Recycled plastics: An alternative material for prosthetic check socket fabrication

Feliz Nicole R. Arcilla, CPO; Anna Katrina M. Garcia, BPO; Marc Andre R. Sarthou, BPO;
Anna Margarita A. Lugue, PTRP, CPO; Andre Dominic M. Rubiano, CPO

Abstract

Introduction Polyethylene terephthalate glycol (PETG), the material used to fabricate prosthetic check sockets is expensive and not locally available. This study aimed to develop an alternative material for fabricating prosthetic check sockets. Specifically, it aimed to determine the material properties of the alternative and to compare it against the standard check socket, PETG.

Methods Alternative materials were made from recycled plastic bottles (PETR), sando bags (PER) and a plasticizer. A two-roll mill and a compression molder were used to fabricate the alternative materials. All samples were prepared and tested according to the American Society for Testing and Materials for each property test. Kruskal-Wallis test with post-hoc analysis of Mann-Whitney-U test was used for impact resistance test results while descriptive analysis was used for Vicat softening point and tensile strength test results.

Results PER performed well against PETR in all tests and exhibited acceptable Vicat softening point (126 vs 75°C) and impact resistance (235 vs 71 J/m) compared to the standard PETG. On the other hand, PETR performed poorly in all three tests: tensile strength (0 vs 56 MPa), Vicat softening point (0 vs 75°C) and impact resistance (20.3 vs 71 J/m).

Conclusion PER was shown to have acceptable properties as an alternative to the standard material. However, further testing must be implemented to improve its tensile strength.

Keywords: Prosthetic check socket, polyethylene terephthalate, polyethylene, recycled plastic bottle

The Philippines, producing almost three million metric tons of plastic garbage annually, is the third major contributor to leakage of plastic to the world's oceans.[1] In Manila alone, major portions (17%) of the total recyclable wastes are plastics and among these wastes, plastic bags and plastic bottles are the most abundant.[2] Polyethylene terephthalate (PET) is more commonly used for the production of plastic bottles while high density polyethylene (HDPE) is a material commonly used for manufacturing plastic trash bags and biomedical liquid containers.[3,4] Both plastics are a good moisture barrier, lightweight, transparent, easier to manufacture, and resistant to chemicals and ultraviolet rays which make them important for packaging.[5-9]

Plastics play an important role in the field of prosthetics and orthotics (PO), particularly in the fabrication of sockets, the part of the prosthesis which encloses the residual limb. Polyethylene terephthalate glycol (PETG) and HDPE are among the most

Correspondence:
Anna Margarita A. Lugue, PTRP, CPO, Philippine School of Prosthetics and Orthotics, College of Allied Rehabilitation Sciences, University of the East Ramon Magsaysay Memorial Medical Center, 64 Aurora Boulevard, Barangay Doña Imelda, Quezon City; e-mail: aalugue@uerm.edu.ph

Oral presentation in the 17th World Congress 2019, International Society for Prosthetics and Orthotics, Kobe, Japan, October 5-8, 2019.

Philippine School of Prosthetics and Orthotics, College of Allied Rehabilitation Sciences, University of the East Ramon Magsaysay Memorial Medical Center

commonly used plastics in manufacturing check sockets.[8-10] Check sockets allows accurate inspection of the residual limb during fitting procedures.[11] Important properties that enable PETG and HDPE to fulfill check socket functions are 1) transparency, 2) Vicat softening point, 3) tensile strength, and 4) impact resistance.[5] Transparency allows the prosthetists to see how the residual limb of the patient fits within the socket and how pressures are distributed.[9,10,12] Vicat softening point determines the capability of PETG and HDPE to withstand being formed into variously shaped or sized prosthetic sockets and be further adjusted during fittings without easily melting.[8-15] Tensile strength and impact resistance are two properties that reflect the ability of sockets to withstand forces involved in weight bearing activities such as standing and walking.[8,16-17]

