters. For example, if the nozzle runs too short routes and comes back to the same place too quickly, the layer below is not cooled down yet and the model is keen on sticking to the nozzle.

Also the material gets overheated. Specially, when the hot steel head runs around the narrow sharp end of the model, we could see the colour and material quality change of the piece. and so far only PLA and ABS were tested (Fernandez-Vicente, 2016).

We had the intention to test the parameters for 3D printing the material b-PET separately, researching one not to be influenced by the other, but we found out, that the setting we started with is being changed throughout the print session. Therefore we prepared separate printing sessions with different starting settings A-F. (tab.1.4) The main criteria was the temperature of the nozzle, the other parameters could be changed instantly during the process. As for the temperature we knew trhat melting point should vary between 250 and 260°C (Gonzáles, 2020).

SETTINGS A

Temperature nozzle 255°C

Temperature bed 90°C

Speed 60mm/s (100%)

Infill: honeycomb 20%

Layer height 0,2mm, first layer 0,35mm

Top and bottom horizontal shells: 3

We used Slic3r slicer to export G-Code file formats of stl test pieces. We chose 100% recycled PET in order to find best settings for a cheap home-assembled 3D Rep-Rap printer. Six test settings were configured in order to find best settings for quality/time ratio, which is publicly applicable even for non-professionals.

First results were surprisingly functional, we received the printed object fine, but the bottom layers looked under-extruded proving not enough thickness.

Second printing under the same settings took 45 minutes. We loaded different model with larger honeycomb infill and observed the behaviour of the printer. In the

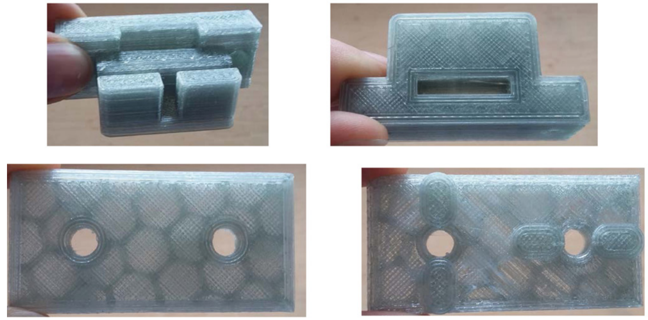


Fig. 2.2 First and second test print of 100% b-PET under configuration A

middle of the print we had to slow it down to 40% of speed. Problem appeared in the first full layer above honeycomb infill The temperature of the nozzle fell to 240 degrees and filament stopped melting. With decreasing the print-speed temperature rose to 255 and print was finished without any further problems. Decays on the final model appeared due to this manipulation though.

SETTINGS B

All settings as in A, but we changed three parameters:

Temperature 260°C

Speed 50%

Infill: triangles 40%

problem appeared again in the first full layer above triangle infill. The nozzle´s temperature fell to 235 degrees for a second and the filament didn´t melt any more. We decreased the speed to 10%, but it was too late. Printer stopped printing under thermal runaway and in this case the print could not continue. "Thermal runaway" is a safety feature designed to prevent printer from catching on fire in the case of dislodged hot-end thermistor. We found out that using these settings for b-PET printing can not be recommended. We also anticipated that printing at 240 degrees is possible only when slowing down the fan to 40%. Next test was designed in order to prove , if decreasing the fan temperature influenced print-ability.

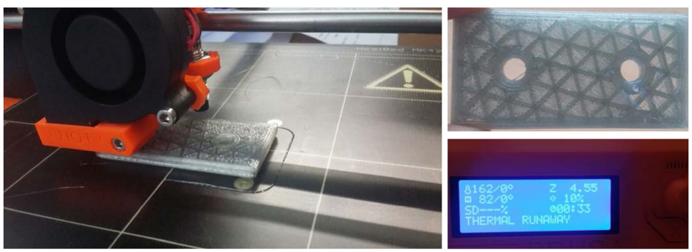


Fig. 2.3 Third test print of 100% b-PET under configuration B – unfinished

SETTINGS C

All settings as in A, but we changed three parameters:

Temperature 240°C

Fan Speed 50% and 60%

Infill: triangles 20% and 30%

Průša printer could not melt PET at such a low temperature as 240. This temperature could not be even tested, because of the thermal runaway of the nozzle. The prints have not even started, no filament went through the nozzle.

SETTINGS D

All settings as in A, but we changed four parameters:

Temperature 250°C

Fan Speed 50%

Bed temperature 90%

Infill: honeycomb 20%

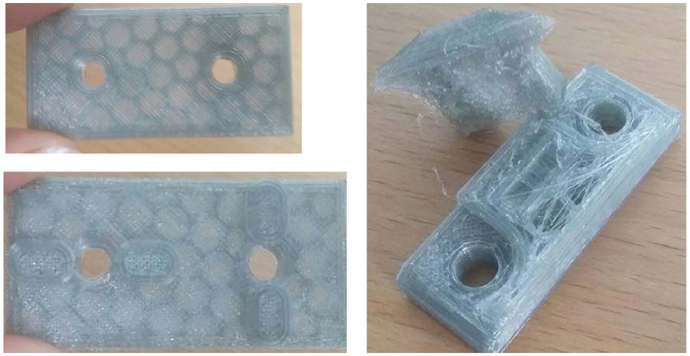


Fig. 2.4 Results from settings D

We were successful with this setting with a small flat object and 35 minuter printing time. After the first model we tried another object of a bigger size and more complex geometry with the same setting and the result wasn´t successful. Problem appeared at the top part of the object. Last layers of the infill weren´t even printed. Only small and thin objects could be printed with this configuration. The nozzle was heated to lower temperature and the filament melted only partly. during longer printing the nozzle got stuck.

SETTINGS E

All settings as in D,

but we changed two parameters:

Temperature 245°C

Speed 100% decreased to 80%

This setting did not allow for printing with100% of printspeed. We tried to decrease the speed of the nozzle and the printer started to heat the nozzle and melt the filament. This setting prolonged the time of printing to 1h and 22min and delivered geometrically satisfactory result without stringing, but the filament was overheated,

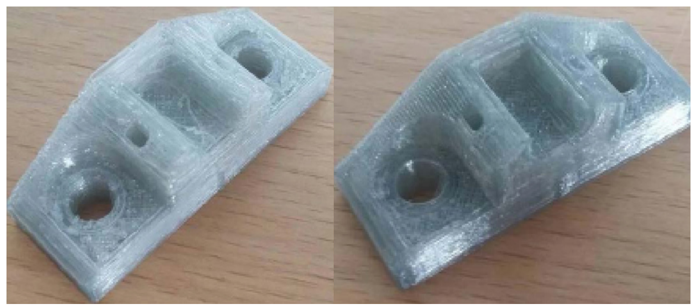


Fig. 2.5 Print result from configuration E and F

which caused the white colour and increased fragility of the piece (Fig. 2.7).

SETTINGS F

All settings as in E, but we changed two parameters:

Temperature 255°C

Bed Preheat 60°C

Finally, the result fulfilled our expectations. The colour of the product showed up to be transparent and homogenous. The print went well and in a short time of 22°C.

Fig. 2.6 Veleprinter and its replication at Futureport Prague 2018

CONCLUSION OF THE STUDY ON PRINTING RPET

We tested 6 types of configurations of the Průša printer with various results.

We concluded, that Průša printer must have 255°C Nozzle temperature with 100% speed. The point was in rising the extrusion in the slicer. All above mentioned together with 60°C bed preheat brings the best results in shortest time for Průša printer. The success of printing recycled PET lies in best temperature setting of around 255°C, fan cooling decrease to 0 for at least for three initial layers, and extrusion multiplying of 1.08.

As a result of this experiment we printed all small pieces of functional printing machine and they really served in constructing a new printer called Veleprinter successfully.

3.CASE STUDY: SMALL OBJECTS - RECOLUMNS

We succeeded with post consumer recycled PET printing of test pieces and as a case study we decided to introduce a studio topic for master students: design of a decorative Column – a typical architectural element free d from the load bearing function. Firstly, the focus was directed to the use of recycled PET for the structure and the advantage of 3D printing technology together with implementation of students' lectures of parametric modelling, We searched for feasible scale in order to produce the models and the printing time occurred to be one of the biggest issues. The models were printed in scale of 1:20, where the exact number oscillated around this value. Rather than researching the strength of diverse constructions we found important to keep the same height of the column models and the possibility to print them in one piece. We had to respect the size of the printing nozzle, which determined the smallest printable piece of the structure.

Secondly, we wanted to research, if the recycled PET is of any relevance in 3D printing models and can fulfil various design demands. We wanted to find a relation between complexity of the model, amount of material and printing time. Students designed various algorithms for the design with the function of a decorative column. We observed if this complexity influences printing time and quality of the print, like colour, stiffness and visual performance.

Thirdly, we pressed the columns in the stress test machine to prove if the load-bearing capabilities of the decorative designs of various structures made of this material are of any relevance at all. We wanted our students to use architecture intuition for the column design rather than computational method and focus more on the aesthetics.

TASK

A group of students was given a task to design a decoration in shape of a column, which is fundamentally a load bearing structure, but in this case we wanted our students to rather develop crazy shapes independent of the functionality. The task was focused on emphasising the potentials of the technology of additive manufacturing – not optimized for the function of load-bearing. With the combination with Rhino-grasshopper we acquainted a number of columns in order to test their possibility as models of being produced by 3D printing. Now, the primary aim of this studio was to design the column with the use of 3D printing technology and its limits and restrictions. Working as decorative elements the columns should have been empty inside in order to have a second function (lighting, air-conditioning, planting greenery etc.) We made a qualitative evaluation of the results and chose 7 models, where the criteria was met on the level of innovation in design, coding and shapes and in terms of the visual performance and respect of the technology of additive manufacturing. The target was not a research of construction systems in real columns.

DESIGNS OF THE COLUMNS

Various algorithms in Rhino Grasshopper were introduced and explained to the students in the workshop in the beginning of the studio. After that, students decided, which codes they should use for achieving a decorative column design.

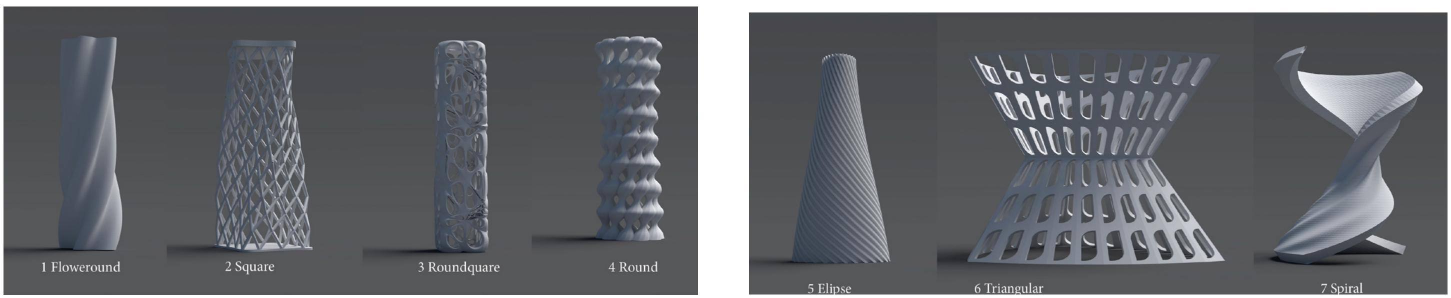


Fig. 3.1 Students models in render

Column number 1 is designed like a simple rotated profile with various angles along the axis. On the bottom, the angles differ more than on the top and this difference is driven by a cubic curve used in Grasshopper's Graph mapper. The profile curve was modelled in Rhinoceros and resembles a starfish outline with uneven yet rounded corners.

Column number 2 uses a custom base curve, which is a blend of a square shape and a four-corner star with certain smoothness applied. This base curve is than moved up and rotated in a linear fashion to provide base surface for a diamond division. Finally, the diamond curves are piped using the smallest printable radius of 1.5 mm.

Column number 3 consists of 3D voronoi cells, which were converted to mesh and then made smoother using laplacian smoothing. The cells were UV mapped from flat surfaces onto all six faces of a 1:4 ratio prism. Therefore the inner volume of the model is hollow.

Column number 4 is modelled using a base curve from Rhinoceros, this version uses an ellipse, which is very close to a circle. This base curve was then divided into 12 or more points, which nested second level of base ellipse curves. Using rotation around the centre of the main base curve and scaling in the plane of each new second level curve a helix-like stream of quickly oscillating radii emerges. Since the oscillation uses sinus function to moderate the radii, (when there is enough division points on the main base curve), some parts of the helix-like streams overlap, which creates connection and produces structural stiffness.

