Development of an Agile, Novel, Expeditionary Battlefield Manufacturing Plant Using Recycled and Reclaimed Thermoplastic Materials

Project Number WP18-1047

Principal Investigator – Dr. Prabhat Krishnaswamy

PI's Organization - Engineering Mechanics Corporation of Columbus (Emc^2), Columbus, Ohio

Project Outbrief Presentation

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14. ABSTRACT

The technical objective of this project was to conduct applied research and advanced development leading to an innovative, mobile, agile manufacturing plant for onsite fabrication of products at forward operating bases (FOB) using recycled Polyethyelene Terephthalate (rPET bottles) that would be useful to the soldier on the battlefield – thereby enhancing DoD Mission Effectiveness USARCENT analysis of waste plastics at FOB estimated up to 0.5 lbs/person/day of rPET is generated; a 2000-person base will generate up to 1000 lbs/day; largest component of plastics waste.

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Waste to energy, emissions, waste reduction, manufacturing, additive, recycling, plastic, re-use, Thermoplastic

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Project Team

- **Dr. Prabhat Krishnaswamy, and Mr. Richard 'Rick' Heggs, Engineering Mechanics Corporation of Columbus, (Emc^2), Columbus, OH**

- **Dr. Peter Stynoski, Mr. Jonathan Trovillion, and Mr. Stephen Cosper, US Army Corps, Engineer Research & Development Center – Construction Engineering Research Laboratory (USACE-ERDC-CERL), Champaign, IL**

- **Mr. Curt Cozart, Common Sense Solutions, Montclair, NJ (*Technical Advisor to Association of Plastics Recyclers)***

Background

- **Project WP 18-1047 Period of Performance:**
  - **June 21, 2018 to March 31, 2023**

- **Excerpt from Statement of Need WPSON-18-C4:**
  - **"Proposed efforts should be scoped to offer a safe and environmentally responsible way to reduce disposal requirements and to *turn a specific waste-stream into value-added products for use by the warfighter*."**

  - **"Proposed equipment capability would need to be *transportable via an International Standards Organization (ISO) container (20-foot)* or interface with multi-modal transportation methods used in the Department of Defense (DoD)."**

Technical Objective

To conduct applied research and advanced development leading to *an innovative, mobile, agile manufacturing plant for onsite fabrication of products at forward operating bases (FOBs) using recycled Polyethyelene Terephthalate (rPET bottles) that would be useful to the soldier on the battlefield – thereby enhancing DoD Mission Effectiveness*

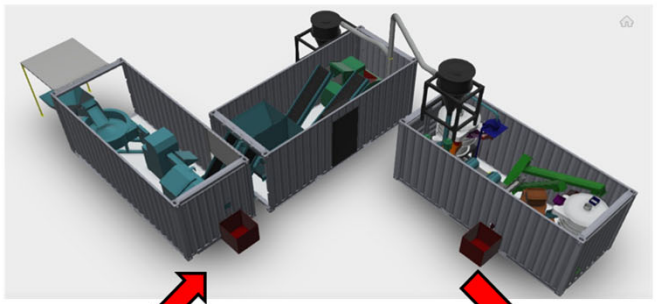
USARCENT analysis of waste plastics at FOBs estimated up to 0.5 lbs/person/day of rPET is generated; a 2000-person base will generate up to 1000 lbs /day; largest component of plastics waste

Technical Approach

- Recycling of waste PET into useful products ***is a mature industry stateside*** – research, select, and modify existing technologies
- Develop modular system to sort, wash, and ***grind PET water bottles into clean flakes*** for developing material formulations
- Develop modular plant to convert ***rPET flake into 3D printer filament and Additive Manufacturing (AM)*** specifications
- Develop modular and agile manufacturing plant for converting ***rPET flakes into dimensional lumber & shapes*** (1x1, 2x4, etc.)
- Evaluate properties, confirm performance specifications, and ***develop design guides*** for above rPET products
- ***Evaluate 'ByBlock' technology*** to convert rPET and mixed plastics waste into 'cinder blocks' for light structural applications

Technical Approach – Overview

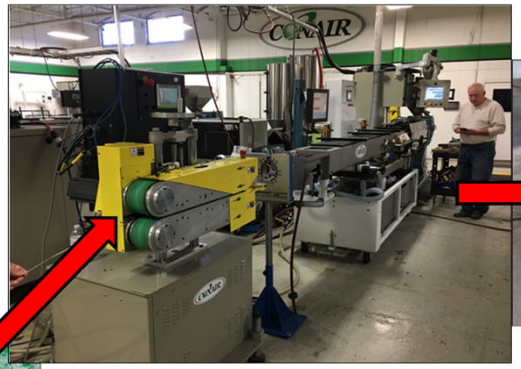
Processing steps to convert rPET bottles into useful products at FOBs