Despite being very useful in PO, PETG and HDPE limit its usability due to their unavailability in the country as these materials are imported from other countries.[8,9,18-20] Additional costs from shipment fee and import tax restrict its full utilization in Philippine settings.[21-22]

Mismanaged plastic waste brings about a steady increase of landfill waste, greenhouse gas and cost of plastic goods, which is why the applications of recycled plastic waste in material production have been given more attention.[23-31] Although PO institutions have yet to incorporate recycled plastic into prosthetic sockets, Prosthetic & Orthotic Component Clearinghouse (POCC), Limbs of Hope Foundation, and Ability Prosthetics & Orthotics with Physicians for Peace, recycle second hand devices and prosthetic components to repurpose them into prosthetic components that can be used to assemble new devices.[32-33] This concept of recycling and repurposing of plastic is encouraged by the World Health Organization (WHO) together with the International Society for Prosthetics and Orthotics (ISPO), and USAID for developing and underdeveloped countries.[34]

Research focused on testing the durability of PETR soda bottles as used in upper extremity prostheses.[35] Results suggest that PETR bottles that are reheated and remolded for a transradial prosthetic socket can withstand an axial load not more than 4 kg, implying that the socket can only be used for simple, light-duty activities such as feeding and self-care.[35] However, standard lower extremity prosthetic components are typically expected to withstand 70 to 100 kg of body weight. According to the statistics on amputees of the Philippine School of Prosthetics and Orthotics (PSPO), lower limb amputee cases outnumbered the upper limb amputee cases in 2016.[36] A study by Jivacate, as cited by Emmons, had lower limb prostheses made from milk bottles for human and elephant subjects with lower limb amputations.[37] Literature did not explicitly mention whether the sockets, componentry, or feet fabricated was made out of recycled plastics. Furthermore, it was unclear if the recycled prostheses were at par with prostheses made from unrecycled materials due to the absence of material property testing and comparison.

Material's Property Testing. One of the characteristics needed for fabricating a prosthetic socket is Vicat softening point because this helps determine the appropriate processing temperature of thermoplastic sheets prior to vacuum forming into a positive mold of a patient's residual limb.[38-43] Gerschutz investigated the ultimate strength of various prosthetic socket materials currently available in the market on prosthetic component adapters using the ISO standard 10328, the highest form of reference available for prosthetic material standards which simulates the forces of gait.[8] The researchers, however, could not determine whether preliminary material properties contributed to socket material pass or failure of ISO 10328 testing since the study was limited to standard procedure testing of only the distal end of the socket material, and not the socket as a whole.[8] Gerschutz later determined that tensile strength and impact resistance was paramount in verifying material safety prior to application on a patient with an amputation.[20] In the absence of standardized procedures for prosthetic sockets, results of the study suggest that tensile strength of around 54 MPa and impact resistance of at least 85 J/m, should be referenced for future researches which determine the quality and safety of prosthetic thermoplastic materials.

Therefore, the aim of the study is to determine if the structural integrity and processing temperature of PETR and PER is comparable to that of PETG.

Methods

A quasi-experimental research design was utilized to fulfill objectives of this study. A range of five to ten samples was prepared from each material (PETR, PER, and PETG) per property of interest based on American Society for Testing and Materials (ASTM) standards and those required by the Department of Science and Technology Industrial Technology Development Institute (DOST-ITDI) Standards Testing Division.[8,16,17] Three materials were tested in this study --- PETR, PER and PETG, with PETG serving as the standard. PETR was made from two components namely: a large portion of recycled plastic bottle flakes and a small percentage of additives.[44] PER, on the other hand was plainly repurposed from its clear sando bag state. PETR and PER were constructed through two-roll-mill mixing and compression molding. All sample groups were fabricated according to specified ASTM dimensions of each of the three property tests.