Column number 5 was modelled using a rotated ellipse with changing focal lengths, which shrink towards the top part. Next, the basic surface is subdivided using ISO-trim, which follows the double curvature of the surface. The divisions follow diagonal lines between UV iso-curves and are extruded to form ridges on the surface.

Column number 6 consist of two horizontally mirrored truncated tetrahedrons with rounded horizontal edges where the plane of mirroring is in the centre of the truncation. This poly-surface is then divided into non-planar four point surfaces using isotrim. In each of these surfaces a smaller offset of the outline was created. Then the offset curve was exploded and two non-neighbouring edges were rounded using a radius close to the length of the shortest edge. All these shapes had to be planarized in order to extrude them as surfaces.

Column number 7 was modelled using a base curve that was derived from a dancer's movement. This curve was then not extruded, but moved in custom directions to provide thickness of the overall shape. Once the poly-surface solid object was created, the outer surface was again manipulated to provide smooth ridging resembling waves on it. Note that in the top view the centre hollow represent almost perfect circle. The base curve was so dynamic that in some cases surface self-intersection had to be detected when modelling the wavy ridges.

3D PRINTER DATA

We measured the amount of material of the columns and the production time, which were the basic data we could read from the sliced objects directly on the display of the 3D printer. Each column was approximately 190 cm of height, but the mass and time differed a lot.

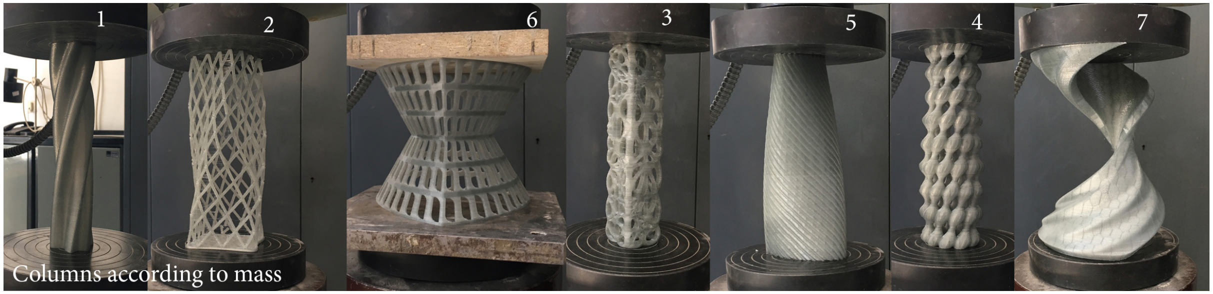


Fig. 3.2 columns rowed from left to right according to mass

Column n.	time	size	mm3
1	02:58:10	43x43x188	42334
2	09:31:53	87x87x190	65798
3	12:07:37	45x45x189	79297
4	12:09:41	65x65x189	222857
5	08:08:17	92x60x191	211223
6	11:02:08	152x152x192	66121
7	07:37:37	148x144x190	337539

Table 3.1 Information about columns. Data was acquainted from the 3D printer and slicer

From the illustrations above we could see, that the ratio between mass and time is not linear. The speed of printing depends on complexity of the structure and movements of the nozzle while printing. This means that the structure, where the nozzle follows fluent routes without stopping, can be produced faster than structures with less material but composed of small closed routes. Surprise was the printing time of n.3 and 4, which took unexpectedly long time due to distributed closed printing paths and irregularity of sliced layers. When printing number 4, the nozzle had to move without printing half of the time. On the other hand, the printed "islands" in layers in number 2 were so small, that we had to forbid the retractions, otherwise nothing would be printed at all.

STRESS TESTS

Finally, we pressed the columns in the regular stress-test machine at the Faculty of Civil Engineering in Prague anyway. We could see, that the material is generally flexible

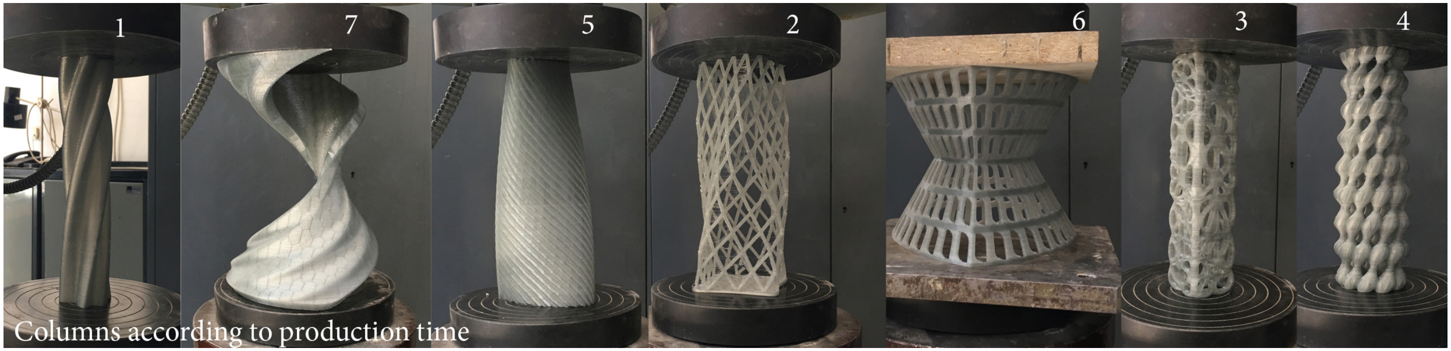


Fig. 3.3 columns rowed from left to right according to production time

no matter what shape and structure it has. All columns decreased with 1,5 mm under initial pressure of 0,1KN. We organized the columns according to their load-bearing capabilities, amount of material and printing time. It can be seen from the illustrations below, that all columns undergo decrease of 1,5 millimetres, which is the plasticity of the material. We wanted to prove if testing recycled PET for load bearing function has any potential at all. The surprise was the value of almost 1 tonne of load carried by column number 5. From 2mm decrease the structure started to play a role. For the future study we know that test on load bearing structures will be relevant. We could see, that the design influence results of the stress tests substantially. The biggest surprise is the ratio between production time, mass and stress test of number 1 – the winner of the contest. This column has features closest to optimum (a cylinder), so here it would make sense to improve this algorithm with holes.

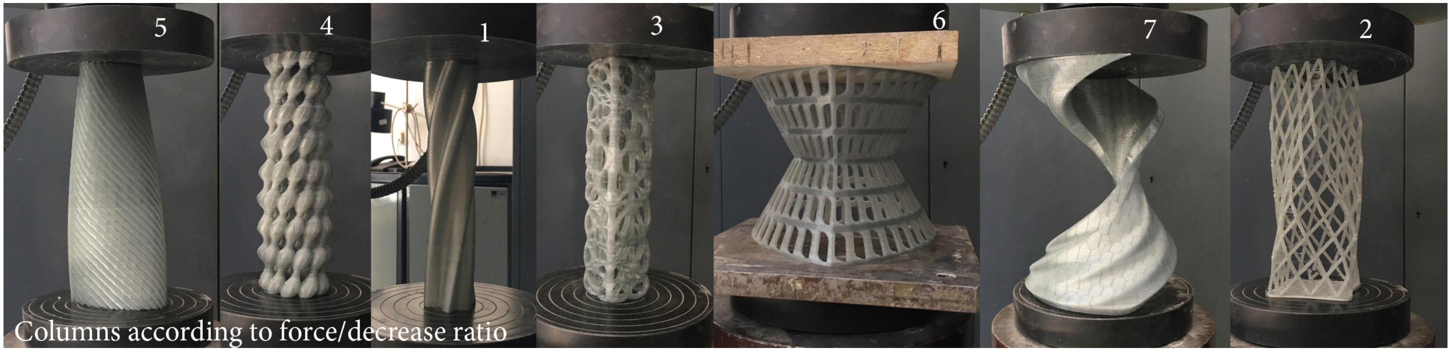


Fig. 3.4 Sorted columns according to stress

LESSONS LEARNED FROM THE CASE STUDY RECOLUMNS

benefits of 3D printing, how to design

We gave our students the task to design a column specially with the aim to be 3D printed from recycled PET. They had to script the design in Rhino grasshopper, they were asked to create the design with the use of computational tool. This means that the realization was done by computational tool too, which understands the code. Making such models by hand seemed stressful. This means the students learned how to prepare parametric scripts for 3D printed objects.

We recognized, that the printing time was not dependent on the volume of the object but rather on the structure of the object. The columns with continuously printed layers were printed faster than the ones printed in the distributed closed "islands", although much less material was invested. The retractions, when turned on, slowed down the process and caused jamming of the nozzle.

Finally, we were just curious in the end, if the load bearing feature was influenced by the amount of material or rather the symmetry and regularity of the design and if students can intuitively tell the results. All of them tipped the worst performance of the model n. 2, but all students thought that the most durable will be the column number

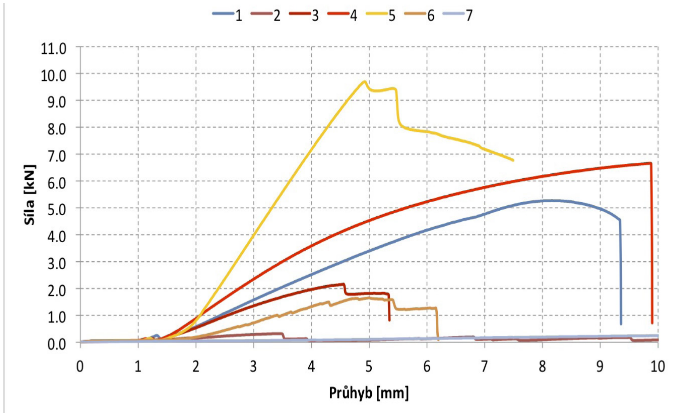


Diagram 3.2 Force/decrease

1 due to its circularity. It can be concluded, that students gained intuition in static behaviour during the study period. The result showed to the students, that the column number 7 with the biggest mass and almost fastest production time failed in the stress test due to its mass asymmetry. On the other hand, the column number 1, which had the least amount of mass and was produced in shortest time performed quite well in the stress test despite its little irregular design. We explained it by the fact it was close to circular layout, which would according to our intuition with comparable mass behave the best.

4. BIGGER OBJECTS

All the products facilitated by our Prusa and Vele printers were small scale objects so far. We focused on enlarging the produced objects by assembling pieces, which were possible to 3D print on small scale printers. Firstly, we had to develop a method of modelling interesting architectural structures with perceiving reasonable amount of data of the models. This depended on the capacity of our computers. Secondly, we tested the adjustment of the printing time. Having gained the knowledge of designing and facilitation small objects, we researched the physical possibility to construct a large object from many pieces in reasonable time. The problem was answered by the distribution of printing task among larger group of people preserving same printing conditions.

DESIGN 1 - HYMN

First tested larger object 3D printed in the experimental studio was a sculpture made of 14 pieces. This design was finally realised in scale 1:1 and all students took part on printing preparation and manufacturing the final model. In the end the pieces were glued together to form a one meter high stable-standing statue.

The design originated in a collection of random points in order to demonstrate possibilities of current design methods. Than, sets of closest points were connected by simple lines. A marching cubes algorithm from Bespoke geometry's Cocoon plug-in was used to generate a mesh hull around the lines based on an arbitrary charge value of each of them. Resulting mesh was already visually attractive, however that was not much related to the new fabrication approaches. Such a statue could be easily created using clay or other traditional modelling methods. That's why the process was subsequently repeated with lines extracted from the mesh to obtain a lattice-like structure. What was a simple line in the previous step now became a complex mesh hull around that line with varying radius and the vertex count grew exponentially. Resulting mesh was consisting of more than 4 millions faces and even current software was having difficulties while handling such geometry. One single move command took around 30 seconds to complete on a laptop although on a more powerful desktop machine the time didn't shrink more than to 20 seconds. Still, the initial point collection could be changed by different random seed values to generate a whole new version of the design. Such a task took about 7 minutes to complete. Having a completely new variation of the same design in a few minutes is still new to architects and even students of architecture. Choosing from a pool of different designs which all meet the same criteria is still relatively new task for today's architects. This design approach was definitely not traditional and showed the generative potential of computational methods well working together with additive manufacturing tools.

We tried to 3D print a piece of the upper mentioned structure under regular settings for PETG materials and although we immediately had the model in hands, immediately problems appeared some of which were not unexpected.