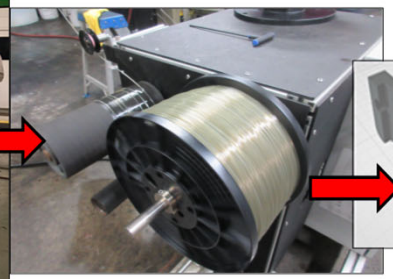


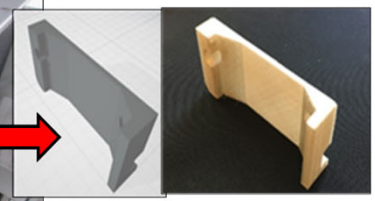
PET Water Bottles

Sorting & Washing

rPET Flake

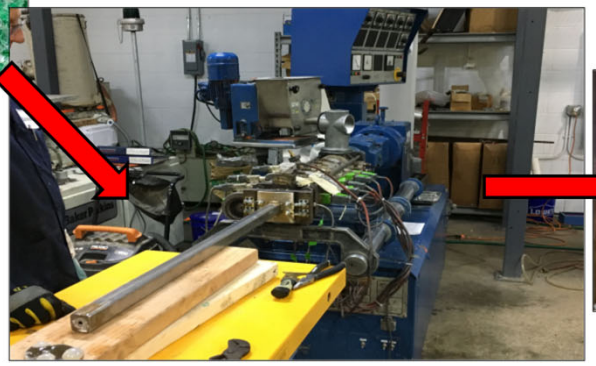






3D Printer Filament Extrusion

3D Printed Parts



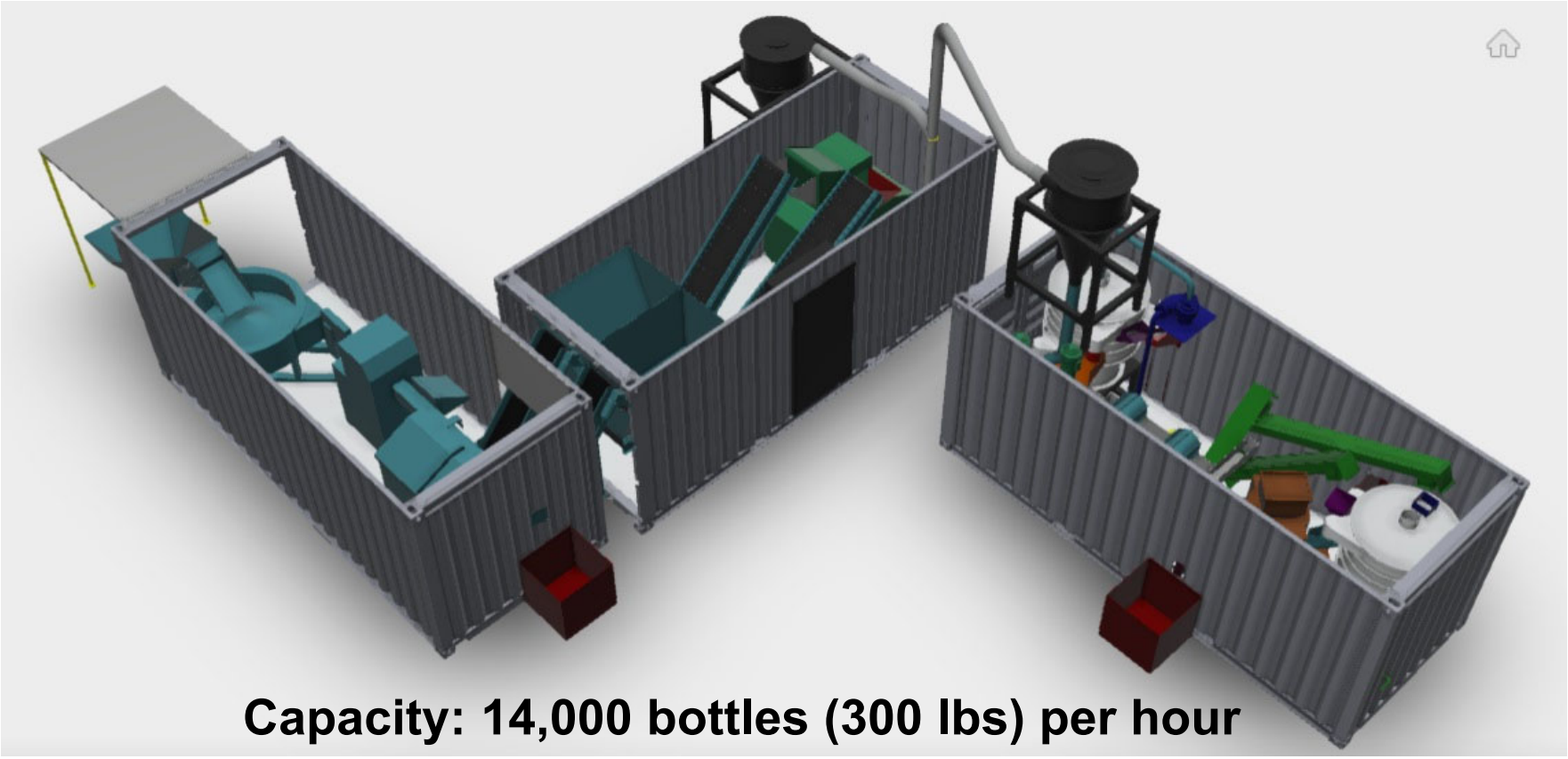
rPET Plastic Lumber Extrusion

rPET Dimensional Lumber

TASK 1 **TASK 2** **TASK 3** **TASK 4**

Results

rPET Sorting and Washing Line



Capacity: 14,000 bottles (300 lbs) per hour

Container 1

Bottle receiving, sorting, singulating, flattening

Container 2

Store flattened bottles in separate bins, grind to size, separate with cyclone

Container 3

Washing with hydro-cyclone, separation with float-sink tanks, delivery of clean flake via spin-dryer

Results
rPET Based Formulations

rPET Pellet

rPET – 4-mm white flake

rPET – Green Flake

rPET materials from mobile plant may be converted to pellets, clean flake or mixed (green) colored flake for various product

Results
rPET Based Formulations

- 300 pounds/hour recycling line for agile and modular rPET manufacturing at FOBs
- Labels complicate steps for washing and sorting line, equipment, and power requirements at FOBs
- Modular system designed and equipment validated
  - ♦ Consistent clean 4-mm flake from water bottles
  - ♦ With or without labels

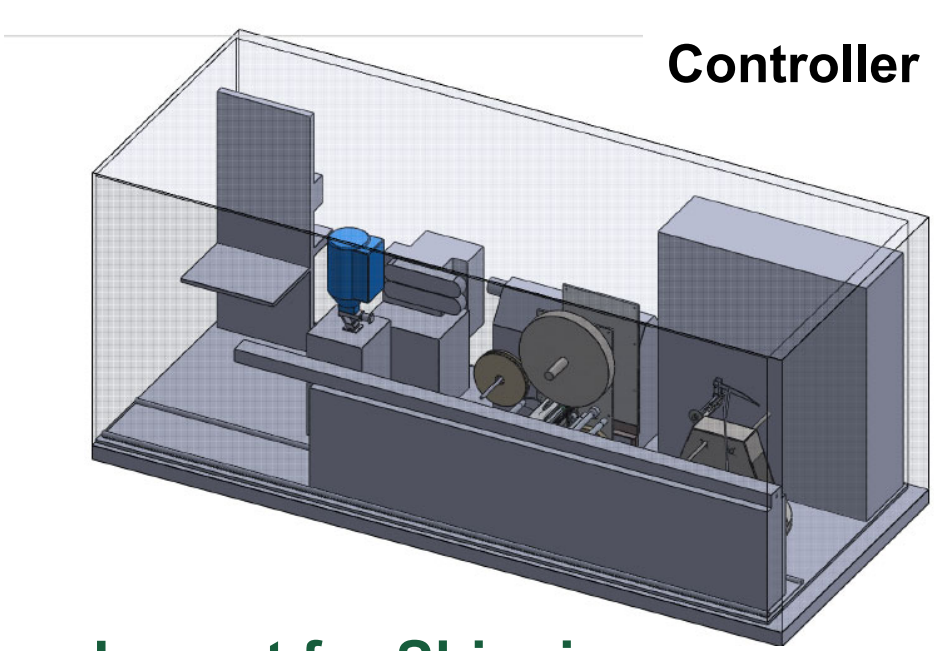
Results
Filament Extrusion Line Design

- **Successfully made 1.75-mm and 2.85-mm filaments**
  - **Using not only rPET pellets but with clean 4-mm flakes from Sorting and Washing Line**

