Developing a room temperature replacement for Roma Plastilina #1 as a ballistic backing material

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Abstract. ARL's Reusable, Temperature-Insensitive Clay (ARTIC) is a new backing material for use during ballistic evaluation of protective systems to simulate the deformation resistance of the human body. ARTIC was designed and developed with the sole intent of meeting the needs of the United States Department of Defense and the broader testing community to enhance the evaluation, certification, and development of ballistic protective systems including vests, protective inserts and helmets. ARTIC provides the desired backing material response at room temperature, with a consistent mechanical properties from at least 5 to 38 °C, and is composed of commodity feedstocks with robust supply chains. This paper briefly describes the challenges of designing a material with a controlled response that exhibits dimensional stability while providing minimal elastic recovery. In addition, we demonstrate the ability to tailor the response and compare with heated Roma Plastilina #1 (RP1), an artistic clay that is commonly used as ballistic backing material through a brief summary of initial ballistic and drop impact test results.

1. INTRODUCTION

Quantification of the back face signature (BFS) due to high rate impact is critical for the evaluation of personal protective equipment including helmets and body armour. A witness material is commonly placed behind the protective equipment prior to impacting the front side to serve two functions: 1) to better mimic the deformation resistance of the human body in a worn state rather than no supporting material behind the armour and 2) to quantify the transient deformation behind the armour. In practice, witness materials provide a quantifiable backface signature related to the transient deformation behind the armour that may not be equivalent to the maximum backface deformation. Common witness materials include clays [1], gelatins [2, 3], ballistic soaps [4], and microcrystalline waxes [1]. In 1977, Prather et al. evaluated the back face deformation behaviour of 20 % ordnance gelatin, Roma Plastilina No. 1 (RP1) and Roma Plastilina No. 2 compared to the lethality probability from soft armour impacts [5, 6]. Both RP1 and 20 % ordnance gelatin exhibited a similar suitable response however, gelatin exhibits elastic recovery requiring the use of high speed cameras and image analysis to accurately measure the deformation depth. In contrast, RP1 provides a permanent deformation that can be measured after the impact event. The reduced infrastructure costs and potential for increased throughput has led to RP1's extensive use as a ballistic witness material for different types of hard and soft body armour in the military and civilian sectors [7].

RP1 is a modeling clay used primarily by the artistic community comprised of 20 to 30 proprietary components including petroleum-based oils and waxes, kaolin clay, colouring agents, and sulfur [8]. The key feature of RP1 for use as ballistic witness material is that it is dimensionally stable at rest but will produce permanent, plastic deformation upon impact [9]. However, it is also critical that any ballistic witness material provides a repeatable and reproducible BFS measurement over the broadest range of conditions possible. Since it's initial use in the late 1970s, RP1's formulation and performance have changed due to the needs of the artistic community and changes in component feedstocks. These changes have resulted in significant time and effort by the testing community to maintain body armour test consistency. One of the more significant examples, is that RP1 is no longer used at room temperature. Instead RP1 must now be softened through physical agitation and heating up to 38 °C (100 °F) for it to pass calibration. In addition, RP1 exhibits substantial temperature- and time-dependent performance that results in a small time window before the material will likely no longer pass calibration [10]. In addition, RP1 also suffers from lot-to-lot variability, aging, humidity sensitivity, and a strong odor. In 2010, the United States National Research Council recommended identifying an improved ballistic backing material that can be used at room

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temperature to improve the accuracy and reproduciblity of protective equipment assesment [1]. To our knowledge, no commercial product was identified that met the performance needs to the testing community which required the development of a new backing material.

In this report, we present a new material, ARL's Reusable, Temperature-Insensitive Clay (ARTIC), as a room-temperature replacement candidate for RP1. The material was developed to meet the specific needs of the testing community. ARTIC is composed of three primary materials and one colourant that have robust supply chains to avoid undesired formulation changes in the future. Although tests are ongoing, ARTIC appears to exhibit a shelf life of at least one year with minimal temperature and time sensitivity. ARTIC also exhibits stability to humidity changes, very low toxicity, low flammability, and no detectable odour. The material can be mass manufactured using traditional polymer processing techniques that can enable commercialization of the material at a cost similar to RP1.