- The material was not consistent in quality and stringing appeared.
- Within the same conditions the filament did not melt properly and the volume started to be fragile. It changed colour to white and sparkled during printing.
- Also a lot of tiny fibres in-between the printed structures appeared. We also found out, that the model had to be improved in terms of design.
- Bigger overhangs than 45° ending with spans longer that 1cm could not be realised, because the filament fell down.

A general study on 3D printing of recycled polyethylene tereftalate in more difficult structures was made and a setting prepared for facilitation 120cm tall model composed of 14 parts.

MODEL DIVISION

To be able to print the whole structure the model had to be cut into more feasible pieces with dimensions less than 250 x 200 x 200 mm to fit into the 3D printer. This task was very challenging in the software which was used to generate the model - Rhinoceros 5.0. After many attempts some of the pieces still wouldn't separate from the whole due to boolean operations failures. After exporting to Blender 2.78 the splitting still took a lot of time and processing power, but thanks to exposed variable of the boolean split accuracy in one of two available solvers the task was completed in reasonable time. In Rhinoceros 5.0 there is a way to change document accuracy which influences all operations including boolean splitting, however this approach is worse than cumbersome when each splitting operation takes more than 3 minutes on a desktop with i7-4770K at 3,5 GHz with 16 GB of DDR3 RAM running at 1600MHz and a SSD drive. Blender 2.78 performed quite similarly but when the operation failed or the results were in-acceptable (invalid mesh, flipped normals and so on) there was still an op-

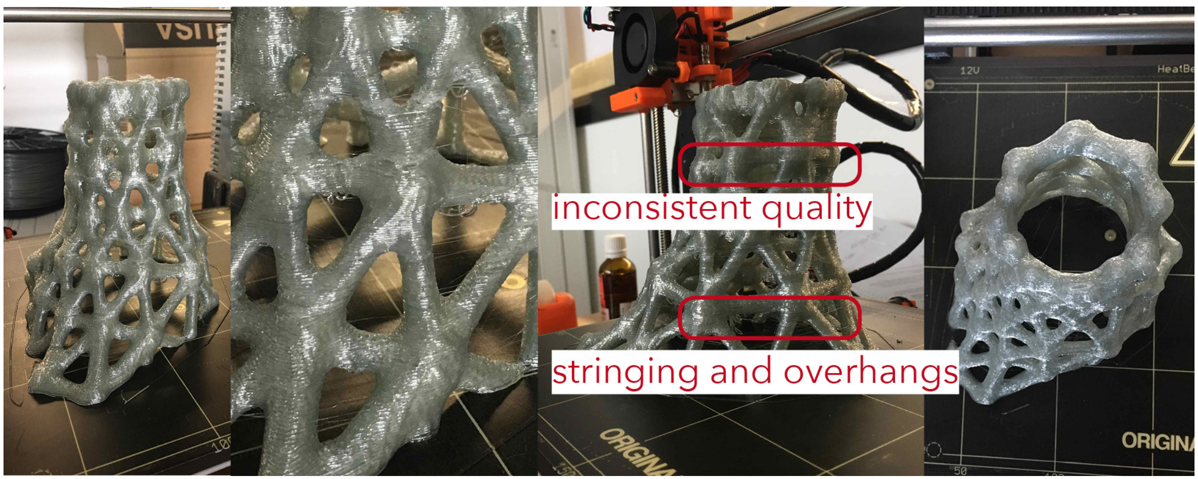


Fig 4.1 A trial of 3D printing complex model from100% recycled B-PET

tion to use the other Boolean solver called BMesh which has the previously mentioned exposed variable called Overlap threshold which basically filtered out problems with vertex collisions.

3D PRINTED CONSTRUCTION

The printing task was distributed among students, one piece per each. We generated a table of pieces/students/settings to be sure that each student had the same conditions and the same filament and the same setting in order to save time and energy per person. There were also lecturing purposes - we aimed at teaching students how to operate a 3D printer themselves with the risk of breaking it. The advantage was, that this type of 3D printer was cheap and easy to repair and if students broke the machine they were also asked to repair it.

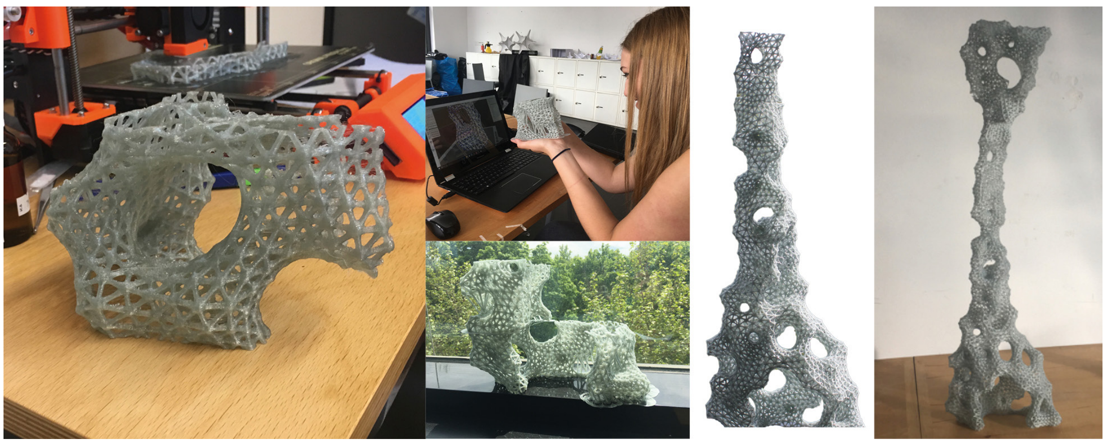


Fig 4.2 - first trial of 3D printing 100% recycled B-PET from Argentina in bigger scale - 14 pieces

COLUMN

On the base of Hymn and recolumns research we created a real product: a two meter high COLUMN made of 5 sections of 8 pieces each. The design was generated in Rhino Grasshopper with voronoi structural division method. The 5 main parts were printed out of PETG, rPET, and PLA and all the materials performed same functionality. The column was used as public interior exhibition piece and furniture. A rotation mechanism was implemented so that the pieces could be moved against each other.

Fig 4.3 - Applied research: an exhibition piece of furniture made of 40 pieces in combination of materials

LESSONS LEARNED FROM BIGGER OBJECTS - HYMN

division into pieces, gluing, assembling

We found out, that bigger objects can be made with the 3D printing method using small printers. With our students we tested the distribution of objects among more people in order to save labour-time of each student. Also we tested, that some designs (like Hymn) cannot be realised using traditional modelling techniques and are produced by 3D printing technology witch advantage. Last but not least, we found out that originally lay persons could learn to operating 3D printer and print unusual non-standard recycled material, which was not easy to print. Using standard superglue was perfectly possible for recycled polyethylene tereftalate and the parts were printed precisely according to the model. Achievement of interesting results lied in understanding of computational design methods and a turnover in thinking of the designer.

5. EVEN BIGGER OBJECTS: CROWD - SEARCHING NR.1

In order to produce even bigger objects than 20cm x 20cm x 20cm in reasonable time, we had to invent a facilitation strategy that would help us to distribute the printing activity among multiple printers and thus save time. We prepared a crowd-printing project in order to test print settings for various printers. This helped the development of recycled filament of a good quality useful in architecture and design. We tested our idea in an arts project called PET(s)culpt [29]. We used the public event called Jinohrátky for motivating people to take part in our research through logging into our web site. Jinohrátky is a public event , which takes place in Jindřichův Hradec city each year during advent. We followed our tradition from previous year and offered a construction of statue made of recycled plastic waste with the participation of public. The point was involving lay 3D printers into the creative process and each of the participants was told to 3D print a piece of the statue. When they were ready, we were sent a photo and consequently, when approved, the ready piece. This way we tested the possibility to print recycled polyethylene tereftalate on 12 various types of printers through 30 participants. On the basis of this experiment we were ready to print a real structural element in 1:1 scale in order to test if recycled PET is feasible material for external participants and various printers. We also gained a small knowledge about its load bearing features to some extend.

CROWDPRINTING - PETSCULPT

When preparing a crowd-printing project, we tested our idea on an arts project called PET(s)culpt. First a sculpture of an angel was designed in Rhino Grasshopper. The design was inspired by traditional "Native scene" by Tomáš Krýza in Jindřichův Hradec and Kafkas' Head from David Černý in Prague.

The ready virtual model was split into separate pieces and saved as "stl" in our database. The innovation was the fact, that each stl had a "json" substitute, which could be previewed by the participant directly in the web browser. The preview was also animated. After the participant logged into our system, the user was allowed to download the stl file with the settings for the 3D printer.

Once this happened we sent the recycled filament to the given address and our participant could start printing. We offered two types of recycled PET filament: 100% b-PET and 90% refill. When the prints were ready, we were sent a photo of the ready piece and checked if the recycled PET was used and if the piece has an adequate quality. Finally we collected the ready pieces of an angel from the participants and glued it together with Super glue and activator. Montage of the angel was made on a steel construction and the whole sculpture was mobile, where the wings could change its visual performance. Recycled PET proved to be a stable material in outdoor conditions. Neither it changed shape, nor the colour. The pieces of the wings could withstand horizontal forces from the wind, even though six floors of the wing construction consisted of five pieces glued together. LED

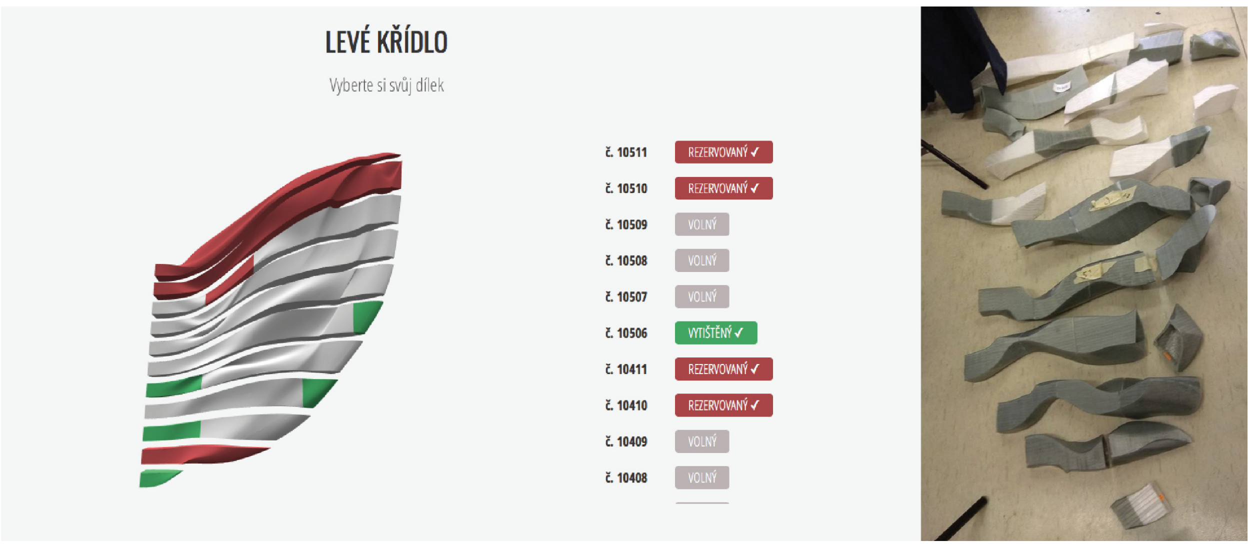


Fig. 5.2 Virtual model on the web page and real collected pieces

lights were put inside of the hollow pieces of the wings. This way we tested the possibility to print recycled polyethylene tereftalate on 12 various types of printers.
On the basis of this use case we were ready to print a real architectural decoration element in 1:1 scale in order to test if recycled PET is feasible material for public use and self load bearing structures.