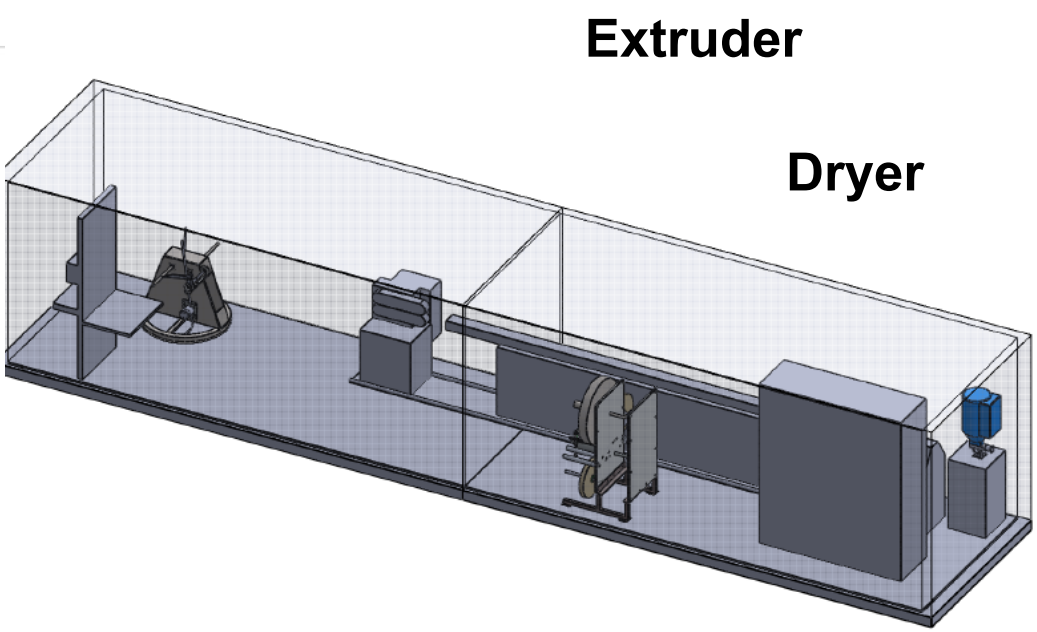
- **Preliminary design of mobile filament extrusion system completed**
  - **20-foot ISO**

Results

Design of Filament Extrusion Line



Layout for Shipping



Layout for Operation

Results
rPET Additive Manufacturing

- rPET filaments used in many commercial printers:
  - ♦ Ultimaker 2 Extended+
  - ♦ Raised 3D (modified)
  - ♦ Lulzbot TAZ6 and Lulzbot Pro
- Need printer specific optimization of processing parameters
- Lulzbot Pro used to print engineering parts and ASTM specimens for evaluating design properties

Results

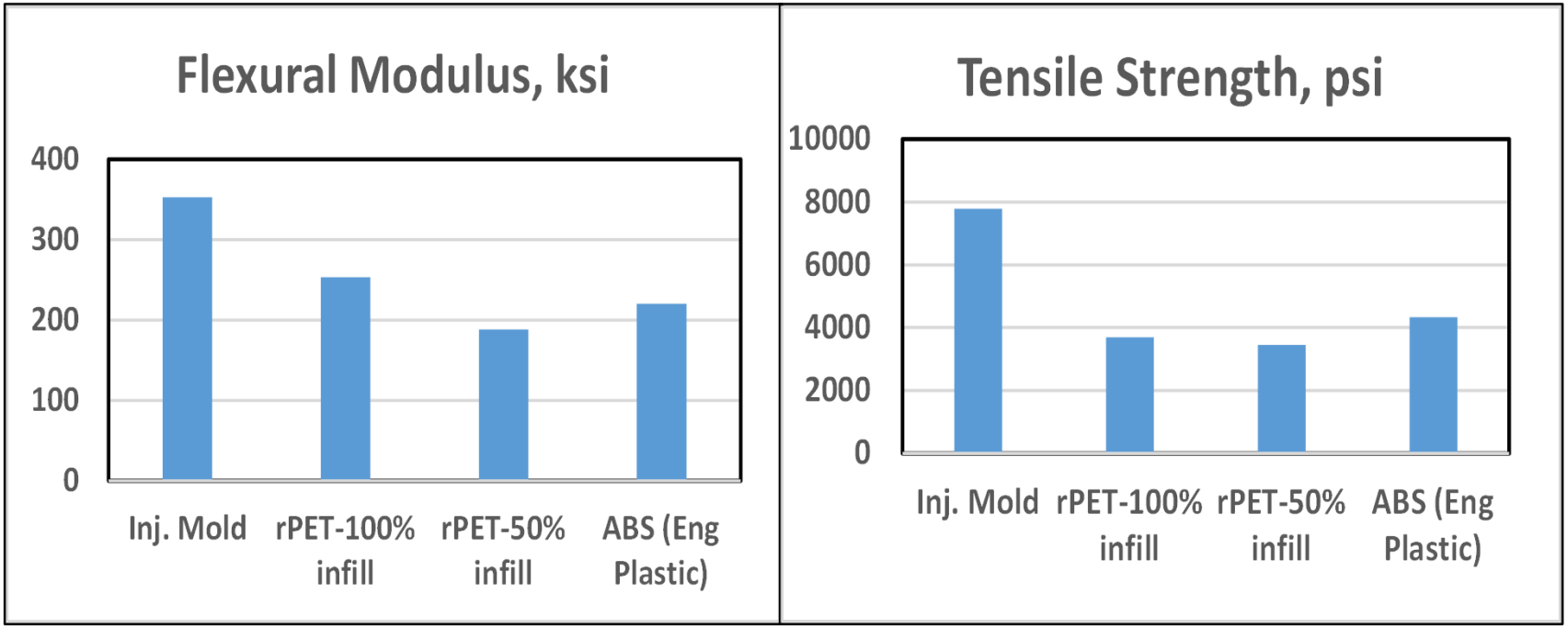
rPET Additive Manufacturing

3D-printed samples, ASTM specimen and 90-degree transmission gear from rPET filament