Vicat softening point. Vicat softening point was tested according to ASTM D1525: standard test method for Vicat softening temperature of plastics.[13] Resultant values are approximately between 80°C to 160°C, where values close to the lower margin of the acceptable range is favored.[9,16] For this measurement, a Heat Deflection-Vicat Softening Temperature (HDT) tester was used. At room temperature of 23 ± 2°C, the specimen was immersed in a silicon oil bath for uniform heating. A needle was applied on the sample with a load of 10 ± 1.0 newtons (N) until penetration into the specimen, while temperature was initially set at 23°C and gradually increased at a rate of 50°C per hour. The temperature upon needle penetration was recorded as Vicat softening temperature, measured in degrees centigrade.

Tensile strength. Tensile strength was tested according to ASTM D638: standard test method for tensile properties of plastics using a universal testing machine with test fixtures for tensile strength testing.[16] Resultant values are approximately 54 MPa, where the higher the value the better.[5,10] Parallel to its long axis, the two ends of the specimen were mounted between the grips of the machine and were pulled away from each other. Measurements, in units of megapascals (MPa) were taken once the material started to stretch, and when the material broke into two.

Impact resistance. Izod impact testing was performed according to ASTM D256: standard test methods for determining the Izod pendulum impact resistance of plastics.[17] Resultant values are approximately at 85 J/m, where the higher the value the better.[8] A pendulum impact tester was used for this measurement. Measurements were taken at room temperature 23 ± 2°C. The sample, with a notch cut angled at approximately 45°, was clamped vertically onto the vise with the notch facing away from the pendulum. The hammer was released onto the sample and data was recorded, in units of joules per meter (J/m), once the material broke in two from the force exerted by the pendulum hammer.

This study involved PETG, PETR and PER's data on Vicat softening, tensile strength and impact resistance. Data gathered in raw and average form were emailed to the researchers after testing. For the Impact resistance test, Kruskal-Wallis test with post-hoc analysis using Mann-Whitney U test, was used for the differences between values of PETR, PER, and PETG samples. Significance level was set at $p = 0.05$. Kruskal-Wallis and Mann-Whitney U test results were computed by hand and using MS Excel 2017. For tensile strength and Vicat softening point, a descriptive analysis was used to compare the results of PETR and PER with PETG.

Results

As shown in Figure 1, the standard material PETG had a Vicat softening point of 75°C. Between the two alternative materials, sando bag (PER) surpassed the Vicat softening point of PETG at 126°C, while plastic bottle (PETR) was at 0°C. Figure 2 shows that PETG had a mean tensile strength of 56 MPa. Both plastic bottles (PETR) and sando bag (PER) had lower tensile strength at 0 and 25.2 MPa, respectively. As seen in Figure 3 PETG's impact resistance was measured at 71 J/m. Sando bag (PER) had higher impact resistance at 235 J/m; the difference with PETG was significant. Plastic bottles (PETR), had a lower impact resistance at 20.3 J/m.