LESSONS LEARNED FROM PET-SCULPT

Interactive crowd printing platform

3D print of structural element models is possible with recycled PET. The scale affects print-ability of the model together with the size of the nozzle. The standard printing area of a printer is around 20X20X20 cm. This limits the models being printed in one piece, therefore we decided to divide our two meter high sculpture into 390 piec-

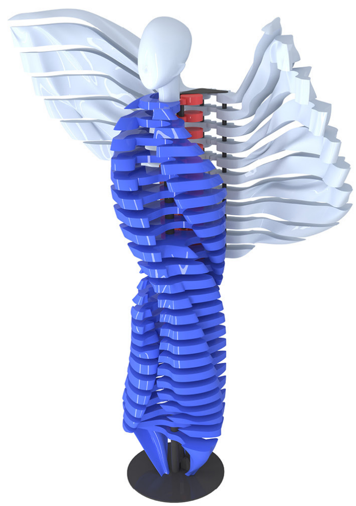


Fig. 5.3
Model and real 3D printed sculpture

es, 210 of which were printed by the public on twelve various small home-printers with limited “printing” area. Three types of Průša printer were used, Cryal Cube, Makerbot replicator, Anet A3, REBEL II, Zayda, Sigma BCN, Ultimaker 2 and 3, Felix 3, Veletiskárna and Rebel II. 90% and100% recycled PET of five colours (white, grey, red, light blue, dark blue) was distributed and both diameters of filament were tested: 1,75mm and 3mm. The melting temperature of each printer differed from 245°C to 270°C, the temperature of the bed varied around 60°C. The speed of printing was set to 100% in most cases. Each printer had to be configured in a different way, therefore there was no exact settings for all printers. It was recommended to switch off the cooling for first three layers.

Generating 1:1 test piece of a structural element out of recycled PET was inevitable in order to find out its load bearing capacities as structural elements, as no models could give us relevant outputs. The structure was divided into smaller pieces and glued together by Pecka speed glue with the use of activator. The glued connections proved to be more stiff than the structure itself.

We learned how to distribute work among multliple public participants and developed a crowd-printing web platform. This principle of interactive web page with interconnected databases of stl and json types of files was our know-how and could be used also for other projects. (Nováková, 2018)

6. DEVELOPMENT OF CZECH RECYCLED FILAMENT RPET

We knew from our previous projects and from newly found existing references (Anderson, 2017) and (Panda, 2017) about the possibility to assemble a statue from 3D printed smaller parts. As we targeted bigger structures made of smaller pieces in order to fulfil the visions of the use of recycled PET in 3D printed architecture, we digitally designed a two meter high sculpture PET(s)culpt as mentioned above. Still, the fact of transporting filament from Argentina was against the idea of environmental friendliness. We also could not be sure about the contents of the above mentioned so-called 100% recycled material, because there was no way how to investigate the production processes in Argentina. There are companies recycling PET waste in the Czech republic which we learned in the preliminary research such as Petka cz. [37], Purum s.r.o. [38], EKO MB [2] or ECO-F [39].

THE CZECH MADE FILAMENT RESEARCH GOAL

So the challenge was to try to develop our own recycled PET material with no additives and test this material in an innovative and creative way. Two outcomes were expected from this study: the properties of the material (feasibility, cleanness, durability, stability, colour and other) and the user experience, which was dependent on various types of printers.

As all our attempts to produce the filament from PET flakes inside of our office failed (Fig 6.1 left) we started to cooperate with professional companies with professional machines (Fig 6.1 right).

To our surprise, the first roll of recycled PET we manufactured (type MB25) worked immediately well on our own Veleprinter and we could use the material (called rPET) directly in real case study project in the hospital in Prague. We tried more types of PET recycled material according to their origin (Bottles, Desks, Yuta – (table 6.1)). All of them were re-granulated into small ball-like pieces

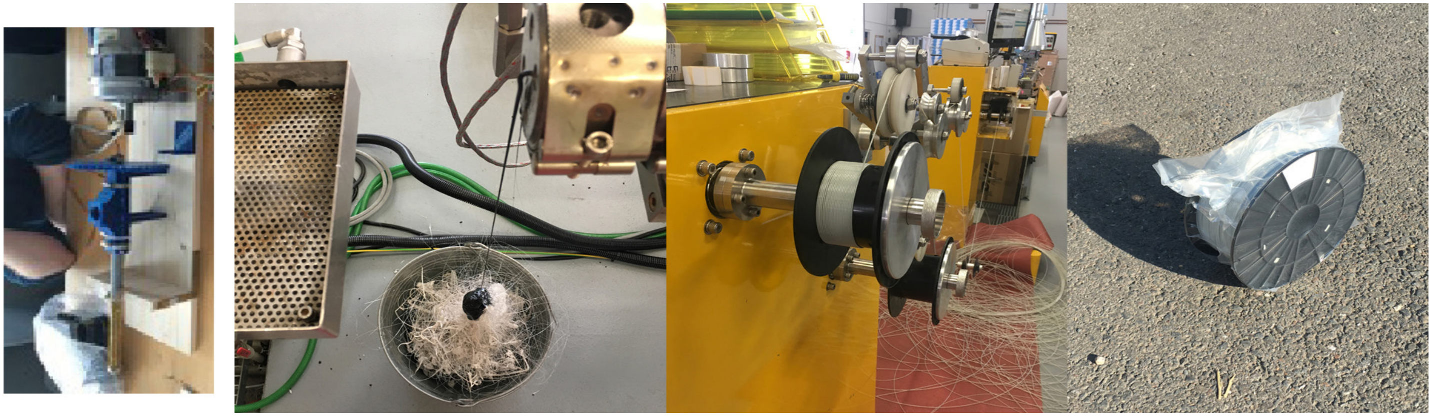


Fig 6.1, left: own extruder, right: professional machine for filament

before being extruded into a long 1,75 cm thick fiber. To our surprise, they served as filament for 3D printers without any other substance (such as glycol) added!

MB 25	rePET silver	Post consumer plastic bottles
MB 46	rePET transparent	Industrial waste from PET desks
MB 53	rePET juta	Industrial waste from juta - no use case

Table 6.1: origin of new filaments rPET

PROOF OF CONCEPT OF MB25: VELEXA JOINTS - FEASIBILITY

We started the test with printing small but functional design. We designed and printed a mechanic arm (Fig 6.2), which was tested on site with the public users. The site was located in VFN Motol at spinal unit, where paralyzed people are situated. Our arm called Velexa carried a communicator Alexa, which helped the patients to take control of some accessories. The arm was designed with a sphere joint and several screw systems in order to accurate it on the bed. We used grey MB25 and all parts were

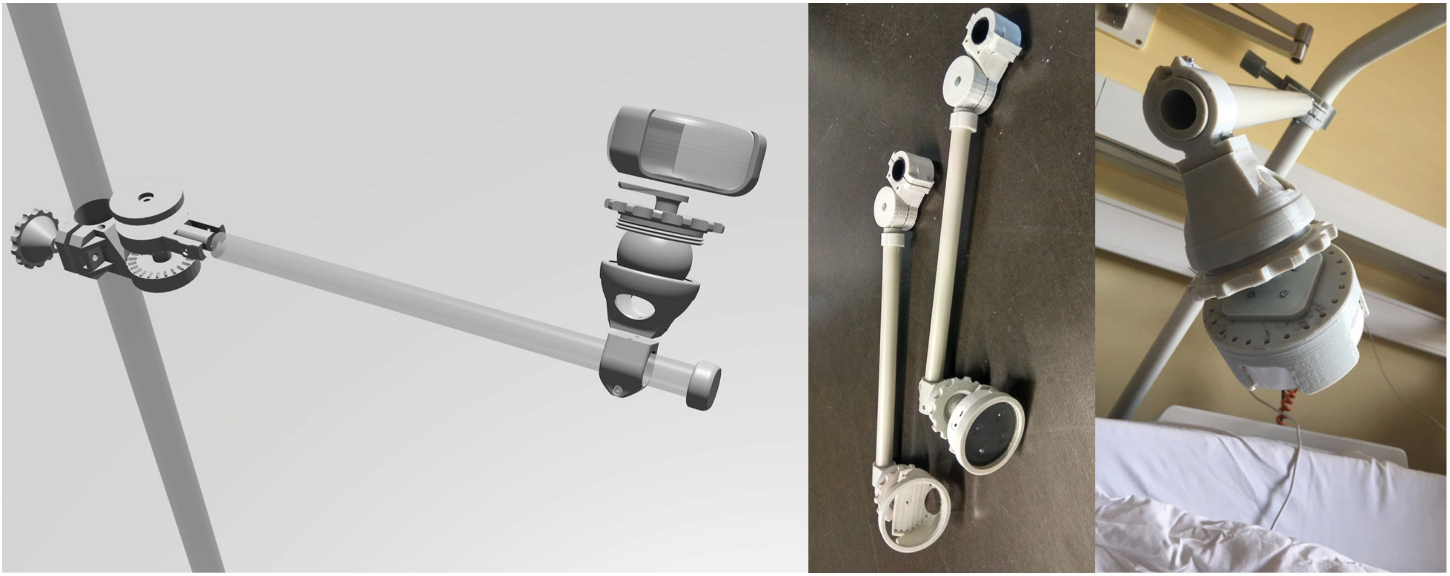


Fig. 6.2 Velexa - mechanic hand - our 3D printed object

printed on custom-built 3D printer. The material proved to be stable in shape and colour. Its combination of stiffness and flexibility surprised us. Everything was exactly dependent on the design of the model and the way of printing it. In additive manufacturing height of layers can be set. It is important, if the object is strained along the layers or perpendicular to layers. We initially set the layer height to 0,3mm and used 0,4mm nozzle. The 3D printed parts were combined with PVC tube, where they were fixed with steel screws. We paid attention, that the strain directs along the printed layers, so that they can not split easily. We only implemented one type of newly developed filament. The project war running for one year and we were improving the model always after the feedback from the users. Here we used the benefit of rapid prototyping, we could facilitate and deliver the new designs instantly. We also wanted to test designing by regular CAD programs like AutoCAD.

LESSONS LEARNED OF VELEXA USE CASE

Usefulness test, print test of Czech rPET M46

This use case proved the usability of the material in particular and very specific hygienically demanding conditions. The design was made distinct, not provocative by wild shapes. The functionality of the tool was proven. The light grey colour of the material was very suitable in the medicine conditions. It was possible to wash and clean the object thoroughly and it was not affected by using disinfection. There were no big forces applied to the object, so the mechanics of it worked fluently. No cracks or other imperfections could be observed after one year of use. There was issue with the printing machine. Only one specific printer was used. We had to introduce a crowd-searching project in order to investigate the potential of the material in public using various printers.

PROOF OF CONCEPT MB46:TOKYO BAR

We chose our recycled filament rPET MB46 transparent in order to observe and test the flow of the nozzle on the basic shapes. We found out that one layer surfaces in small dimension up to 10cm in diameter are quite flexible and strong. Whereas shapes with more layer walls are more fragile. On the other hand, in order to 3D print bigger structures, the single-wall structures are too flexible and not strong enough for significant loads. With more layers the details of the 3D printed objects show the impreciseness of the big nozzle, when the targeted objects are too fine with the detail.

We initiated the idea of using 3D printed “basic” shapes as moulds or lost casts for much more traditional material such as concrete. As the material is recycled waste already, we could allow ourselves to “spoil” it using the 3D printing technology in order to achieve interesting shapes made of concrete. A bar was designed in the experimental studio at FA CTU, where the layout of roads and railways was adopted from the Tokyo bay in Japan. On the basis of this grid a system of “square-shapes” was

Fig. 6.3
structure moulded with recycled filament moulds

derived, which formed the outcome for next steps. All of them were off-set in order to estimate size of the roads.

The scripting support for this project involved three phases. Map simplification, closed curves extraction and offsetting with extrusion. For the most of the modelling tasks Grasshopper was used, however in two cases Rhinoceros 6.0 and Blender 2.78 was a better and more precise option.

Map simplification took place. Due to inherent complexity of the city map curves a polyline simplification and also significant detail filtering had to be used in order to come up with a manageable number of printing parts. One approach was changing the scale, the other one was to find city mega-blocks - similar to complexity reduction in maps while zooming. In the end a mixture of these two approaches had to be used to produce a model with 122 3D printed pieces of casts.

We exported two STL files from Grasshopper. One was a complex of Tokyo blocks and second was overall shape of final bar. We also split Tokyo blocks in five layers, so they could be printed. Following pictures represent fourth layer. Then we exported those two STL files into

Blender, because of its reliable boolean modifier. Then we used boolean on Tokyo blocks to treat edges, then we exported every single block as a solid object and in Slic3r we set zero infill, zero top layers, two bottom layers and one perimeter, thus we got simple vase type model. At first we tried off-setting walls and printing it like that, but offset didn´t work well on sloping sides, making them thicker, thus printer printed more layers in that part, making that side rougher. On such a tall object printed with only one perimeter became visible bending of material due to plastic shrinking when it cools but in our opinion it makes nice detail in the final concrete model.