Results

Evaluation of 3D Printed rPET Properties

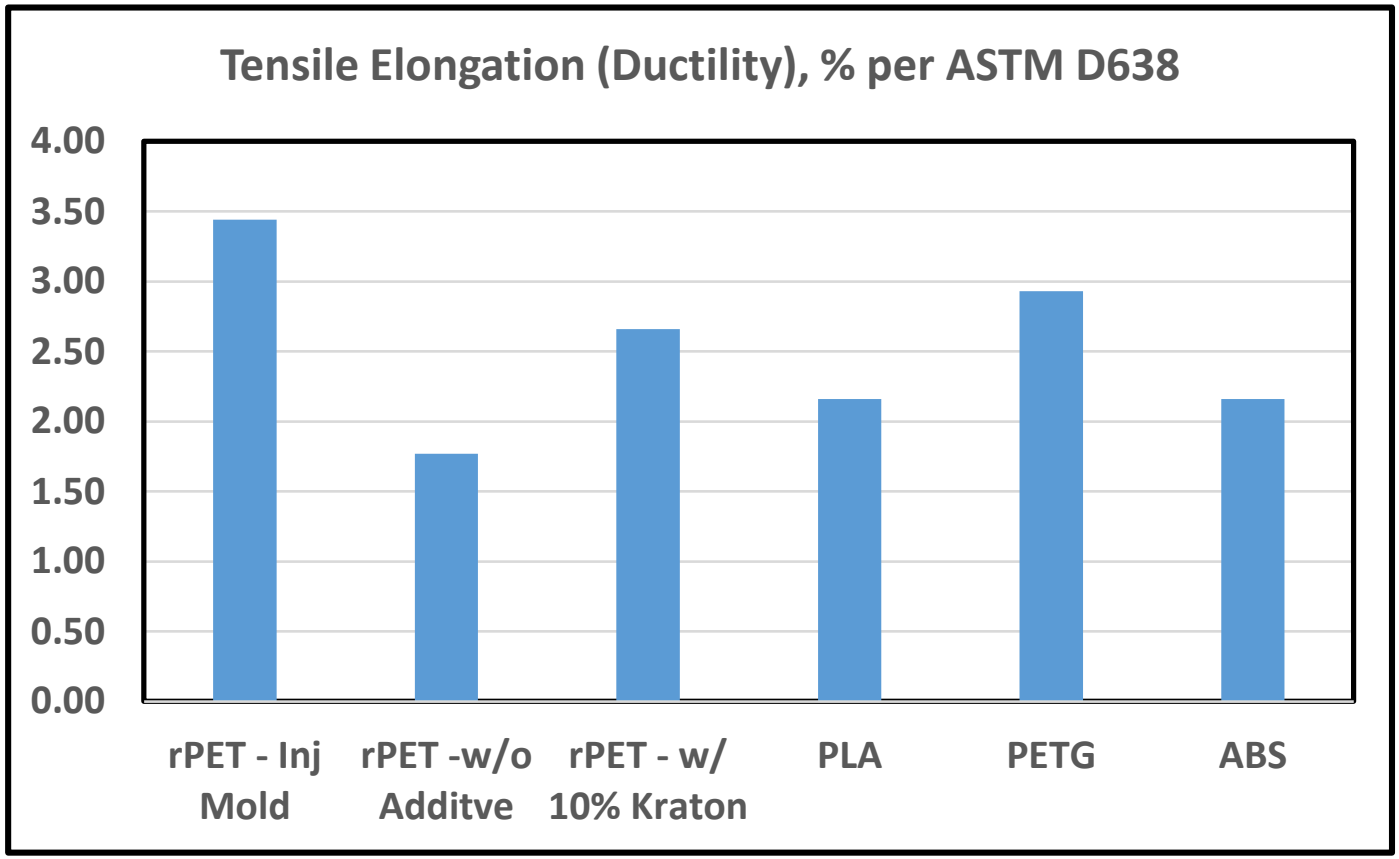
- **Comparison of properties of 3D printed and injection molded specimens**
- **Properties for printed specimens lower than those for injection molded parts**
  - ♦ **Still comparable to those for other engineering plastics i.e., ABS**



Results

Evaluation of 3D Printed rPET Properties

- **Lotader and Kraton impact modifiers evaluated to enhance ductility of rPET**
- **Kraton increased ductility by ~ 55% and compares with other engineering plastics**



Results

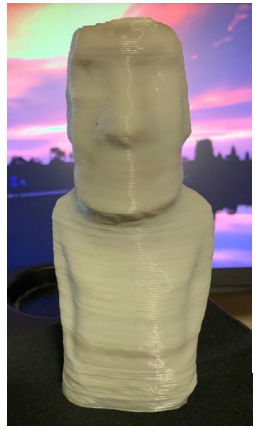
DoD Relevant Parts for AM

- **Parts from DoD JAMMEX database for test prints at ERDC-CERL**
  - ♦ 55-gallon drum wrench
  - ♦ MEP 1070 Wrench
  - ♦ M777 TrAK L Handle
  - ♦ NVG Purge Kit Handle
  - ♦ M240 Cheek Rest
  - ♦ Rotary Switch Collar
  - ♦ HMMWV Door Handle(s)

Results

AM Parts Directly from rPET Flakes?