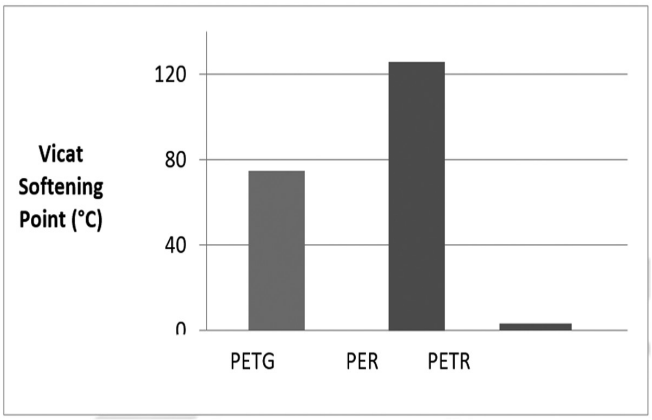

Figure 1. Mean Vicat softening point of PETG, PER, and PETR

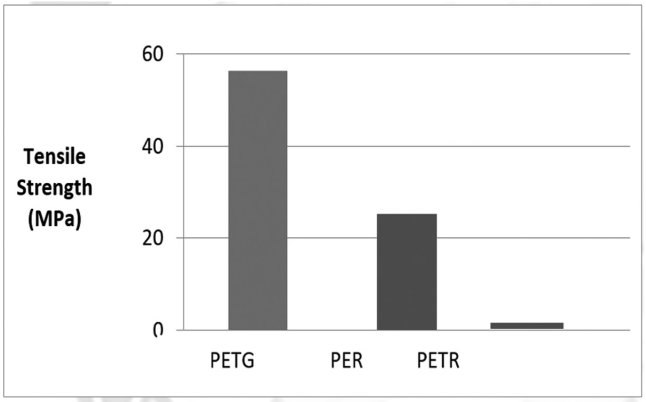

Figure 2. Mean tensile strength of PETG, PER, and PETR

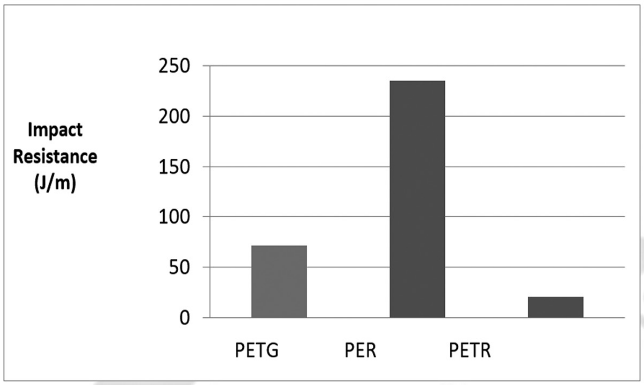

Figure 3. Mean impact resistance of PETG, PER, and PETR

Discussion

The standard material displayed similar tensile strength results with other published works. The studies of Gerschutz and Curbell Plastics showed that PETG's tensile strength is approximately around 54 MPa.[8,45] However, the standard material exhibited noticeable differences with literature in terms of impact resistance and Vicat softening point. Impact resistance of PETG showed lower results (71 J/m) compared to the standard value of 85 J/m.[8] For Vicat softening point, only PETG met the reference standard of 80-160° according to the data sheet from North Sea Plastics.[18] This may be because testing procedures differed from that of North Sea Plastics, since temperature for the study's PETG was recorded when the surface of the material began to soften secondary to heat applied by the silicon oil bath as per ASTM standard D1525, whereas temperature for North Sea Plastics® PETG was taken once the entire material started to soften and became processable.[8,9] The first alternative material PETR performed poorly in all three materials tests done, indicating that PETR was not at par with the standard material, PETG, in terms of Vicat softening point, tensile strength and impact resistance. Results show that PETR possesses a lower Vicat softening point (0˚C) compared to PETG (75˚C). Since PETR's Vicat softening point could not be recorded, temperature setting of ovens prior to vacuum forming for fabricating check sockets could not be determined. Tensile strength and impact resistance also displayed a lower value compared to PETG, where PETR scored 0 MPa and 20.3 J/m while PETG scored 56 MPa and 71 J/m for tensile strength and impact resistance, respectively. Resulting material properties of PETR also displayed no similarities to reviewed articles, as their results showed a range of 2-7 kJ/m^2 for impact resistance, around 50-60 MPa for tensile strength, and 83˚C for Vicat softening point.[46-48]

The possible reasons for the poor performance of PETR could have included 1) the different fabrication method, 2) the plasticizer, and 3) the plastic recycling generation. Differences with the fabrication method of samples were noted as PETR was fabricated through two roll mill and compression molding machine while plastic extrusion and injection molding process were used in the literature.[46,47] The extrusion method and injection molding process make the plastic more ductile and impact resistant. Compression molding, on the other hand, increases the plastic's rigidity and brittleness.[49] Likewise, only pure recycled plastic bottles were used whereas a plasticizer was added to PETR which produced no effect on the sample as it may have evaporated prior to melting of recycled plastic bottle flakes during fabrication.[46,47]