The overall consumption of the material was 9 kg of recycled filament. One cast was printed from approximately 20 meters of filament.

The final object should have appeared outside of the casts. The walls of the squares were extruded with 20 cm upwards, which was the estimated thickness of the final layer of the bar. The idea was to print very fast one-layer moulds and fill them with sand in order to fill the area in-between the casts with concrete. In order to create 1x1meter "surface" around 120 moulds had to be printed, where the printing time for one mould differed from 30 minutes to 1.5 hours. The overall time was 24 hours

Fig. 6.4 3D printed moulds distribution and filling with sand

with 6 printers.

In order to prevent the concrete thin structure from cracking, we used UHPC (ultra high performance concrete) with 0.6 to 1.1mm sand grain and plastificator.

Once the layout of the moulds was printed on paper, we filled all moulds with sand and also the surrounding of the determined area in order to stop the concrete from escaping. We surrounded the complex of moulds with sand too. Inside of a simple cast made of wooden panels, the plastic casts on the outline were glued to the paper with a tape in a way that the concrete could not pass through. We poured the concrete inside of the thin areas between the casts and waited for one week. The final object (Fig. 6.3) had the weight of eighty kilograms a and could be lifted by a group of 4 people. The bar changed into a table and the table was exhibited at the final presentation of semester work.

Fig. 6.5 Ready outcome of the studio: Tokyo table

LESSONS LEARNED FROM CASTING USE CASE

Casting with rPET, print test of Czech rPET MB46

Printing casts for bigger (concrete) structures was possible and made sense with recycled material, which can not be used for very fine resolution models. This was determined by the need to use larger nozzle (0,8mm) than with virgin materials due to impurities in the substance and its lower viscosity. Anyway, the height of the layer could be the same, so that the surface of the printed objects looked smooth. As casts, the 3D printed rPET in this form of one layered object was not waterproof. The material proved to be strong enough to overtake the forces of sand on one side and the concrete on the other side. In some cases where cast moulds were bigger, we could observe a significant change of the straight wall of the mould after finishing the experiment and remoulding the structure. The forces of the liquid concrete caused vawy appearance of the plastic walls. Only two moulds broke during the casting process out of 120.

7. EVEN MORE BIGGER OBJECTS: USE CASE N. 2 CROWD-SEARCH-ING-USER EXPERIENCE: PETANGELS

Fig 7.1 Parallel world of angels project - a street-view of Jindřichův Hradec

We made a study of the use of two types of Czech recycled PET material on various types of printers: MB25 Silver (made of post consumer plastic bottles) and MB46 Transparent (made of industrial waste from desk production). Both of these materials could be rolled up in the factory after 1 hour of drying without problems.

There was an annual advent public project in Jindřichův Hradec called "Parallel world of angels" where we participated collaborating with a sculptor Michal Trpák. The task was to decorate the main street of the city with sculptures flying above peoples heads. We accepted this opportunity to test the recycled PET in bigger scale installation placed in winter exterior environment. The plastic seemed ideal material: it was lightweight and hard to damage. Plus the material had basically low primary value and it needed to be tested in public space. The project was demanding on printing time and therefore we opened our previously invented crowd-printing project platform, where volunteer people could participate with printing pieces of the common work of art. The outcome was 85 participating volunteers with 25 types of 3D printers. 690 pieces were offered on a web page [30], around 100 people took part in the project and 28 respondents gave us feedback about printing settings in the questionnaire. The study included two types of prototype filament MB25 and MB46, which was made of Czech waste plastic bottles/fiber and PET desks. This was the firs time, when the filaments packed in professional conditions. We supplied the volunteers with filament and collected pieces, which we assembled into 18 statues of angels in life scale. Next, we sent the printing participants a questionnaire (table 7.1), where they shared their type of hardware and slicer settings, findings and experience with the filament used and their printer. The participants were lay people as well as experts, and the results of the study were therefore dependent on the level of expertise of the participants. Anyway, it monitored user experience in combination with the type of printer.

1	Printer type	39% Průša, 17% Rebel2
2	Slicer	61% Slic3r
3	Nozzle type	72% PTFE technology
4	Nozzle size	61% of participants had 0,4 mm
5	Temperature of the nozzle	Average of all participants 258,80°C, varies between 220°C and 285°C
6	Temperature of the bed	Average of all participants 83,0°C, varies between 70°C and 100°C
7	Speed of printing	Average 58,5mm/s
8	Setting of fan and cooling	32,1% had FAN OFF, 32% had fan up to 50%, 17,8% ignored the setting,
9	Retraction	64,3 % had the retractions off or very low

Table 7.1 Questions posted to the public and winning values

PUZZLE LOCKING SYSTEM

The printing time of this installation was calculated to 354 hours for Průša printer and printers of the same type. We used only 1.75mm filament and the nozzle size varied from 0.2mm up to 0.8mm. The most recommended size was 0.6mm nozzle thickness. Since the printing size of most 3D printers was limited, the sculpture models needed to be divided into printable pieces. We introduced third dimension into puzzling process and cut the statues into 3D puzzle with interlocking locks. (Fig. 7.2)

While separating pieces many assembly details and strategies had to be already assessed, due to sculpture shape complexity. Initially, the team tried to divide the sculptures using a script. In the case of the testing project, it would follow a set of lines depicting a ragdoll representation of the sculpture's limbs and also wings. The problem was that this approach was not general enough for certain shapes of wings which were topologically more like a limb.

The second strategy was just simple modelling which turned out to be extremely time consuming and also in some cases some previous decisions while modelling led to a model which could not be assembled. This was discovered only after finishing the most parts of a sculpture.

The last approach was to find a grid of 3D boxes (Fig. 7.2) which would separate pieces of the sculpture data model. In case of some local issues like bad print-ability, need of excessive amounts of supports or splitting pieces into two or more disjoint chunks, these were solved by splitting the particular 3D box into two separate cutting objects which then had to be assembled first to form the original piece that would be cut by the original 3D box.

This approach was best implemented in the software Blender 2.78 thanks to its variable Boolean tolerance and also automatic object naming. Since the grid of boxes was generated in an automated way – meaning in a strict order – all pieces of the sculpture took their names after Boolean from their cutting object. This little detail helped tremendously with later exporting of pieces into stl files for printing and also json files for web displaying.

There was a discussion on how big the gap between

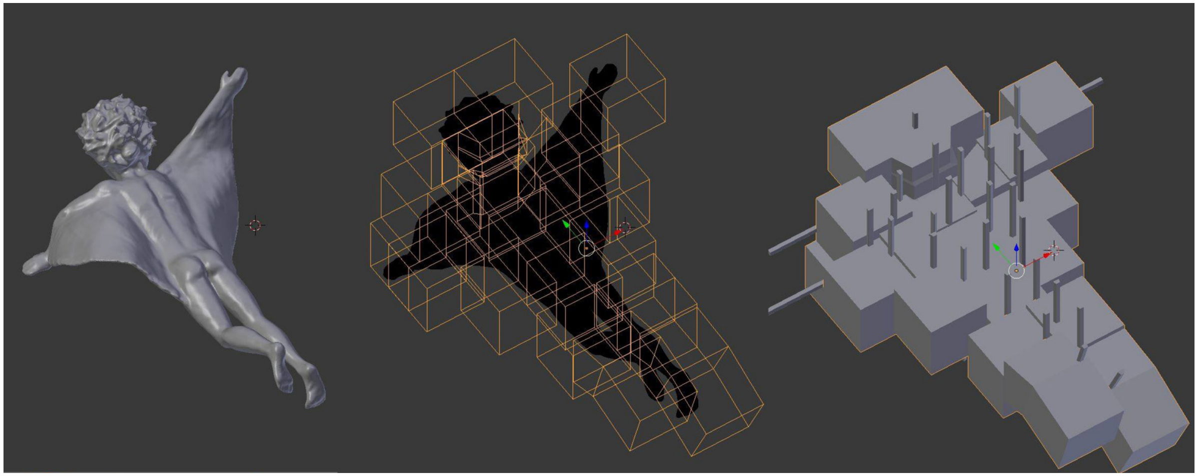


Fig 7.2 Cutting the statue with boxes and Fig 7.3 assembling printed pieces

each piece should have been to achieve a smooth sliding assembly and get over natural screwing of the material. The gap was finally set to 0.5 mm with aim to eliminate potential differences in models printed with different nozzle sizes on different printers. In the end this decision was very beneficial due to after-print shrinkage of rPET on some of the printers.

FINDINGS FROM THE VOLUNTEERS

There were 85 volunteer participants in the project out of which 73 were succesful with printing. The settings of the printers were not simple though and many printers had problem to achieve satisfactory results. A lot of problems was reported, mainly that the nozzle got stuck immediately or after a short time of printing on various printers. We had no clue to this problem, but finally we found out, where the filament caused troubles.

The construction of the printers differed in placement of PTFE tube inside of the nozzle (fig 7.3). RPET filament was extremely sticky when melted and some of the printers had nozzle stuck after only a few minutes of printing. Mainly only hotend type MK8 was suitable to print out

Printer	Temperature
Rebel 2.c s vlastními úpravami	265
Rebelix	270
MK2,5S	260
Delta Kossel QX	255°C
Ender3 AnetA8	235°C
Creality Ender-3 3d	255°C
HyperCube	232-240°C
REBEL2	220°C
KRYAL Cube	240-260°C
Prusa MK3	285°C
Prusa MK3	285°C
Creality Ender 3	270 a 280°C
Rebel2, Rebelix X2, Rebelix Box	240-250°C
Prusa i3 MK3	270°C
Průša MK3	230 - 260°C

Printer	Temperature
Průša M 2,5	270°C
Anet A8	260°C
Mendel - samovýroba	230°C
Prusa i3 mk2S, mk3	257°C
Anet AM8	255°C
Prusa I3 Mk 2, Mk 2,5	265°C
Ender 3	275°C
Prusa I3 MK2S	265°C
Rebel2Z	270°C
original Prusa Mk2,5	260-280°C
Kryal Cube	255°C
Rebel 2.c s vlastními úpravami	265
Rebelix	270
MK2,5S	260
Delta Kossel QX	255°C

Printer	Temperature
Ender3 AnetA8	235°C
Creality Ender-3 3d	255°C
HyperCube	232-240°C
REBEL2	220°C
KRYAL Cube	240-260°C
Prusa MK3	285°C
Prusa MK3	285°C
Creality Ender 3	270 a 280°C
Rebel2, Rebelix X2, Rebelix Box	240-250°C
Prusa i3 MK3	270°C
Průša MK3	230 - 260°C
Rebel II	265°C

Tab. 7.2 User feedback of nozzle temperature, example of the collected data

recycled PET. Its construction was very simple and PTFE tube ended aligned with steel nozzle throat. Filament melted in brass nozzle and never touched the steel. During retractions, melted filament was brought back to PTFE tube. PTFE tube prevented filament sticking on the steel. Printing temperatures of recycled PET were quite high (approx 250 degrees) and over time PTFE tube degraded too and parts of it were extruded through nozzle. That may have caused nozzle jamming. Degraded tubing exposed steel nozzle throat and filament started sticking during retractions. With this type of hot-end it was necessary to change PTFE tubing after 100 hours of printing time to prevent filament jamming. Hot-end that was used in Prusa MK2 printers had different construction. PTFE tube was thicker, but it ended before heatbreak. Filament touched the steel nozzle throat and then melted in brass nozzle. But during retractions, melted filament was lifted to exposed steel throat and stuck there. We recommended turning off retractions and faster printing, so that no melted filament touched the steel throat was the solution to the problem.

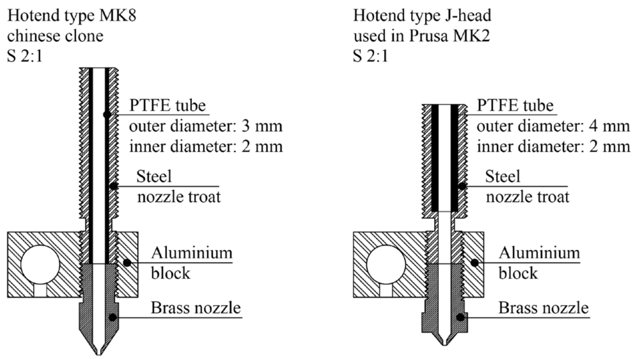


Fig. 7.3 types of most common nozzles: MK8 and J-head

ISSUES OF THE PRINTING TECHNOLOGY

The final product differed from the model. One issue appeared with slicing of the pieces: the voluntary printers sometimes rotated the piece in 90° and suddenly the resulted piece was striped perpendicularly to the other ones. We had to accept this as part of the design. (Fig. 7.4)

Second impact on the final product was caused by the type of the infill. Each printed part was not defined by the organisers and the infill was set by the voluntary printers. Some parts were made with 20% and some with 80% infill and this caused different weight of each piece. Luckily, the sculptures were hung with 3 anchors evenly distributed over the body. Anyway, by the transparent sculptures this had a big influence on the design.

