Thermo-Rheological Characterization on Next-Generation Backing Materials for Body Armour Testing

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Abstract. The current standard backing material used for ballistic resistance testing of body armour, Roma Plastilina No. 1 (RP1), is known to exhibit complex thermomechanical behavior under actual usage conditions. Body armour test standards that specify RP1 often establish a performance requirement for the RP1 before it can be used. To meet this requirement, RP1 most likely must be temperature conditioned. This conditioning step adds to the complexity of the test and introduces temperature-time variables into the test, which serve as incentives for finding potential alternative materials that perform similarly at room temperature. To achieve the goal of replacing the current standard backing material, the U.S. Army Research Laboratory (ARL) and U.S. Army Aberdeen Test Center (ATC) have taken the lead to develop a family of room-temperature backing materials that exhibit dynamic properties that are consistent and similar to temperature-conditioned RP1. These candidate materials, named ARTIC, have fewer components than the RP1 clay. The research at NIST focuses on rheological characterization and thermal analysis of these next-generation backing materials to understand structure-property relationships and compare to the current RP1. In this work, we show that ARTIC materials exhibit minimal temperature dependence of mechanical properties and consistent thermal properties over a wide temperature range.

1. INTRODUCTION

Roma Plastilina No. 1 (RP1) is a manufactured oil-based clay that was chosen by both the National Institute of Justice (NIJ) and the U.S. Army as the standard backing material for ballistic resistance testing of body armour [1-3]. Body armour is tested by placing the armour against a backing material, also known as a ballistic witness material (BWM). After a ballistic impact, evaluation of the armour's performance is based on assessing perforation of the armour and deformation depth of the backing material. RP1 clay is primarily a sculpting clay that is a multicomponent, multiphase formulation composed of oils, waxes, and clay minerals with additives. Unfortunately, over the decades since RP1 was first adopted as the standard, changes have been made to the RP1 formulation by the clay manufacturer. Those changes were not driven by BWM performance requirements, but to meet the demands of other users, primarily from artist communities. As a result, newer versions of RP1 are stiffer at room temperature than the original RP1 selected by NIJ and the Army. In order to meet the specifications, ballistics researchers and practitioners must now thermally condition the material prior to use, which involves heating RP1 to approximately 40 °C or higher.

A dynamic test procedure to verify that clay can be used for ballistic testing of body armour is called a "drop test", which involves dropping an impactor of specified mass and geometry from a specified height onto the surface of the clay box and then measuring the indentation depth to ensure that it falls within specification limits. In addition to the undesired extra thermal conditioning step, the mechanical properties of clay depend on work and thermal history, temperature, and time [4-7]. The complex relationships between these factors have led to an initiative to develop an alternative backing material to replace RP1, as recommended in the National Research Council reports [8, 9]. The major requirements of the alternative backing material are that it provides desirable, predictable, and controllable properties. Our motivation for this research is to understand structure-processing-property relationships for BWM candidate materials and compare to the current RP1.

The Army Research Laboratory (ARL) has taken the lead to develop a replacement backing material, named ARTIC, and initial success has been achieved [10-11]. The name ARTIC is taken from ARL reusable, temperature insensitive "clay" [10]. The ARTIC material has fewer components, which is expected to show more consistent behavior. Freeney and Mrozek [10] reported that formulation of ARTIC can be tuned to match the behavior of RP1 at 100 °F (37.8 °C) in force penetration experiments, and they show that ARTIC materials are room temperature materials with no temperature dependence up to 100 °F. Those ARTIC materials satisfied the drop test requirements and yielded ballistic test results that were statistically similar to those obtained with RP1 as the BWM [10-11]. Furthermore, ARTIC materials show no ageing effect; the ballistic and indentation response does not change with time. To help with evaluation of the ARTIC material, we use thermo-rheological characterization methods to investigate the backing material.

2. EXPERIMENTAL[1]

2.1 Materials

Roma Plastilina No. 1 (RP1) clay was used as received from the manufacturer (Sculpture House, Springhill, NJ). The ARTIC materials were provided by the Army Research Laboratory (Aberdeen Proving Ground, MD) and were designated as ARTIC 5.5, ARTIC 6.5, and ARTIC 8.0 based on different formulations.