Plastic recycling generation was not taken into account when provided with the raw recycled plastic bottle flakes. This may have been another contributing factor to PETR's poor mechanical and thermal performance since its recycling generation was not consistent throughout the entire structure of the sample. Comparing third, fourth, and later generation plastics to second generation plastics, performance is best in favor of the latter in terms of mechanical properties.[50] Moreover, lower results for Vicat softening point, indicate that PETR does not have the ability to be moldable to any shape.

The second alternative material PER performed well in terms of Vicat softening point (126°C) as it surpassed the standard (75°C). The Vicat softening point of PER is similar to NorthPlex plastics' molding temperature which then implies that PER has the ability to be easily molded when adjusting the material in different forms.[18] The tensile strength of PER (25.2 MPa) was lower compared to the standard (56 MPa), as this was also recorded at yield. This indicates that the sample deformed earlier than expected before splitting apart. Although PER is weaker compared to PETG, it is still comparable to another check socket material, thermolyn rigid.[8]

Fabrication method and reinforcement procedures may also influence the mechanical properties of PER especially in terms of tensile strength. In another study, a twin-screw extruder and an injection molding machine were used to manufacture a sheet of plastic. Reinforcement with polyacrylonitrile (PAN) fiber was added to the mixture in different percentages to improve the properties which resulted to a higher tensile strength and Vicat softening point.[51] This signifies that PER as a socket may possibly deform if patient puts weight but will not break easily. Lastly, the impact resistance of PER performed well (235 J/m) compared to the standard (71 J/m). The value of impact resistance is comparable to the results of copolymer prosthetic sockets (211 J/m) from the study of Gerschutz.[8] Zhu, on the other hand, stated that the values of PER for impact resistance performed closely to that of recycled pure HDPE.[52] The result was expected due to PER's inherent ductility which allowed the material to absorb increasing amounts of force.[5] In another study where PAN fibers were added, the impact resistance property of the sample was compromised due to the brittle nature of PAN fibers and because of the improved crystallinity which decreased the impact strength of the material faster.[51]

Since contracted plastic manufacturers and raw material providers sell by the ton, the study was limited to 3 kg of PETR flakes which contained unsegregated and unaccounted for plastic generation. The amount of raw material available limited the number of trials in determining the best plastic to additive ratio for a good sheet output despite the plastic generation. Furthermore, equipment for processing samples into sheets were also limited to using the two-roll mill and compression molding, where samples fabricated from this technique tended to be more rigid and brittle as evidenced by results of PETR.[46] This technique, however, inversely affected PER in terms of its Vicat softening point and impact resistance.

Even though transparency is enumerated as another important property of a prosthetic check socket, testing it was not performed due to the lack of locally-available testing apparatus despite extensive search, while ISO 10328, the highest form of standardized testing for PO materials, was not performed due to the lack of recommended vacuum forming techniques for processing PETR and PER into a prosthetic socket.[38,20]

The researchers therefore recommend that PETR be processed into sheets through an extrusion or injection molding process and be polymerized with a different plasticizer or reinforcement. Likewise, the three mechanical properties should be tested again before proceeding to the properties not yet tested. Since PER displayed potential to become an alternative material for prosthetic check socket fabrication, the researchers recommend changes to improve the tensile strength property through the addition of reinforcements without affecting Vicat softening and impact resistance. Furthermore, tensile strength testing should be reperformed together with the properties not yet tested. Additionally, the researchers would like to further recommend testing of PER for structural testing of ISO 10328 to determine its integrity with distal prosthetic componentry attached, biological hazards to determine reactions of skin when in long-term contact with the plastic, and to explore the use of PER as a definitive prosthetic socket. Since budget exceeded the allocated amount for funding the study, where one ton of PETR flakes: and fabrication of bigger sheets cost PHP 11,000.00, an extensive prospective review of the cost of manufacturing recycled plastics on a large scale should be considered.

