Construction and Building Materials 167 (2018) 846–852

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

On the tolerable limits of granulated recycled material additives to maintain structural integrity

L.M. Clemon [*], T.I. Zohdi

Department of Mechanical Engineering, University of California, Berkeley, CA 94720-1740, USA

HIGHLIGHTS

- Provides a tool to aid circular economy pathways for 3D printer waste.
- Added distribution effects to correlated microstructural stress-macrostructural loads.
- Added distributional effects to particle-matrix stress concentration factors.
- Developed method for rapid material property estimates of mixed waste materials.
- Computational method to accelerate mixed-waste recycled material development.

ARTICLE INFO

Article history:
Received 26 November 2017
Received in revised form 15 February 2018
Accepted 15 February 2018
Available online 22 February 2018

Keywords:
Particles
Composites
Additive manufacturing
Recycling
Phase averages

ABSTRACT

Production and maker spaces are increasingly generating mixed plastic material waste of varying quality from 3-D printers. Industrial interest is growing in embedding granulated recycled particulate material additives into a virgin binding matrix. Examples include the introduction of granulated mixed recycled materials into 3-D printer material, concrete, and pavement. The stress load-sharing between the particulate additive and the binding matrix is an important factor in design and development of these composite materials. With mixed material additives, a designer is interested in the variation of such predicted load-sharing. However, experimental development is costly and time-consuming, thus analytical and semi-analytical estimates are desired for accelerated development. In this work, we expand on previous analytically correlated phase-averaged micro- and macrostructural loading to include variational effects present in mixed recycled material. In addition, model trade-offs are provided to aid designers in quickly selecting application specific mixtures. This framework identifies the stress contributions, and their variation, to reduce product development time and costs, which could greatly accelerate material recycling and reuse for improved infrastructure materials, low-cost 3-D printer filament, and reduced waste towards a more circular economy.

1. Introduction

Many organizations have stated goals of becoming zero-waste entities, namely no material going to landfills-*anywhere* [1–4]. In addition, municipalities are ever more concerned with odor pollution and potential seepage from landfills within their borders. Strategies have emerged to combat the disposal of plastic waste, in particular [5,6]. Instead, plastic waste products may be processed with automated collection, cleaning, sorting, and grinding for reuse and recycling. Such processes can downcycle the waste into products with less stringent purity requirements than the original. Or, with sufficient sorting and processing, waste may be recycled into the original product [7]. These efforts facilitate a more circular economy. In particular, two target end products are of interest for re- and downcycling nearly all plastics:

1. 3-D printer filament for educational demonstrations and prototypes
2. filler for bulk construction materials, such as construction materials

Education at virtually all levels and in many fields of study have undergone massive changes due to the rise of inexpensive 3-D printers. Unfortunately, the price of 3-D printer material over time is not trivial. In educational and early design environments, the printed material is used primarily to develop form and fit prototypes, which need not be made of high-grade materials. Thus,

---

[*] Corresponding author.
E-mail addresses: mclemon@berkeley.edu (L.M. Clemon), zohdi@me.berkeley.edu (T.I. Zohdi).

https://doi.org/10.1016/j.conbuildmat.2018.02.099

we provide a design framework with example calculations which will aid in determining the maximum extent to which plastic waste may be processed into 3-D printer feedstock and bulk construction material filler. Materials unsuitable for 3-D printer filament may be used in bulk construction materials as a filler thereby closing the loop on the full set of plastic waste. In urban areas with high waste generation and infrastructure needs, the colocation of waste generators and reprocessing facilities would be advantageous for minimizing transportation costs as well. The design methodology in this manuscript may be used to determine mixtures of such particulate materials with existing types of pavement and roadway materials to create near zero-waste materials to maintain and rebuild roadway infrastructure.

Regardless of the final use of the materials, they can be compacted and/or packaged efficiently through grinding and shredding. Collocating the product use with recycling and fabrication would also minimize transportation impact and contribute to local economies. In addition to the obvious reasons for grinding, such as volume-reduction and homogenization, others include secure disposal of potentially sensitive information on electronic devices and storage units. It is particularly important to recognize regulations that are moving towards the responsible reduction and handling of waste to reduce an enterprise's carbon footprint. Granulated waste products can be sold to other enterprises or recycled within the community as filler, pavement, insulation, or other building materials, such as resin-combined briquettes and composite wood products.

It is now commonplace for plastic pellets to be sold as feedstock to a converter for fabrication into consumer products or recycled by hobbyists for individual use. This framework serves to aid designers in diverting more waste from landfills by estimating the composite strength of recycled and virgin material. Thereby enabling rapid development of product streams for recycled waste. Moreover, the statistical variation in such estimates for mixed waste recycling is included for broad applicability.

2. Methodology framework

Industrial interest is growing in particulate-enhanced composite materials for structural applications (Fig. 1). Similarly, many particle-matrix choices available to designers and analysts. Limited experimental success has shown recycled materials may be used in concrete and cement [8,9]. However, such experimental development is expensive and time-consuming for such applications. Thus, characterizing these materials computationally may significantly reduce development time and cost.