The filament was fabricated - extruded under 285°C , which was also an expected printing temperature. To our surprise various printing machines were able to operate

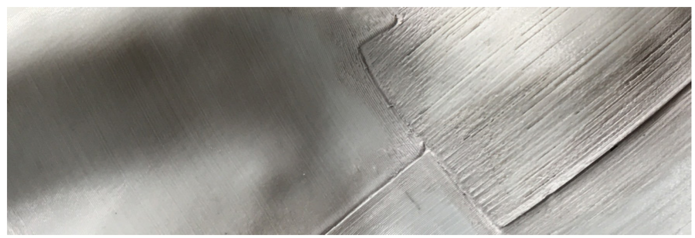


Fig. 7.4 Perpendicular stripe patterns caused by the technology principles.

the filament under temperatures varying from 214°C to 270°C. From these values, temperatures around 250°C were used mostly. See the Table 7.2 of printers and printing temperatures.

LESSONS LEARNED FROM PROJECT ANGELS

Czech filament test, crowd-searching method, puzzle interlocking system

The conclusion of this testing was positive: first Czech recycled PET filament MB25 and MB46 could be used for 3D printing on multiple regular home 3D printers with the printing space of 20x20x20 cm used by lay public people. We found out, that the printing problem was mostly caused by inner construction of the printing head and that the nozzles with PTFE tube are more suitable for printing 100% recycled filament. By a questionnaire we made a method of crowd-searching among voluntary

Fig. 7.5 the influence of infill on the weight and design of the pieces.

Fig 7.3 From 3D printing pieces to ready statue

participants and came to average values for the recommended printing settings. There were still issues to target and solve. The material could not be used on all of the printers without problems due to its tendency to stick to hot steel parts and clog the nozzle. Also the final success of the output is dependent on how the model is actually sliced by the participant. The quality of the output is dependent number of retractions and consistent flow of the material.

By exhibiting the statues outside in winter hanging 4 meters above ground we approved the strength and bio-stability of the products, when not being damaged by snow, wind, rain or frost. There were no effects of UV light, but after 6 weeks the plastic was simply dirty with ash from the chimneys.

8. LAB TESTS ON RECYCLED CZECH FILAMENT

The user experience study said nothing about the material itself apart of that it was hanging outside 4 metres above the ground in temperatures below and above zero, rain, snow and wind almost without any damage for 6 months. (We could partly see colour change due to dirty air at 5% of the surface.) Together with this case study we made laboratory stress, flexural and tensile tests on sample pieces of both materials at the faculty of engineering at CTU Prague. We printed predefined pieces of standard shape of both materials in order to test tensile and flexural strength, together with 3x3 cubes of both materials for simple press tests. We decided to test the cubes with different infill of 20, 40, and 60 percent, type honeycomb. The results of tests were compared with same pieces printed from virgin PETG. We accepted the material as homogenous because of its good isotrophy characteristics. (Dolczyk, 2019) First results incline to show rPET to be very flexible and strong material. We decided to make laboratory tests in order to support our hypothesis, which anticipated hight strength of the material from previous tests in experimental studio on blow-moulded plastic bottles (Nováková, 2016). Even the thin layered bottle could withstand unexpected tension and pressure forces comparable with steel. [28] or concrete [35].

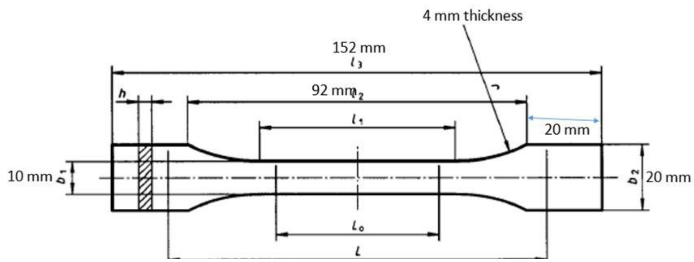


Fig. 8.1 Scheme of the test-pieces

TENSILE STRENGTH

Tensile analysis is rather critical at the recycled materials due to the impct of degradation processes that the material must have gone through whene being recycled. (Gonzales, 2020) Specially shaped units are pre-designed to be tested to declare official features of the material. (Fig. 8.1) We managed to 3D print virgin PET samples as well as recycled samples of MB25 and MB46. The testing was made on the Universal testing machines FP100. (Fig 8.3) Resulting values between 24 and 30 MPa were expected (De Moura, 2005), but our values grew up to 50 MPa in average by the virgin PET and 47MPa by the recycled PET. There was no rule in final cracking observed, each sample cracked somewhere else within the thin part. The weakest points were detected close to the wide edges. It was found though, that the results of MB 46 are worse than MB25 and these are slightly worse than those of MAG - virgin PETG. The broken edge of the recycled material was not fpound clean and mostly it went weaker and cracked due to impurities incorporated inside the material, which disrupted its homogenity.

On the other hand, the virgin material withstanded bigger tension forces and cracked clearly in the end. Tensile strength of concrete is cca 10 times less than its pressure

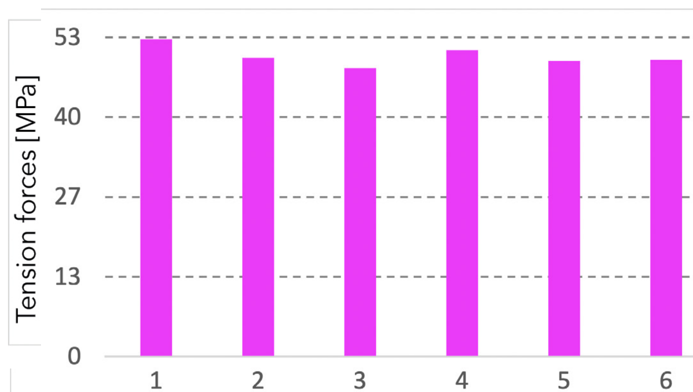


Fig. 8.2 tension forces of virgine PET

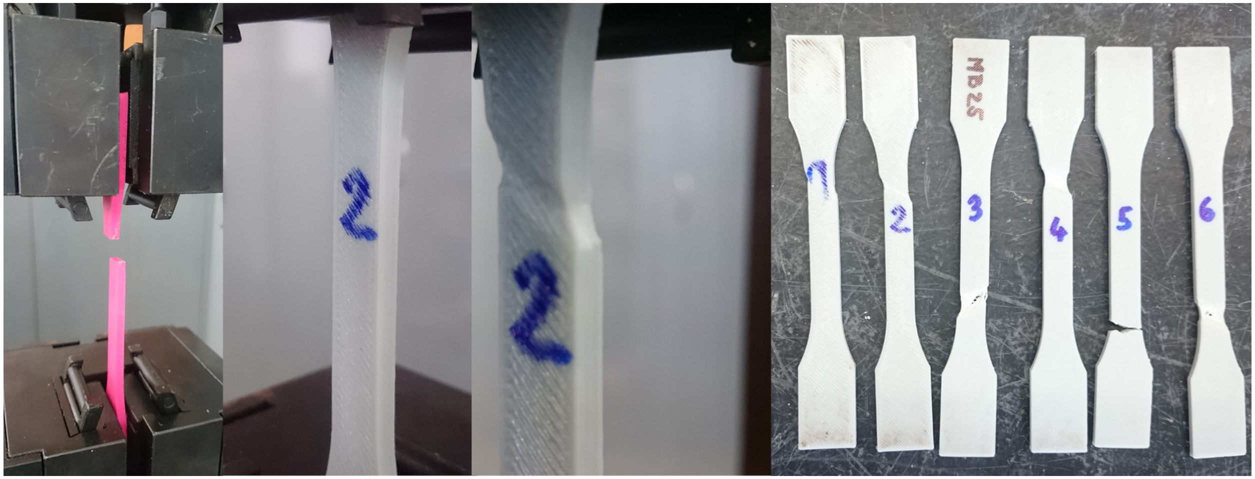


Fig. 8.3 Left: virgin PET, middle and right: tested rPET MB25

strength, so here the plastic is obviously better material to apply: The values reach maximum of almost 53MPa. [36]

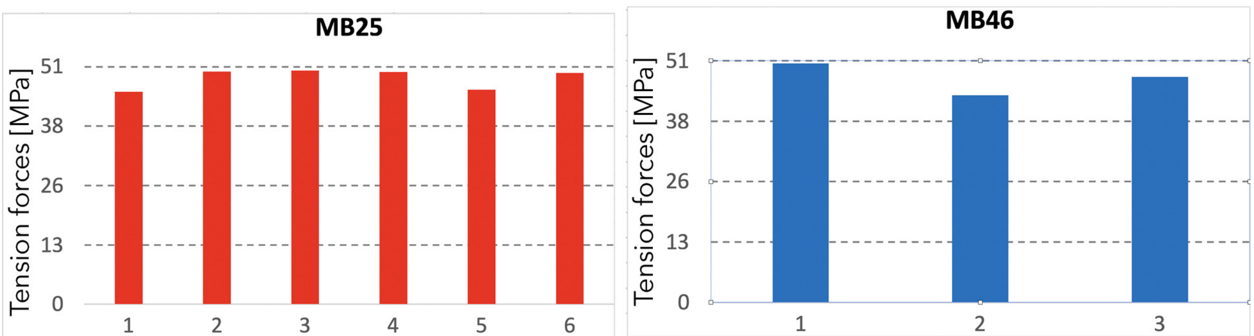


Fig. 8.4 tension forces of MB25 and MB46

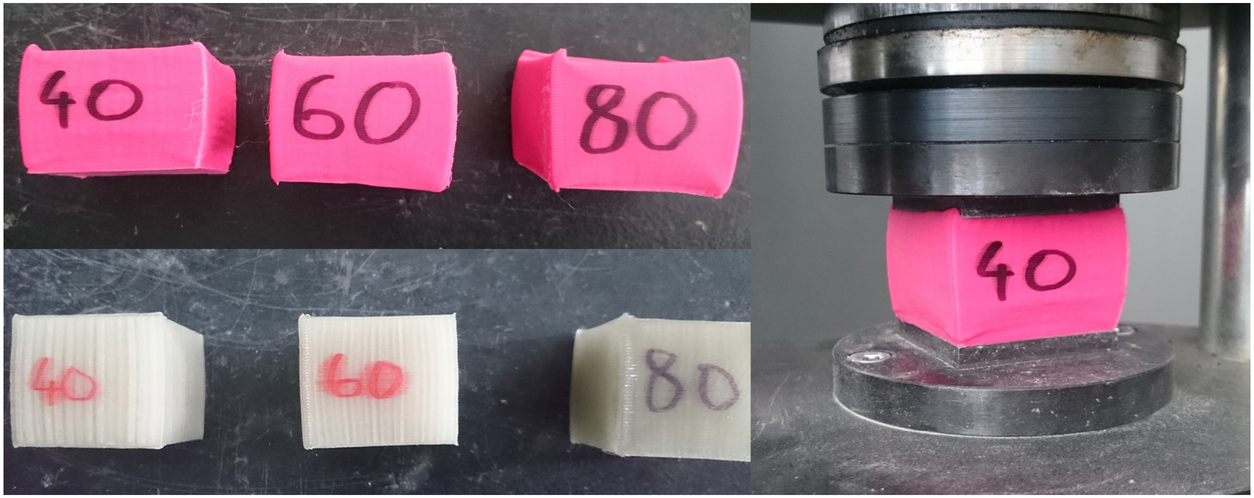


Fig. 8.5 Left: virgin PET, middle and right: tested rPET MB25

STRENGTH IN PRESSURE

We expected the relatively satisfactory results in tension tests and we expected also the satisfactory results in pressure tests with the recycled PET (Ávila, 2001) caused by cristalinity process during recycling. Speaking about the strength of polymers, addition of PET particles is said to stiffen constructions made of much weaker polymer materials (Marques, 2018). The recycled material MB46 with 80% infill could withstand 59MPa, which was higher pressure forces than the virgin MAG (32MPa) and even higher than typical concrete C30/37 with values between 30MPa and 46MPa [36], which absolutely surprised us. It had worse results when testing tension forces, which could be caused by lower viscosity of the recycled material. Furthermore, we compared the pressure strength of recycled PET with concrete and found out, that it is highly comparable, because it very much depends on the level of concrete and percentage of infill of our plas-