2. MATERIAL DESIGN OVERVIEW

It is critical that any RP1 replacement candidate provide dimensional stability at rest but deform readily upon impact while exhibiting minimal elastic recovery. Polymer-based materials were obvious candidates due to similar consistency with RP1 however, the mechanical response of the material is typically described as viscoelastic which is not ideal for a witness material. Too strong viscious character would eliminate the dimensional stability while strong elasticity could allow for the BFS to recover between impact and measurement, reducing accuracy. RP1 accomplishes this balance of properties through 20 or more components whereas a new material would need to accomplish the same performance using a minimal number of commodity components. ARTIC is composed of three primary components: silicone oil, fumed silica, and corn starch. Carbon black is also added to the formulation as a colourant at a loading of 0.004 wt % and has no detectable influence on the performance. Non-crosslinked, linear polydimethylsiloxane (PDMS), within a class of materials commonly referred to as silicones, was chosen due to its long performance lifetimes and uniform performance over a broad range of temperatures. It is important that the PDMS is not cross-linked to limit the potential for elastic recovery. As a single component, the PDMS will readily flow so fumed silica was added as a thickener to produce a dimensionally stable, "grease-like" consistency [11, 12]. Corn starch was added as a third component to reduce the tack adhesion (i.e. "stickiness") of the PDMS-fumed silica material and to promote compatbility with laser-based measurement techniques by virtue of the individual corn starch particles being larger than the laser wavelength (Figure 1). The material is batch mixed using a commercial stand mixer to grossly mix the components and then it is passed through a twin-screw extruder to refine the mixing and enhance the material reproducibility.

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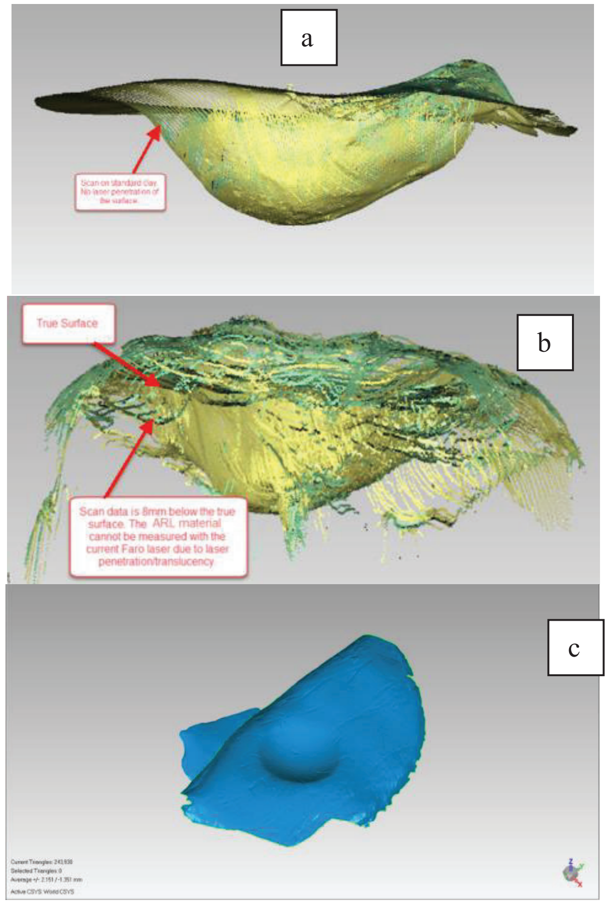

Figure 1. Laser scanning images of a) RP1, b) PDMS and fumed silica, and c) PDMS, fumed silica, and corn starch. Figure 1c was obtained later using a different indenter.