2.2 Characterization Methods

2.2.1 Differential scanning calorimetry (DSC)

Calorimetric measurements were performed under nitrogen flow using a TA Q2000 differential scanning calorimeter (TA Instruments, New Castle, DE). Two methods were employed: Method 1) A one-step heating scan at 10 °C/min from 25 °C to 300 °C and Method 2) a two-step heating scan at 10 °C/min from 25 °C to 130 °C, followed by an isotherm for 30 min at 130 °C to ensure dehydration, then heating up to 400 °C at 10 °C/min. For Method 1, hermetic aluminum pans were used; for Method 2, aluminum pans with pin hole lids were used. A second heating scan was also performed after cooling from 300 °C (Method 1) or 400 °C (Method 2) to 25 °C at 10 °C/min.

2.2.2 Rheology

Rheological experiments were performed using a rubber process analyzer RPA *elite* (TA Instruments, New Castle, DE) with enhanced air cooling system. The first advantage of the rubber process analyzer for measuring BWMs is that is offers a higher torque range for solid materials than that of a commercial rheometer, so that information under large deformation can be obtained. Second, it provides a consistent sample loading procedure, as ensured by the pressure pneumatic system together with the automated gap closure, such that the loading effects from sample to sample are minimized.

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[1] Certain commercial equipment, instruments, or materials are identified in this presentation in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Figure 1. Test specimen (Roma Plastilina No. 1) is placed between two sheets of polyester film for rheological tests using rubber process analyzer. The image shows the specimen in a pressed form after the test is done.

The specimen was cut in the form of a rectangular parallelepiped from a larger block of material as received using a stiff blade and weighs approximately 5 g to ensure consistency. The test specimen was then placed between two sheets of polyester film and loaded onto the lower platen of the instrument for measurements (Figure 1). Upon initiating the test, the platens automatically close to compress the test specimen between the biconical platens. Frequency sweep experiments were performed at 0.01° strain (equivalent to 0.14 % strain) from 0.05 Hz to 50 Hz at five temperatures: 20 °C, 25 °C, 30 °C, 40 °C, and 50 °C, which covers the operating temperature range for current RP1 calibration. Three samples were tested at 25 °C to obtain the standard deviation of the results.

3. RESULTS

Figure 2 shows the normalized DSC heat flow responses measured on heating at 10 °C/min for the three ARTIC materials. The dashed lines correspond to the results obtained from Method 1, one-step heating scan from 25 °C to 300 °C (see Section 2.2.1). First, there is no thermal transition in the temperature range of interest, i.e., 25 °C to 50 °C, which is in contrast to the complex thermal behavior of the RP1 clay [5]. Second, an endothermic melting peak is observed for all three ARTIC materials upon the first heating scan. The endothermic peak with a maximum at ≈ 290 °C relates to the cleavage of macromolecular chains, resulting in thermal degradation [12]. On the second heating scan, no melting transition is present (results not shown for brevity). The solid lines represent the results from a two-step heating method by first heating up to 130 °C and holding for 30 min, then heating up to 400 °C at 10 °C/min. The two-step DSC results are identical for all ARTIC materials, which is as expected because those ARTIC materials have essentially the same constituents, and the only difference is the amount of solids loading. No melting transition is observed before degradation, indicating that the melting peaks seen in Method 1 may be due to moisture involved structures [13]. The sample dehydrates during the isothermal holding step at 130 °C using a DSC pan with a pin hole lid.

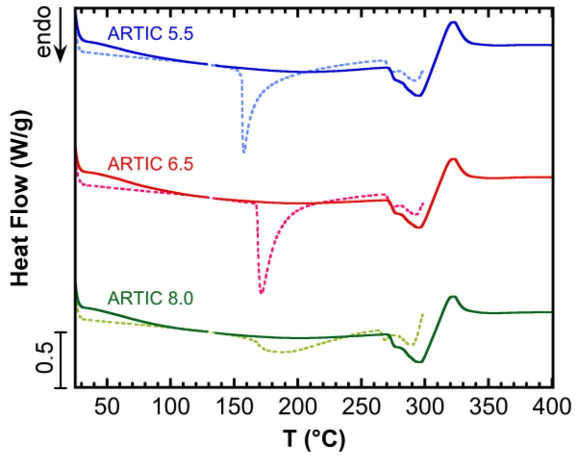

Figure 2. DSC heating scans at 10 °C/min for the ARTIC materials. The dashed and solid lines are results from Method 1 and Method 2, respectively. See Section 2.2.1 for details.