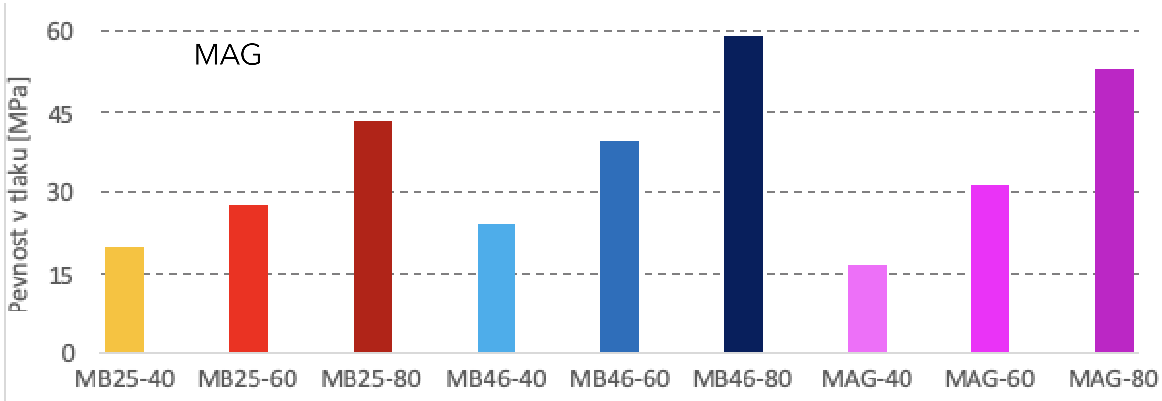


Fig 8.6 Press test MB25, MB46, MAG - virgin PETG

tic samples. The concrete of highest strength level 50/60 achieves the strength level of 58MPa, which competes the MB46 with 80% infill, which reached 59MPa.

Furthermore, following the linear line in the graph, we could expect values around 80MPa with 100% infill. From this test we could also see the linear influence of infill on the pressure strength of the sample. PETG and rPET obviously have a satisfactory strength in pressure compared with concrete.

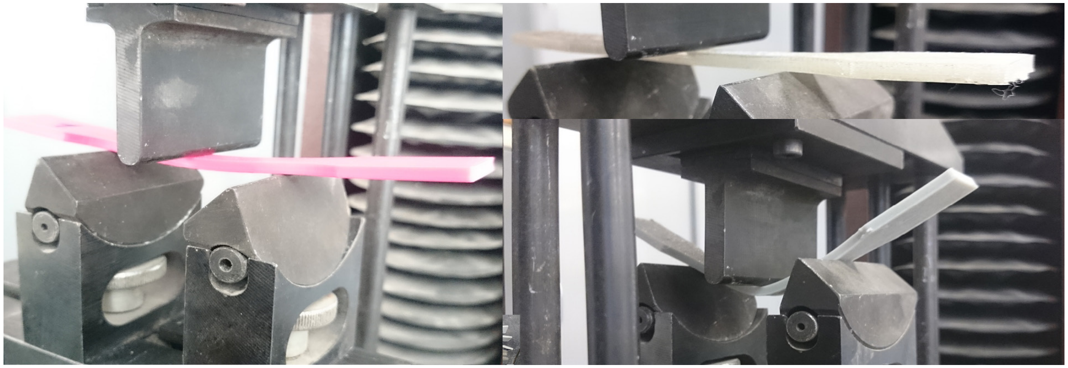


Fig 8.7 Left: virgine PETG - MAG, right: tested rPET MB46 and MB25

FLEXURAL STRENGTH

We can see from the images (Fig.8.4) that a three pointed support/pressure assembly was organized as a basic test for concrete, which we wanted to compare. In this test made with the universal measuring FP100 machine we could see, that recycled materials achieve values of 80% of the virgin PETG - MAG material and MB46 reaches slightly better values than MB25. Again, the values of PET plastic materials are 10 times higher than the ones of concrete, where the values reach maximum 7,5 MPa (Coufal, 2017). In the future research we shall work with different in-fills of our samples and compare more diverse materials such as wood and steel, which can reach 1000 MPa. [28]

LESSONS LEARNED FROM THE STRENGTH TEST

material strength

We could observe, that the virgin material performed higher score in tension forces, but only differs with 3% from MB25 and 5% from MB 46. For the purpose of the manifested use cases the recycled material proves to be

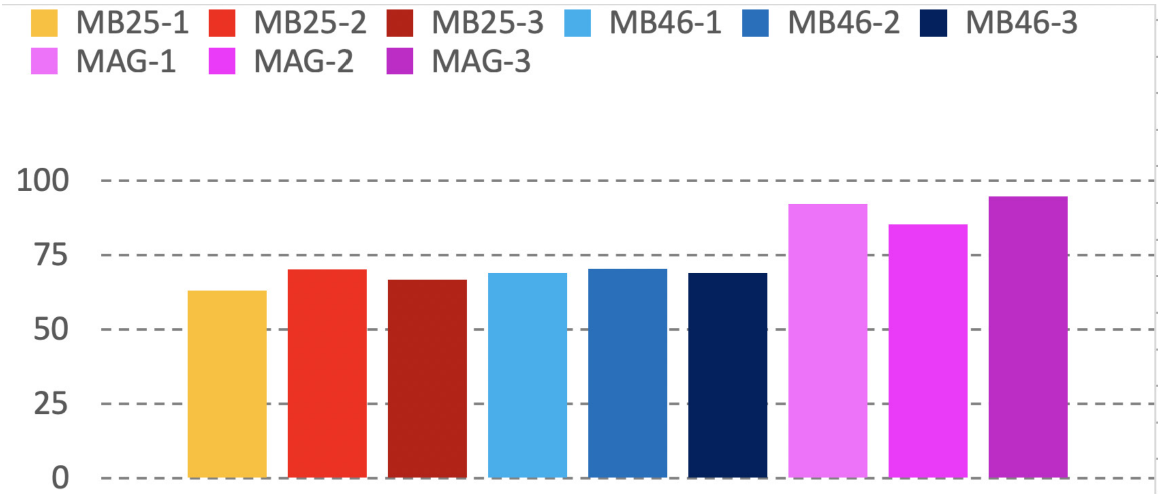


Fig 8.8 Press test MB25, MB46, MAG - virgin PETG

of comparable sufficient durability in all three tested features: Tension , pressure and Flexure.

We compared the results of recycled and virgin PET with values of cement materials, where the normative strength is 59,7MPa. The outcome was surprising: the plastic can compete with such materials traditionally used in architecture. The compression forces of concrete vary from 12MPa to 58MPa according to its sort/level. [40] We found out, that tensile and flexural forces of concrete reach more than 10 times lower values than their pressure forces, while PET and recycled PET behave constantly almost similar and the values vary around 50MPa in pressure, tension and flexure.

9. USE CASE N. 3 FINAL CROWD-SEARCHING-DIGITAL FACTORY

Having developed filament out of PET recycled and re-granulated grey and transparent waste material, we collected the feedback from volunteer printers. On base of that, we decided to collect cleanest possible material: so called industrial waste. There was less than 10% of the amount of post consumer waste. Green coloured waste preforms directly from the producer of the PET bottles were used to produce green filament.

The material is made of best quality recycled PET material with the aesthetic features, which are relevant in architecture. Firstly, the material is translucent, which can be used in combination with light and used as light shades of any type. Furthermore, we can design parametric shapes and patterns almost restriction-less in modelling, so that the surface can carry information. Secondly, the surface of the material remains glossy even when 3D printed and thus again melted and deposited by fusion. Thirdly, the infill is visible and its structure can influence the outer aesthetics of the hollow structure. Each piece was supposed to have 5% to 20% infill of type of pattern chosen ba the participant. Therefore, the visual appearance of the pieces varied randomly. The inner structure had bigger influence on the finished piece than actual layering, which we saw by the Angels project.

In order to test this material in bigger scale, we opened a third project of crowd printing - crowd searching. With this project we aimed at final testing the print-ability of the material which was prepared for introduction to the market. Furthermore, this project worked also as a collaborative project between institutions (FA CTU Prague and MPO CZ [41]) and aimed at promotion of circular economy at ministry of Industry and Trade in the Czech Republic.

COMPETITION

There was a competition called Digital Factory announced, where only students could participate. The task was to design a two meter high artificial object performing the idea of the era: digitalisation of the society, machines, nature. The project supported the idea of the circular economy with the use of recycled plastic through 3D printing. Seven relevant projects were collected and design called Kaleidoscope by Turkish student Ekin Ünlü was elected by professional jury. This statue was designed with Rhino grasshopper with voronoi plug-in and

Fig. 9.1 Digital factory, Kaleidoscope

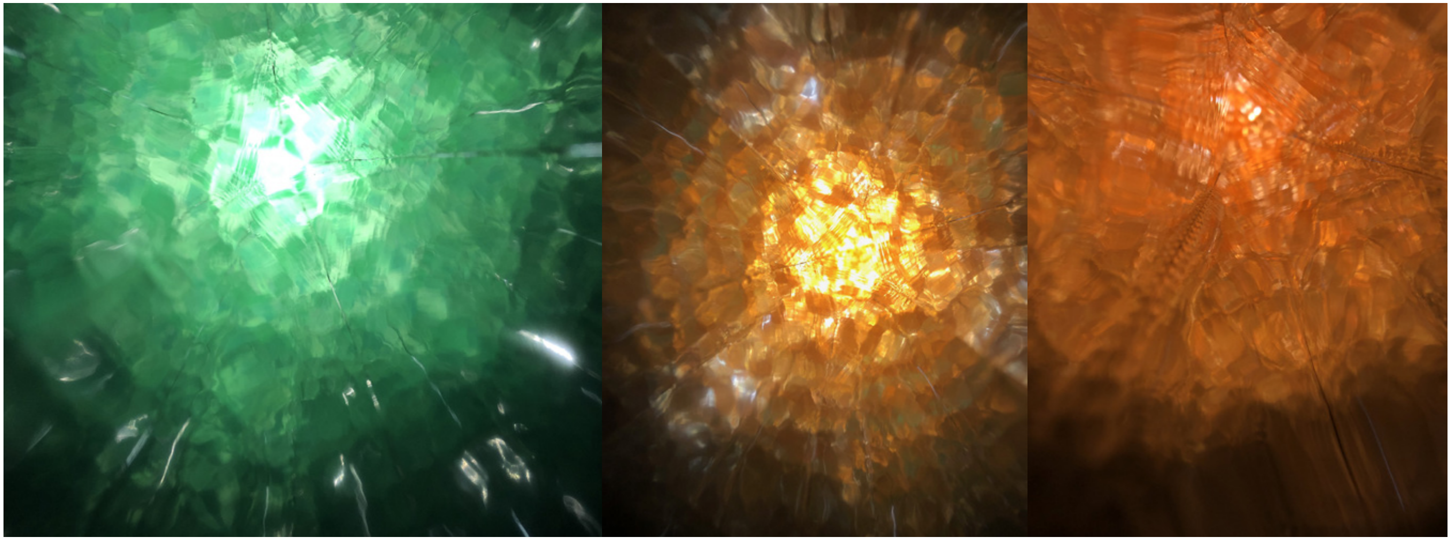


Fig. 9.2 Views inside the kaleidoscope

divided into 150 pieces. These fitted into regular home printers. The statue was divided into 4 layers, which could be rotated around the vertical axis. Some of the openings were equipped with a triangular kaleidoscopic window, where the visitor could change the point of view. (Fig. 9.4) This was empowered by shining core of the statue covered into a coating made of cut plastic bottles and offering instantly changing view.

Volunteer printers 3D printed 152 pieces and 85% of them recommended the filament for 3D printing. Each participant was free to choose their type of infill, which caused variable look of the skin of the structure. (Fig.9.3) Some of the openings were filled with images of evolution of a factory (Fig.9.4) and the others we having a circular opening which allowed for a look inside of the kaleidoscope and ejoy the show of colours and light.