The aim of this study was to produce an alternative material made of recycled plastics with properties comparable with PETG. These mechanical properties include Vicat softening point, tensile strength and impact resistance. PETR performed poorly against PETG in all three tests. This may have been due to several factors which include fabrication method, plastic sample generation, and ineffectiveness of plasticizer. The investigators therefore conclude that PETR, in its current state, cannot to be used as a check socket due to its brittleness and weak thermal properties. PER displayed lower tensile strength compared to PETG but performed better in the Vicat softening point and impact resistance tests. PER may be a viable prosthetic check socket alternative because of its high impact strength and thermoformability provided that the tensile strength is increased without affecting the Vicat softening point and impact resistance.

Disclosure: The study was funded by a grant from UERMMMCI-The Nippon Foundation Fund.

References

1. Jambeck JR, Geyer R, Wilcox C, et al. Marine pollution: Plastic waste inputs from land into the ocean. Science 2015; 347(6223), 768-71.
2. Antonio LC. Study on recyclables collection trends and best practices in the Philippines. In: Kojima M (ed.), 3R Policies for Southeast and East Asia. ERIA Research Project Report 2009-10, Jakarta: ERIA. 2010; 40-70.
3. American Chemical Society. Discovery of polypropylene and high-density polyethylene [Internet] 2015. Available from: https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/polypropylene.html
4. Bandla S. Evaluation and stability of pet resin mechanical properties. Masteral thesis. Oklahoma State University; 2010 May.
5. Alro Plastics. Reference Guide. 4th ed. Your complete plastic materials source [Internet]. 2013. Available from: http://www.alro.com/datapcatalog/plastics_refguide_full.pdf
6. Fadlalla N. Management of PET plastic bottles waste through recycling in Khartoum State. Masteral thesis. Sudan Academy of Science Engineering Research and Industrial Technology Council; 2017.
7. Lukkassen D, Meidell A. Advanced materials and structures and their fabrication processes. 3rd ed. Vol 2. Narvik, Norway: Narvik University College; 2007. 1–14.
8. Gerschutz M, Haynes M, Nixon D, Colvin J. Tensile strength and impact resistance properties of materials used in prosthetic check sockets, copolymer sockets, and definitive laminated sockets. J Rehabil RD 2012; 48: 987-1004.
9. Northsea Plastics. Northsea plastics product range [Internet]. n.d. Available from: https://www.northseaplastics.com/our-product-range/
10. Coombes AGA, Greenwood CD. Memory plastics for prosthetic and orthotic applications. Prosthet Orthot Int [Internet] 1988; 12: 143–51. Available from: http://www.oandplibrary.org/poi/1988_03_143.asp
11. Reger S, Letner I, Pritham C, Schnell M, Stamp W. Applications of transparent sockets. J Prosthet Orthot 1976; 30: 35-9.