Figure 3 shows a double logarithmic plot of the dynamic storage modulus (G') as a function of frequency for the ARTIC materials and the RP1 clay. The trend of G' follows ARTIC 8.0 > ARTIC 6.5 > ARTIC 5.5, consistent with ARL's plateau modulus results from force penetration tests [10]. Second, the modulus of the RP1 clay shows a clear temperature dependence, i.e., G' decreases as temperature increases [7]. At 2 Hz, G' decreases from 14 MPa at 20 °C to 3 MPa at 50 °C for RP1 (Figure 4). For the ARTIC materials, the modulus data at different temperatures almost overlap with each other for each sample, indicating that the ARTIC materials are temperature insensitive within the measured temperature range (20 °C to 50 °C). In other words, ARTIC materials could be considered "room-temperature" backing materials, as shown in Figure 4 where G' at 2 Hz exhibits minimal temperature dependence. Furthermore, a stronger frequency dependence is observed for the RP1 clay. A weaker frequency dependency, as reflected in the ARTIC results, may be beneficial to reduce variations in material response when tested under different conditions.

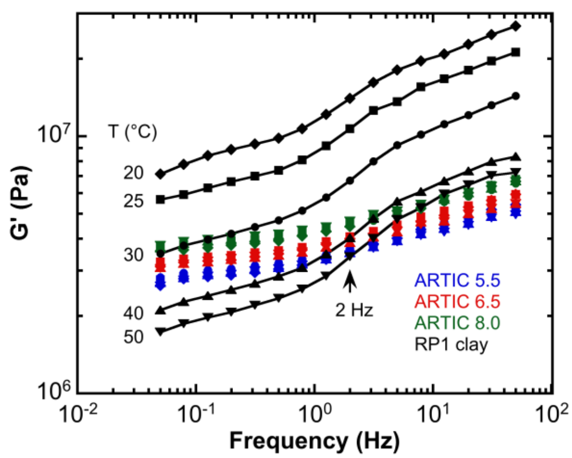

Figure 3. Dynamic shear storage modulus (G') as a function of frequency measured at a strain of 0.14 % (within linear range) at different temperatures ranging from 20 °C to 50 °C for the ARTIC materials and the RP1 clay [7]. Different symbols represent data points at different temperatures.

The RP1 clay is typically conditioned at or above 100 °F (~37.8 °C) to satisfy the drop test verification requirement. The G' data at different temperatures for all three ARTIC materials fall within the range of the 40 °C data of the RP1 over the same frequency range, suggesting that the ARTIC materials show promising properties as alternative BWMs. This also suggests that our approach of measuring G' may be used as a validation method to narrow down the formulations of ARTIC, similar to ARL's force penetration experiments where the responses of ARTIC were found to match the results of the RP1 clay at 40 °C [10-11].

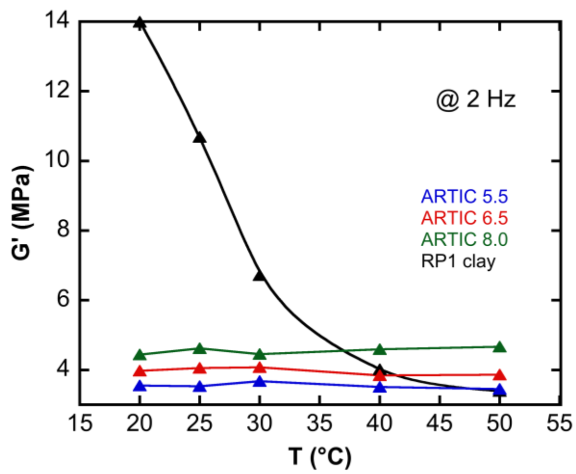

Figure 4. Dynamic shear storage modulus (G') as a function of temperature at 2 Hz from frequency sweep experiments (data extracted from Figure 3).

4. CONCLUSIONS

In this work, we used thermo-rheological methods to characterize the current standard backing material for body armour testing, Roma Plastilina No. 1 (RP1) clay, and a family of candidate backing materials, designated as ARTIC, developed by the Army Research Laboratory. The thermal studies show that there is no thermal transition in the temperature range of interest for the ARTIC materials, i.e., 20 °C to 50 °C, in contrast to the RP1 clay that exhibits complex thermal behaviour due to its multiphase formulation. The melting peaks observed using a hermetic pan for the ARTIC materials are absent after dehydrating the materials, indicating that the melting transitions may be caused by moisture involved structures. The effects of temperature on the rheological properties were investigated. The results show that ARTIC materials are promising room-temperature ballistic witness materials, as shown by minimal temperature dependence of the shear modulus and the agreement of the modulus data with those of the RP1 clay at the conditioning temperature for validation tests.

Acknowledgments

The authors thank Mr. Anicet Djakeu Samen for help with the rheological measurements.

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