3. TAILORED PERFORMANCE

It was demonstrated in a previous report that ARTIC can provide a uniform performance from at least 5 to 38 °C (41 to 100 °F) and provide a similar response to heated RP1[13]. However, it is important to understand how changes in the material compliance, or resistance to deformation, alters the measured backface deformation. The deformation resistance of ARTIC can be readily controlled through the fumed silica loading. Decreasing the fumed silica loading produced a more compliant soft backing whereas increases in the fumed silica content produced a more rigid material. The materials were produced in 90.9 kg (200 lb) lots, enough to fill a standard ~ 61 cm x 61 cm x 14 cm (24 in. x 24 in. x 5.5 in) test box, with an additional 5 kg of material to repair indents during testing. The quasistatic deformation resistance was measured on every 0.9-1.5 kg of material produced to monitor uniformity of the entire lot (Figure 2). The numbers in parenthesis represent the targeted average value for the penetration force of each formulation and the respective red dotted lines are the manufacturing tolerances for each formulation set at the average ± 0.5 N.

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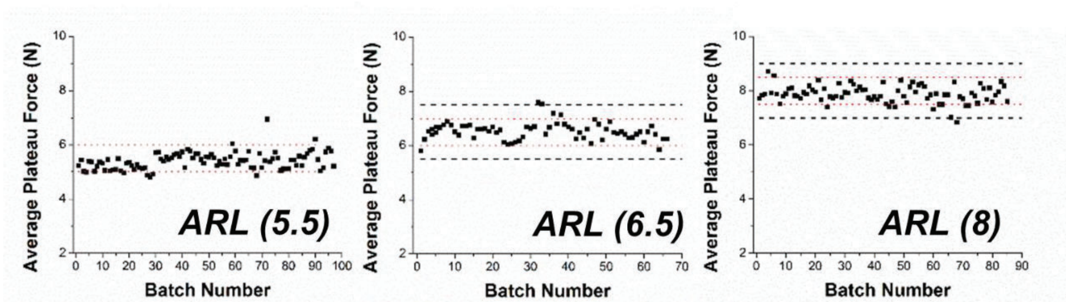

Figure 2. Deformation resistance data on every 0.9 to 1.5 kgs of material to ensure uniformity during manufacturing.

The test boxes were used to back soft armour shoot packs impacted with a 9 mm FMJ projectile at 0° obliquity and matching impact conditions. Figure 3 includes the BFS data for all three formulations side-by-side with heated RP1. From this limited data set, it appears that the softest formulation (ARL 5.5) is much softer than heated RP1 with an average BFS depth 5 mm deeper. However, the medium and relatively rigid formulation were similar to each other and to RP1 exhibiting a 0.7 mm deeper BFS depth and the same depth on average when compared to calibrated RP1, respectively. It also appears that both formulations exhibit a lower standard deviation than heated RP1 however, the time limitations of RP1 required the use of four different RP1 boxes for this study whereas only one box of each ARTIC formulation was used for the testing. This data set indicates that the BFS can be tailored through the formulation and that the ballistic response follows similar trends to those observed in the quasistatic data.

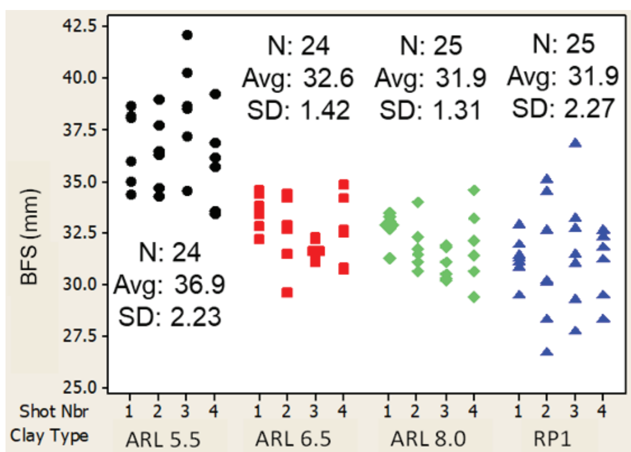

Figure 3. Soft armour BFS data for three different ARTIC formulations compared to heated RP1.