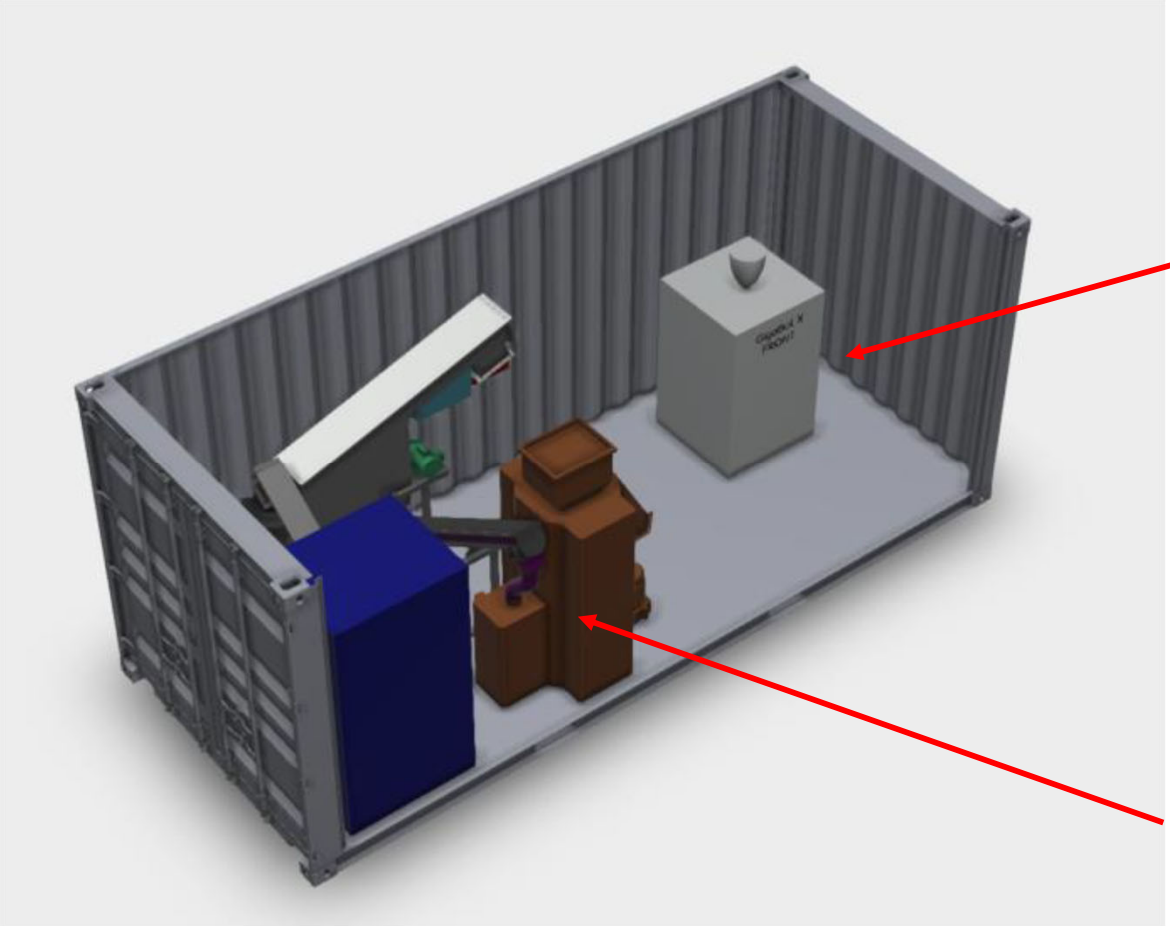
- **3D printers commercially available for manufacturing from pellets (no filament)**
- **Preliminary trials at two vendors with rPET flakes**
  - **Calibration cylinder (4-inch-diameter)**
  - **Hollow box (12-inch x 12-inch x 12-inch)**
- **Significant breakthrough allows using rPET flakes at FOBs for making parts**
  - **No need for filament extrusion system**



Results

AM Parts Directly from rPET Flakes?

Small-scale rPET flake manufacturing system designed (100 lbs/day) exclusively for AM applications – in single 20-foot container