PRINT SETTINGS

The collaborating company offered the material on the

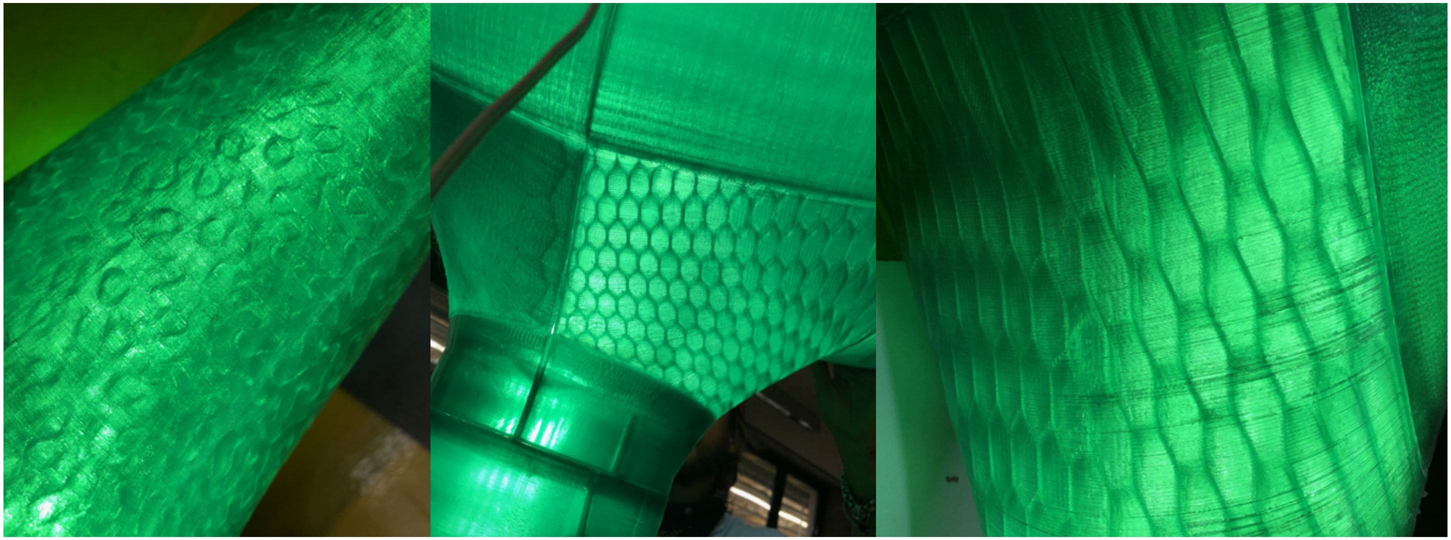


Fig. 9.3 Internal structure with diverse infills

market and the price was lower, respecting that the material is a second hand recycled material with worse print-ability. Also it was recommended to use the printing head with the PTF tube and avoid contact with hot steel. It is being sold until now and still more experienced people are needed for printing. The final settings still differ according to the exact machine, but generally following points must be respected:

Nozzle temperature: 265°C

Bed temperature: 70°C and more

No retractions

No ventilation

Size of the nozzle: 0,6mm and more

The model must be printed in stable room temperature and the warmer the air temperature the better. The more mass the product involves, the natural shrinkage of the material causes shape deformation. Object sliced into continuous layers proves to be of better quality than the one divided into printed islands, because the material strings and the product must be cleaned by knife and hot air gun after the printing.

The statue was exhibited at international trade fair in Brno, representing Czech ministry of industry and trade. In the end it was sold in an auction. Transparency and glossy surface is one of the valuable features of this material, that makes it beneficial to use together with lighting. In this project, we modelled amorphous shape, which was cut afterwards into printable pieces. It was highly important to preserve the exact sizes and shapes in order to be able to assemble the statue and preserve its functionality. The pieces were designed relatively thin (1,2 to 2 centimetres thickness) in order to eliminate bigger mass of the material causing screwing of the printed rPET piece. Here we applied what we learned from previous projects. In order to preserve quality and aesthetics of the statue together with flexibility, the gap between the connected

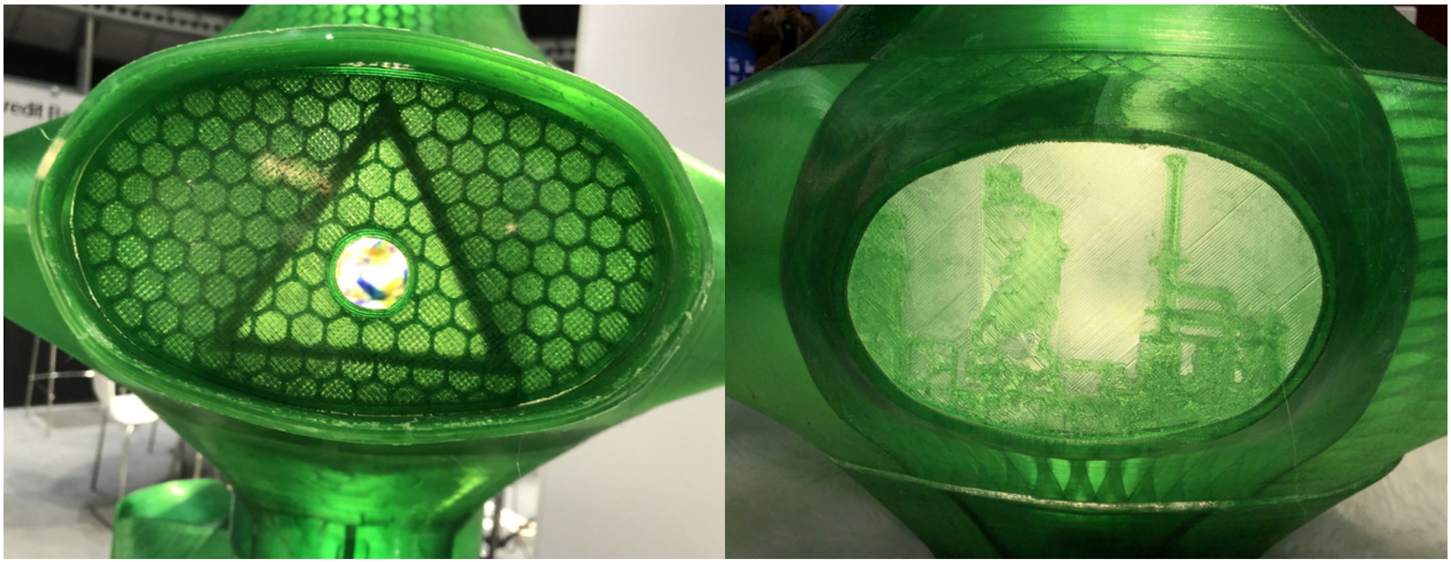


Fig.9.4 The views of the openings of the object: left: kaleidoscope, right: factory

surfaces was not bigger than 2mm.

LESSONS LEARNED FROM THE DIGITAL FACTORY PROJECT

lighting, glossiness, amorphous 3D shells

There was extremely positive reaction in the questionnaire to the green filament and its print-ability which was possible even on Průša printers (the nozzle had to be cleaned by nylon string often and nozzle 0,6mm was recommended). Respondents used various types of printers and have proven print-ability. Some participants also replied they liked the transparency and the colour of the material. Respondents also appreciated there was no extra colouring or additives added into the material and it is possible to recycle as is.

The final statue was sold in an auction, where the winner of the auction said she "fell in love" with the work of art due to its aesthetic appearance and shining feature."

10. CONCLUSION

It is possible to use recycled polyethylene in architecture and product design and in education. It is applicable in model generation as well as self standing structures such as furniture, interior architecture and architectural decorative detail such as small objects incorporating fittings and equipment of the peoples homes. The research in this paper can be split into several areas where we tested the use of rPET in architectural design and education:

3D printed architectural models designed by parametric modelling (ecology, saving raw material)

3D printed tools (ecology, functionality)

3D printed moulds (ecology,casting time save)

3D printed larger architectural decorations independent of the method, they were designed with.

Fig. 10.1 Realizations of smaller objects based on the results of the research

The hand-sculpted statue could be scanned and the 3D model could be adjusted with computational method. Furthermore, the work of art could be replicated with machinery, in our case 3D printed from recycled PET. (preserving work of art, adjusting it, correcting it and improving it) (ecology, durability, economy)
3D printed larger architectural decorations designed with the use of computational technologies and could be designed by hand with problems. (ecology, promotion of circular economy, design-time low, variability)
3D printed interior architectural equipment. (ecology, lighting, aesthetics)

In past 3 years we ran projects which demonstrated the use of lowest quality recycled PET filament in 3D printed architectural projects as well as the highest possible quality rPET. We found out, that 100% recycled PET can be used in interior architecture through 3D printing and the filament found its place on the market. It has been marketed for lower price since than. Anyway, in order to rise the trade and offer the product to the users of Průša printers, the producing company started adding 2% of

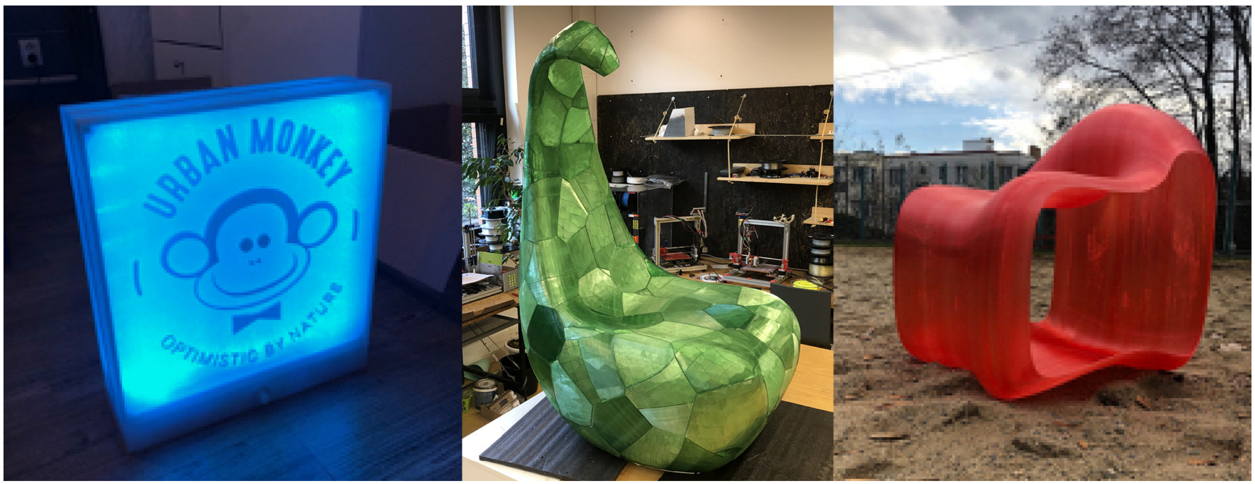


Fig. 10.2 Realizations of bigger architecture interior objects based on the results of the research

glycol and variety of colour additives. This invited more lay customers to take part in using recycled material in 3D printing.

The 3D printed moulds out of low quality recycled PET can be used for generating concrete structures of irregular shapes. We have proven the stability of such moulds when thin layered and thus produced very fast. Also the de-moulding process was easy and fast and caused no damage on the resulting object.

We tested production of small objects as well as big objects. It is possible to 3D print architectural models from recycled PET as well as regular house fittings such as plugs, hangers and small objects. It is possible to divide bigger objects in parts and functionally glue them together. Multiple people can be invited to participate in 3D printing many pieces in order deal with the relative time-consuming production.

During our research we not only promoted recycling PET bottles in form of transforming them into a plastic fibre. We brought recycled filament to the market. We also researched design methods of architectural designs, which are beneficial to use when applying additive manufacturing method: 3D printing. These can be applied in architectural education in form of models as well as in architectural practice in form of real size architectural interior equipment, decorations and details (Fig. 10.1 and 10.2).

OUTLOOK INTO THE FUTURE

It is obvious, that the research of the use of recycled PET in architecture heads towards generating bigger volumes by different means of machinery. Not only we can imagine using 3D printers of bigger sizes but also implementing robotic arms of any kind together with granulated recycled material. It is anticipated from our research that there will be problems with bigger volumes of the material at one place like screwing and deformation of the outcomes.

Examples of bigger sculptural objects were found already, such as pavilion in Dubai [9] and the possibility of adding recycled polyethylen tereftalate into concrete mixtures in order to improve the durability of the material and the favourableness of use rPET in architectural structures was described (Byung-Wan, 2006). We believe we can start experimenting with robots soon through collaboration with private experimental companies such as Scoolpt [32] or universities (VUT Brno). The solution might be found in combining polymer materials, mixing recycled material with concrete or turning to natural degradable matters on the basis of pla [33] or mycelium.

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