Prior to ballistic testing, heated RP1 is assessed using an impactor drop test (ASTM E3004) that consists of a 1 kg mass with a 45 mm diameter hemispherical end dropped from 2 m. The penetration depth of the impactor needs to fall within 25 ± 3 mm for the heated RP1 to pass calibration. Impactor drop tests were performed under the same conditions on the three different ARTIC formulations prior to testing. The drop depths of all three formulations along with heated RP1 are plotted against the measured BFS in Figure 4. As anticipated, the drop depths follow similar trends as the quasistatic penetration testing and the BFS. What is interesting is that the ARL 5.5 formulation that provided a significantly larger BFS falls within the drop calibration range of heated RP1 whereas ARL 8.0 falls below the calibration range of heated RP1 and provides similar BFSs as heated RP1. The ARL 6.5 falls within the calibration range for heated RP1 but is localized towards the lower end of the range. This data supports that the impactor drop can still be used as a calibration method for the new material however, the range to be within calibration may need to shift lower.

The calibration drops values will continue to be monitored during the material evaluation to better correlate the ARTIC drop values with the measured BFS. More work needs to be done but the differences in depth may be attributed to slightly different shear thinning behavior by RP1 than ARTIC. RP1 exhibits shear thinning behavior at slightly lower strains than ARTIC (0.04 vs 0.4 %) which may reduce the effective friction under low velocity, high surface area impacts.

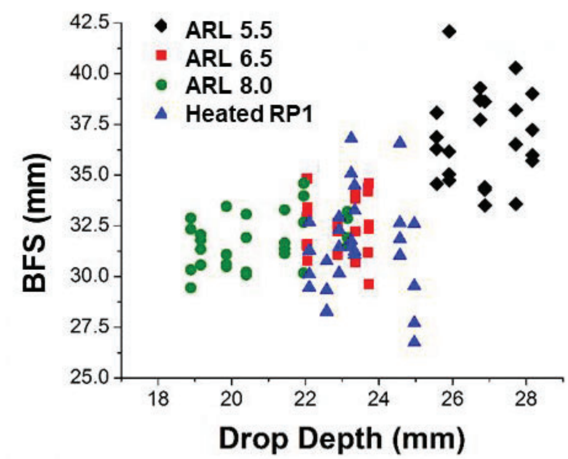

Figure 4. Soft armour BFS data for three different ARTIC formulations compared to heated RP1.

4. DETERMINING FACTORS THAT CONTROL THE DEFORMATION BEHAVIOUR

While the primary goal is to provide a backing material with the desired response at room temperature, a more comprehensive understanding of the deformation behaviour in clay-like materials may benefit the testing community by validating calibration ranges and links between low and high rate testing. Performing these studies is complicated with RP1 due to the time- and temperature-dependent performance. Specifically, it can be a challenge to verify that the RP1 is not changing for the duration of the test. ARTIC's consistent performance over a broad temperature range avoids these issues to increase the confidence of the measurement and the ability to tailor the formulation enables a direct understanding of how backing material compliance influences deformation behaviour.

In addition to ballistic testing, deformation behaviour during impact will be evaluated using a temperature-controlled drop tower. While the drop tower is not capable of reaching ballistic rates, it has the advantage of impacting the backing material at higher rates while eliminating any variability associated with the protection equipment or ballistics. The CEAST 9350 drop tower is spring assisted and enables impact velocities as high as 20 m/s (Figure 4a). It also has a heated chamber that enables temperature-dependent testing and direct comparison of impact behaviour with heated RP1 (Figure 5b). Test boxes with lateral dimensions of 28 cm x 28 cm have been fabricated to fit into the heated chamber at depths of 14, 23, and 28 cm to accommodate the study of clay deformation in excess of 22 cm. Additive manufacturing techniques were used to produce multiple impactor lengths, diameters, and radii of curvature (Figure 5c). Penetration depth and force, as a function of time can provide insight into the behaviour of the backing material when subjected to various impact conditions (Figure 6). The drop tower does not have the ability to monitor depth inherent to the instrument. To measure depth we use a high speed camera to capture the displacement of the cradle as the impactor enters material. During the initial drops, a slight reduction in the depth is observed after it reaches the maximum for some of the impact conditions that would be suggestive of elastic recovery. The extent of that depth change does not follow trends with impactor diameter, mass, or velocity. Current efforts are focusing on determining the cause of this observation however it is suggestive of inherent compliance to the test setup rather than the material itself.