Similarly, municipal governments are increasingly concerned over waste quantities and pathways to recycling. The rise of additive manufacturing and 3D printing in classroom, art, hobby, and production environments provides both a source of increased plastic waste and a potential recycling pathway. The use of lower grade materials in prototypes, art, and education is acceptable due to lower strength and durability requirements; some industrial applications may also prefer some quantity of recycled content. The large portion of input material into additive manufacturing that emerges as waste has a distribution of quality ranging from that equivalent to pristine material to some which must be downcycled or disposed of (Fig. 2). As a result, much of the "used", or previously processed, material may be directly inserted into new products. However, the distribution of quality is specific to each additive manufacturing process and machine. The methodology described in this manuscript is broadly applicable to all processing methods given the relevant data.

For a simple mixture of known specific particles mixed into a binding matrix, the effective macroscale (structural) material response seeks a relationship, $\langle\boldsymbol{\sigma}\rangle_\Omega = \boldsymbol{I\!E}^* : \langle\boldsymbol{\epsilon}\rangle_\Omega$, where $\langle\cdot\rangle_\Omega \overset{\text{def}}{=} \frac{1}{|\Omega|}\int_\Omega \cdot\, d\Omega$,and where the mechanical properties of micro-heterogeneous materials in the structure are characterized by an elasticity tensor $\boldsymbol{I\!E} = \boldsymbol{I\!E}(\boldsymbol{x})$ varying in space, with $\boldsymbol{\sigma}$ and $\boldsymbol{\epsilon}$ as stress and strain tensor fields within a Representative Volume Element (RVE) of volume $|\Omega|$. The effective property, $\boldsymbol{I\!E}^*$, is the usual elasticity tensor for macrostructural analyses. Computationally intensive methods may be used to solve the loadings over the RVE (Zohdi and Wriggers [10]). However, it is often advantageous to seek faster approximation methods. *Such quick approximations accelerate initial design iteration to minimize time and experimental cost–the objective of this paper.* In this manuscript, we utilize the correlated phase-averaged micro- and macrostructural loadings to explore the distribution of expected responses for in the unique setting of mixed recycled material content in construction materials. We will focus on isotropic materials for both the particulate and the binder.

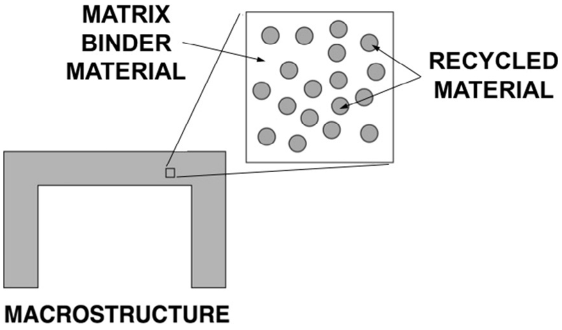

Fig. 1. Example structure with a matrix binder and recycled particulate additives.

The objective is to provide designers with an easy-to-use framework that identifies the distribution of stress contributions from the micro- and macroscale based on mixed recycled content, in order to reduce product development time and costs.

The following sections define the modeling method and results. Section 3 provides the fundamental property estimates for particulate mixtures. Section 4 derives the formulae for estimating variable properties from a distribution of particle properties starting from the fundamental property estimate equations in Section 3. Section 5 applies the variable property estimates developed in Section 4 to the particle-matrix stress concentration relations developed by [11] to provide quick estimates in material development of mixed recycled waste and infrastructure materials.

3. Effective property estimates

Maxwell [12,13] and Lord Rayleigh [14] were some of the first to propose models to estimate the macroscopic properties of heterogeneous materials. An extremely important contribution came in the 1960s: Hashin–Shtrikman bounds (Hashin and Shtrikman [15,16], Hashin [17]). These bounds provide the tightest range where volumetric data and phase contrasts of the constituents are the only known parameters. Interphase boundaries are assumed to be well bonded. For bulk modulus, we write,

$$\kappa^{*,-} \overset{\text{def}}{=} \kappa_1 + \frac{v_2}{\frac{1}{\kappa_2-\kappa_1}+\frac{3(1-v_2)}{3\kappa_1+4\mu_1}} \leqslant \kappa^* \leqslant \kappa_2 + \frac{1-v_2}{\frac{1}{\kappa_1-\kappa_2}+\frac{3v_2}{3\kappa_2+4\mu_2}} \overset{\text{def}}{=} \kappa^{*,+}, \qquad (1)$$

and for the shear modulus

$$\mu^{*,-} \overset{\text{def}}{=} \mu_1 + \frac{v_2}{\frac{1}{\mu_2-\mu_1}+\frac{6(1-v_2)(\kappa_1+2\mu_1)}{5\mu_1(3\kappa_1+4\mu_1)}} \leqslant \mu^*$$

$$\leqslant \mu_2 + \frac{(1-v_2)}{\frac{1}{\mu_1-\mu_2}+\frac{6v_2(\kappa_2+2\mu_2)}{5\mu_2(3\kappa_2+4\mu_2)}} \overset{\text{def}}{=} \mu^{*,+}, \qquad (2)$$