12. American Society for Testing and Materials. ASTM Standard D-1746-09. Standard test method transparency of plastic sheeting [Internet]. West Conshohocken, PA: ASTM International. Available from: https://www.astm.org/Standards/D-1746-09
13. American Society for Testing and Materials. ASTM Standard D-1525-09. Standard test for Vicat softening temperature of plastics [Internet] West Conshohock-en, PA: ASTM International. Available from: https://www.astm.org/Standards/D1525.htm
14. Davies Molding. The thermoset difference: thermoset vs. thermoplastic [Internet]. 2014. Available from: http://cdn2.hubspot.net/hub/317097/file-450098412-pdf/Thermoset
15. Namhata S, Santolini L, Locati G. Rationalisation of Vicat softening point measurements. Polym Test [Internet] 1990; 9(2): 75-89. Available from: http://dx.doi.org/10.1016/0142-9418(90)90021-5
16. American Society for Testing and Materials. ASTM Standard D638-14. Standard test method for tensile properties of plastics [Internet]. West Conshohocken, PA: ASTM International. Available from: https://www.astm.org/Standards/D638.htm
17. American Society for Testing and Materials. ASTM Standard D256-10e1. Standard test methods for determining the Izod pendulum impact resistance of plastics [Internet] West Conshohocken, PA: ASTM International. Available from: https://www.astm.org/Standards/D256.htm
18. North Sea Plastics, Ltd. Technical data sheet for Northplex [Internet]. 2008. Available from: https://www.northseaplastics.com/wp-content/uploads/Northplex-technical-data-sheet2008.pdf
19. Ottobock. Thermolyn rigid material safety data sheet [Internet]. Available from: https://professionals.ottobockus.com/media/pdf/616T52_en-US.pdf
20. Gerschutz M, Haynes M, Nixon D, Colvin J. Strength evaluation of check sockets, copolymer sockets and definitive laminated sockets. J Rehabil R D [Internet]. 2011; 49: 405-26.
21. Philippine import one rates Fedex Express [Internet]. 2017. Available from: http://images.fedex.com/downloads/ph/rates/import_2017.pdf
22. Republic Act No. 1937: An act to revise and codify the tariff and customs laws of the Philippines [Internet]. 1957. Available from: http://www.gov.ph/1957/06/22/republic-act-no-1937
23. Siddique R, Khatib J, Kaur I. Use of recycled plastic in concrete: A review. Waste Manag [Internet] 2008; 28(10): 1835-52. Available from: http:// dx.doi.org/10.1016/j.wasman.2007.09.011
24. Hopewell J, Dvorak R, Kosior E. Plastics recycling: challenges and opportunities. Philosoph Transact Royal Soc B Biol Sci [Internet] 2009; 364(1526): 2115-26. Available from: http://dx.doi.org/10.1098/rstb.2008.0311
25. Welle F. Twenty years of PET bottle to bottle recycling—An overview. Resourc Conserv Recycl [Internet] 2011; 55(11): 865-75. Available from: http:// dx.doi.org/10.1016/j.resconrec.2011.04.009
26. Tawiah PO, Andoh PY, Agyei-Agyemang A, Nyarko F. Characterization of recycled plastics for structural applications. Int J Science Technol [Internet] 2016; 5(6): 259-67.