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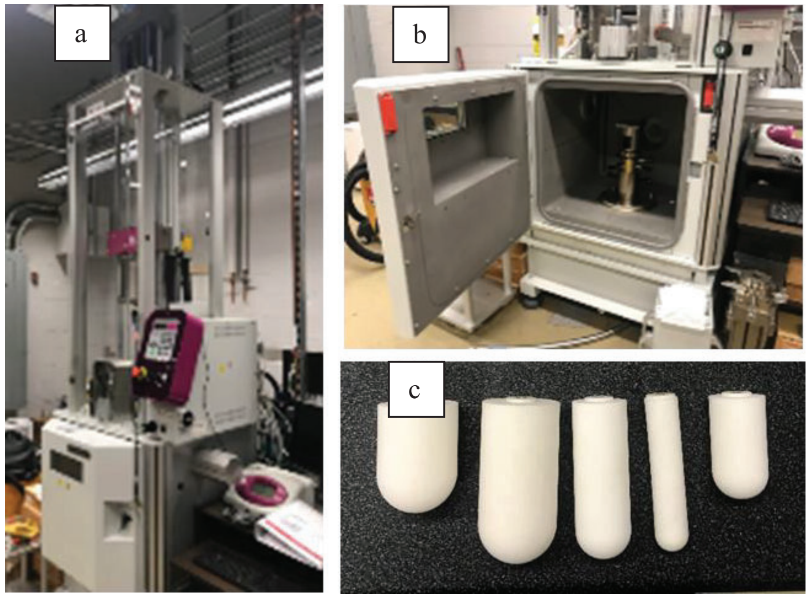

Figure 5. Pictures of the a) CEAST 9350 drop tower, b) temperature controlled chamber, and c) additively manufactured impactors in a range of shapes.

a

b

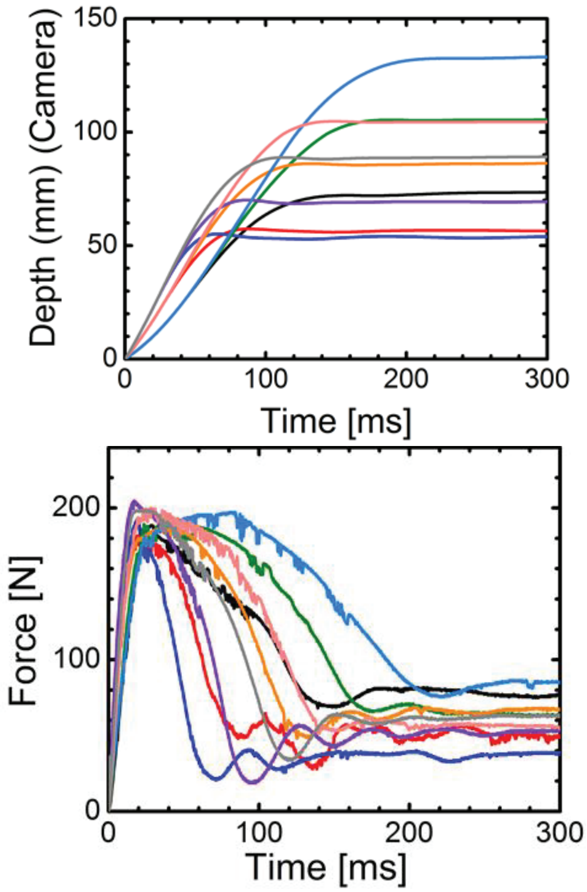

Figure 6. Plots of a) depth as a function of time and b) force as a function of time during an impact event on ARTIC in the drop tower.

5. SUMMARY/CONCLUSIONS

A new clay-like backing material has been developed that does not require heating and exhibits temperature and humidity stability, very low toxicity, low flammability and no detectable odour. Initial ballistic and drop impact tests results indicate that the material can provide a similar performance to heated and RP1 and has the potential to be implemented using existing RP1 infrastructure and calibration techniques. The material has been developed explicitly for the testing community using three commodity materials and a colorant, each with robust supply chains. Therefore it can reasonably be expected that the formulation will not change unless desired by the ballistic testing community.

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