3D Printer for rPET flakes

Small-scale system to convert water bottles to clean rPET flake

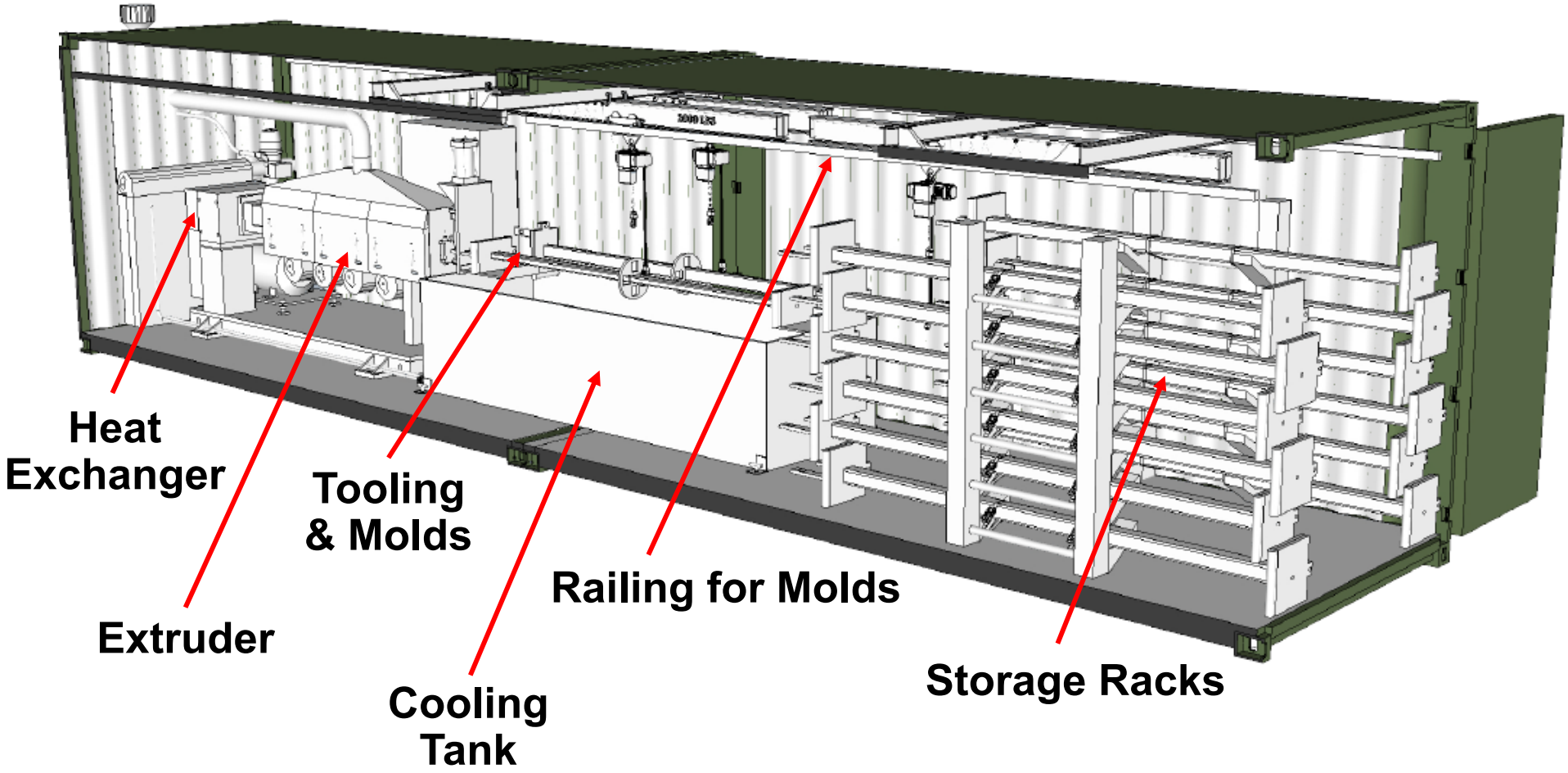
Results

Design of rPET Plastic Lumber Line

- **Completed trials successfully**
  - ♦ **Made 1x1 and 2x4 plastic lumber specimens with rPET formulations using 'flow molding'**
- **Designed rPET mobile extrusion system for plastic lumber (can also use mixed plastics)**
  - ♦ **Two 20-foot-long, 8.5-foot-high ISO containers**

Results

Design of rPET Plastic Lumber Line



Results
rPET Plastic Lumber Test Samples

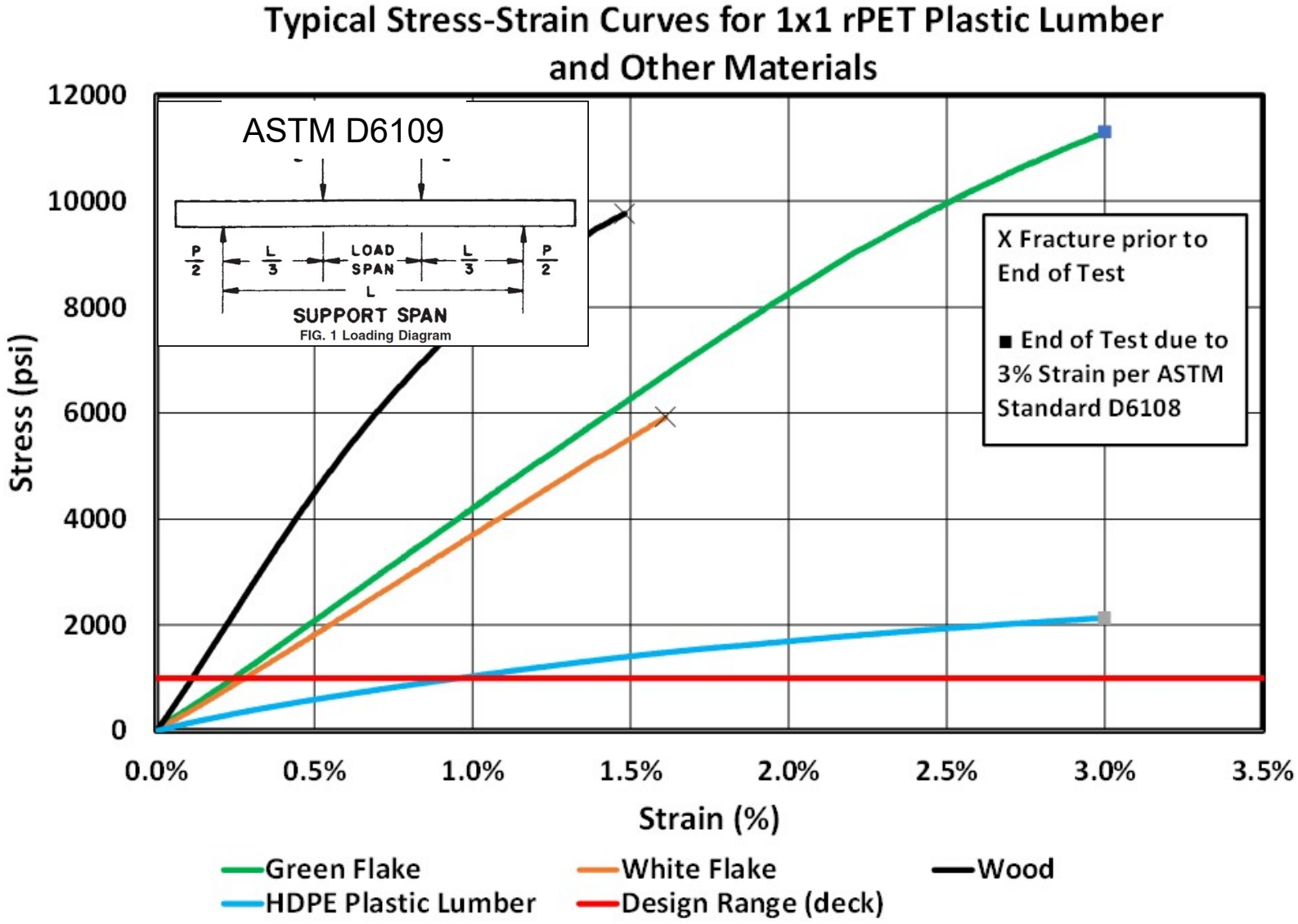
- **All three materials flow-molded successfully**
  - ♦ **Flake, pellet, and green flake**
- **Used only water and water + air cooling**
  - ♦ **Water cooling most effective**

1-inch x 1-inch x 36-inch specimens

2-inch x 4-inch x 96-inch (nominal) specimens

Results

rPET Plastic Lumber Properties



Results

Evaluation of Mixed Plastics' ByBlocks

- **ByBlocks in concrete masonry unit (CMU) dimensions (8x8x16) may be used for Light Structural Applications outdoors**

- **Full-scale compression tests conducted on two rPET based formulations**

Results

Evaluation of Mixed Plastics' ByBlocks

Specimen	Max Load (kip)	Max Stress (psi)	Max Strain (%)	Load at 3% Strain (kip)
Formulation 1	41.9	360	23.4%	5.67
Formulation 2	46.4	395	23.8%	5.02