27. Sojoboi A, Nwobodo S, Aladegboye O. Recycling of polyethylene terephthalate (PET) plastic bottle wastes in bituminous asphaltic concrete. Cogent Engineering [Internet] 2015. Available from: https://doi.org/10.1080/23311916.2015.1133480
28. Wrap.org. Using recycled content in plastic packaging: the benefits [Internet]. n.d. Available from: http://www.wrap.org.uk/sites/files/wrap/Using%20recycled%20content%20in%20plastic%20packaging%20the%20benefits.pdf
29. Bundesinstitut fur gesundheitlichen Verbarucherschutz und Veterinarmedizin. Use of mechanically recycled plastic made from polyethylene terephthalate (PET) for the manufacture of articles coming into contact with food [Internet]. n.d. Available from: http:// www.bfr.bund.de/cm/343/use_of_mechanically_recycled_ plastic_made_from_polyethylene_terepthalate__pet__for_the_manufacture_of_articles_coming_into_contact_with_food.pdf
30. Hakkens D. Precious plastic products [Internet]. 2017. Available from: https://preciousplastic.com/en/creations.html
31. Yam KL, Gogoi BK, Lai CC, Selke SE. Composites from compounding wood fibers with recycled high density polyethylene. Polymer Engineering and Science 1990; 30(11): 693-9.
32. Prosthetic Hope International. The Prosthetic & Orthotic Component Clearinghouse [Internet]. 2011 [Accessed Aug 3, 2017]. Available from: http://prosthetichope.org/projects/pocc/
33. Green Eco Services. The importance of recycling prosthetic limbs [Internet]. 2016 [Accessed Aug 4, 2017]. Available from: http://www.greenecoservices.com/the-importance-of-recycling-prosthetic-limbs/
34. World Health Organization. Consensus conference on appropriate lower limb orthotics for developing countries [Internet] 2006. Available from: http://www.who.int/disabilities/technology/Orthotics%20Consensus%20conference%20report.pdf
35. Wu Y, Casanova HR, Ikeda AJ. Plastic soda bottles: A reusable material for making transradial sockets [Internet] 2009 Jun; 33: 100–6. Available from: https://doi.org/10.1080/03093640902810717
36. Philippine School of Prosthetics and Orthotics. PSPO Charity Clinic Amputees Statistics. 2016
37. Emmons K. Work for Asia and the Pacific: A leg up. Asian Development Bank 2012 Apr-Jun; 48–9.
38. Northsea Plastics. Northplex Specification [Internet]. n.d. Available from: https://www.northseaplastics.com/products/northplex/
39. Tait M, Pegoretti A, Dorigato A, Kalaitzidou K. The effect of filler type and content and the manufacturing process on the performance of multifunctional carbon / polylactide composites. Carbon [Internet] 2011; 49(13): 4280–90. Available from: https://doi.org/10.1016/j.carbon.2011.06.009
40. DeArmitt C. Raising the softening point of PVC. Plastics Additives & Compounding 2004 Aug; 32–34.
41. Gottschalk A, Breulmann M, Fetter E, Kretschmer K, Bastian M. PVC becoming even "hotter." Kunststoffe International 2006; 1–3.
42. Zeus Industrial Products, Inc. Performance of high temperature plastics. 2005; 1-7.
43. Smith A. The essential roles of impact and HDT / Vicat testing in a compounder's laboratory. Plastic Additives & Compounding 2002 May; 4(5): 16–20.
44. Sanyang M, Sapuan S, Jawaid M, Ishak M, Sahari J. Effect of plasticizer type and concentration on physical properties of biodegradable films based on sugar palm (Arenga pinnata) starch for food packaging. J Food Sci Technol [Internet] 2015; 53(1): 326-36. Available from: http://dx.doi.org/10.1007/s13197-015-2009-7
45. Curbell Plastics. Plastics for orthotics & prosthetics. In Curbell O&P. 2017. Available from: www.curbellplastics.com/oandp
46. Imamura M, Sakamoto H, Higuchi Y, et al. Effectiveness of compatibilizer on mechanical properties of recycled PET blends with PE, PP and PS. Materials Science and Applications 2014; 5: 548-55.
47. Salminen P. Using recycled polyethylene terephthalate (PET) in the production of bottle trays. Masteral thesis. Arcada University of Applied Sciences, Helsinki, Finland; 2013.
48. Smile Plastics. Smile plastics materials guidelines [Internet]. 2018. Available from: https://smile-plastics.com/wp-content/uploads/2017/09/Smile-Plastics-datasheet.pdf
49. Skrobak A, Stanek M, Kyas K, Manas D, Reznicek M, Senkerik V. Comparison of mechanical properties of injection molded and compression molded rubber samples. Int J Mechanics 2016; 4:7: 409-16.
50. El-Khair A, Ali A. The mechanical behavior of recycled high-density polyethylene. Int J Modern Engineer Res 2013; 3:2: 798-808.
51. Zhu L, Wu D, Wang B, Zhao J, Jin Z, Zhao K. Reinforcing high-density polyethylene by polyacrylonitrile fibers. Pigment & Resin Technology [Internet] 2018; 47(1): 86-94. Available from: http://dx.doi.org/10.1108/prt-03-2017-0030
52. IBM. Breakthrough polymer could lead to endlessly recyclable plastics [Internet]. 2016. Available from: https://www.ibm.com/blogs/think/2015/11/breakthrough-polymer-could-lead-to-endlessly-recyclable-plastics/