ByBlock Pavilion Installed in Kauai, HI

Results

Design of ByBlock Fabrication Plant

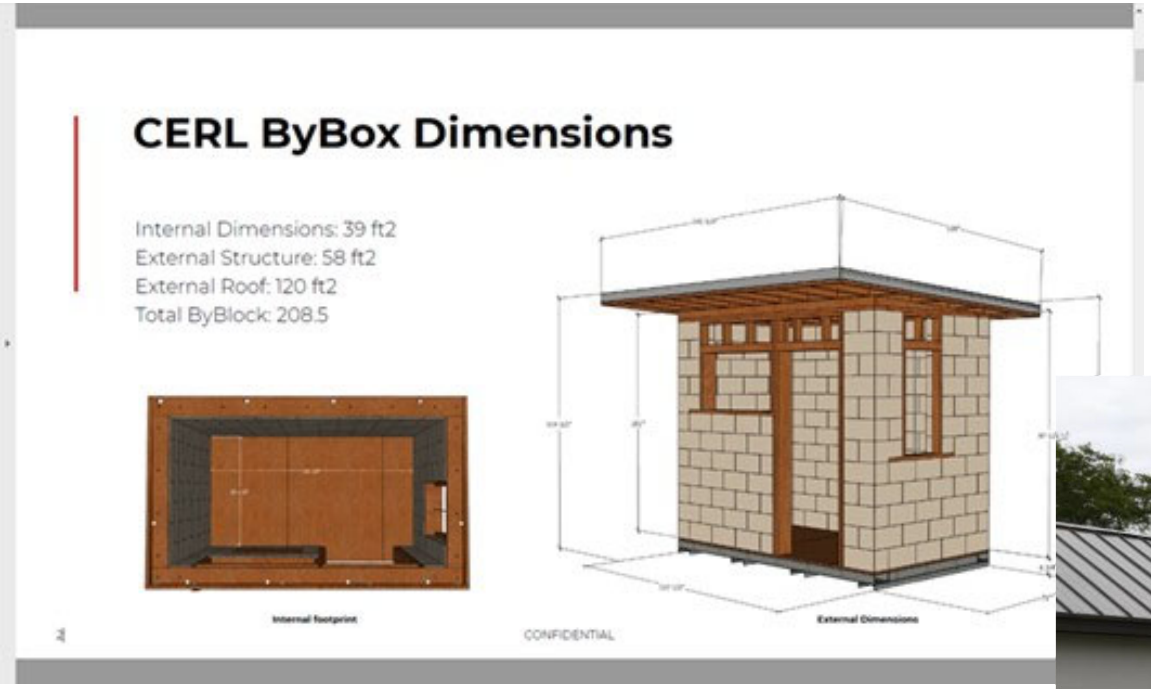
- **Successfully modified standard ByBlock Plant from 40-foot container to**
  - **Operate in two 20-foot ISO containers**
  - **Larger base applications, capacity 30 tons/month (one shift/day)**

- **Demonstration structure involving a ByBlock 'Storage Shed' successfully installed at ERDC-CERL!**

Results

Evaluation of ByBlock Demonstration Structure

Storage shed 'demonstration project' at ERDC-CERL successful



Key Points - Conclusions

- **Waste plastics such as PET can be successfully converted to useful products at FOBs**

- **Four mobile and agile manufacturing plants designed to be shipped and operated in 20-foot ISO containers**
  - **Sorting and washing plant can make clean rPET flake 300 pounds/hour; small-scale system for 100 lbs/day for AM**
  - **Filament extrusion plant for high valued AM products manufactured at PON**
  - **Dimensional plastic lumber (rPET and mixed plastics) at 200 pounds/hour**
  - **ByBlock fabrication plant for converting mixed plastics waste into light construction blocks at 30 tons/month**

Notes: PON = point of need

Key Points - Conclusions (Cont'd)

- Properties of rPET AM filament comparable to engineering plastics (i.e. ABS) for replacement parts
- Specifications for printing with rPET filament in various 3D printers
  - ♦ Impact modifiers enhance rPET ductility
- Potential for clean rPET flakes for use directly in AM
  - ♦ Without need for filament
- rPET based dimensional plastic lumber may be used for outdoor uses
- ByBlocks may be used for light outdoor structures

Key Points - Benefits to DoD

- Agile manufacturing plants designed and evaluated to both
  - Solve thermoplastics waste issue at DoD FOBs
  - Fabricate directly useful warfighter products with PON manufacturing
- Water bottles consumed by warfighter converted to clean rPET flake as feedstock
- Clean rPET flake available for AM of parts at FOBs
- Larger mixed rPET flake quantities may be used for dimensional lumber profile with design guides
- Mixed thermoplastics waste (# 2-7 including film) may be converted to ByBlocks for light outdoor structures
- rPET recycling system developed for AM applications to produce rPET flakes for smaller (~200 servicemember) bases

Technology Transfer

- **SERDP-ESTCP Webinar presented in April 2022**
- **Presentation at Society of Plastics Engineers, Annual Technical Conferences (SPE-ANTEC),**
- **Presentation at American Chemical Society, Green Chemistry Conference**
- **Poster Presentations at SERDP-ESTCP Symposiums**
- **Invited Presentations at SERDP-ESTCP AM Sessions**

Technology Transfer

- **ARL coordination led to Army xTECH SBIR Project with re:3DInc. (AM equipment manufacturer, Houston, TX) for printing directly with rPET flakes**

- **Coordination with EPA funded SBIR project on mobile recycled plastic lumber production system in Alaska**

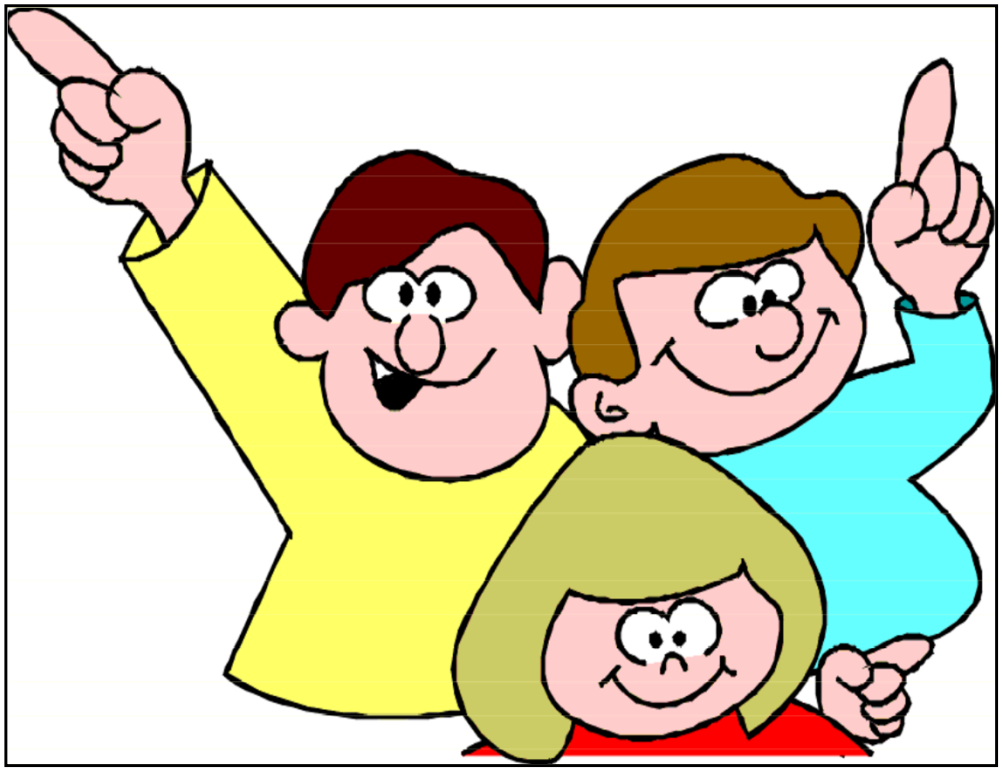
- **Follow on project for further evaluation of ByBlock at USACE-ERDC-CERL, Champaign, IL**

- **Final Report on project has been submitted and approved - to be published in the public domain; has design guidance documents and recommendations for rPET applications**

Acknowledgments

- Dr. Robin Nissan, SERDP-ESTCP Program Manager
- Dr. John La Scala, SERDP-ESTCP, Program Manager
- Mr. Marc Pepi, ARL, SERDP Technical Committee
- Mr. Braxton Lewis, Noblis, Project Coordinator
- SERDP-ESTCP Office, Administrative Staff

Thank you!!



Questions??

BACKUP SLIDES

Publications

1. Krishnaswamy, P. et al. "*Development of an Agile, Novel Expeditionary Battlefield Manufacturing Plant Using Recycled and Reclaimed Thermoplastic Materials*," Presentation at the Annual SERDP Symposium, Additive Manufacturing Session-2B, December 4, 2019

2. Krishnaswamy, P. et al., "*SERDP Project WP 18-1047: Development of an Agile, Novel Expeditionary Battlefield Manufacturing Using Recycled and Reclaimed Thermoplastic Materials*," Poster Presentation No. 249 at the SERDP Symposium, December 4, 2019.

3. Krishnaswamy, P. et al, "*Development of an Agile Battlefield Additive Manufacturing Plant for Recycled Polyethylene Terephthalate (rPET) Materials*," Proceedings of the Society of Plastics Engineers Annual Technical Conference (SPE ANTEC 2020 Virtual Edition), April 6, 2020.

4. Heggs, R. et al, "*Recycling PET into Plastic Lumber at Forward Operating Bases*," Proceedings of the Society of Plastics Engineers Annual Technical Conference (SPE ANTEC 2020 Virtual Edition), April 13, 2020.

5. Krishnaswamy, P. et al, "*System for recycling PET bottles into plastic lumber for U. S. Army's forward operating base applications*," Presented at the 24th Annual Green Chemistry & Engineering Conference, Seattle, WA, June 16-18, 2020.

6. Krishnaswamy, P. et al., "*SERDP Project WP 18-1047: Development of an Agile, Novel Expeditionary Battlefield Manufacturing Using Recycled and Reclaimed Thermoplastic Materials*," Poster Presentation at the SERDP Symposium, December 4, 2020.

Publications - Cont'd

7. Krishnaswamy, P. et al, "*System for recycling PET bottles into plastic lumber for U. S. Army's forward operating base applications*," to be presented at the 25th Annual Green Chemistry & Engineering Conference, (Virtual), June 14-18, 2021

8. Technical article to be submitted to the trade publication "*The Military Engineer*", Society of American Military Engineers (SAME), 2023

9. Krishnaswamy, P. et al "*Additive Manufacturing with Post-Consumer Polyethylene Terephthalate (rPET) Pellets and Flakes for Military Applications,*" to be presented at ASTM ICAM session on Additive Manufacturing, Washington, DC, October, 2023

WP18-1047: Development of an Agile, Novel Expeditionary Battlefield Manufacturing Plant Using Recycled and Reclaimed Thermoplastic Materials

Performers: Engineering Mechanics Corporation of Columbus (Emc^2) & USACE–ERDC-CERL (Champaign, IL)

Technology Focus

- ***Modular manufacturing plant to recycle PET bottle scrap into useful products at FOBs***

Research Objectives

- ***Develop formulations, processing methods, and equipment specifications for FOB manufacturing***

Overview of mobile and modular *design of an FOB manufacturing plant in 20-foot ISO containers*

Key Achievements

- ***Four agile, mobile manufacturing plants designed to convert (i) rPET bottles into clean flake, (ii) flake to filament for Additive Manufacturing (AM), (iii) flake to plastic lumber, and (iv) mixed plastics into construction blocks - all in 20-foot ISO containers***
- ***Products with rPET materials demonstrated successfully at TRL 3-4: (i) AM parts from flake and filament, (ii) Plastic lumber meets ASTM specs, and (iii) Blocks validated in vertical construction***

Technology Transition

- ***AM and Block applications being pursued by team members with other DoD funding; ESTCP proposal for demonstration and validation of manufacturing rPET flake feedstock and conversion to plastic lumber to be resubmitted***

Acronyms and Symbols

- ARL – Army Research Laboratory
- Emc^2 – Engineering Mechanics Corporation of Columbus
- ERDC-CERL - Engineer Research & Development Center – Construction Engineering Research Laboratory
- ESTCP – Environmental Security Technology Certification Program
- FOB – Forward Operating Base
- HDPE – High Density Polyethylene
- NSWC – Naval Surface Warfare Center
- rPET – recycled Polyethylene Terephthalate
- SERDP – Strategic Environmental Research & Development Program
- USARCENT – US Army Forces Central Command
- USACE – U. S. Army Corps of Engineers