IMPACT TOUGHNESS AND MOHS HARDNESS OF SIMPLE HYDROCARBON AND NITRILE ICES AT TITAN TEMPERATURES

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Introduction: Titan features many familiar terrestrial processes and landforms such as dunes and streambeds, but under exotic conditions (temperature, gravity, etc.) and with unfamiliar materials. Titan materials may include water ice, as well as photochemically-derived complex organics of arbitrarily high molecular weight ("tholins") may be rather hard. Because Titan has a hydrological cycle involving methane, low molecular weight organics such as benzene, alkanes, and acetonitrile could form bulk solid deposits by being dissolved by rainfall and precipitating as evaporites in dried-out lake beds, e.g. [1]. Many of these compounds are liquids at room temperature and are used as solvents. Here we freeze these materials and test their impact hardness with a view to providing a basis for interpreting Titan's geomorphology by analogy with the hardness of terrestrial rocks.

The presence of rounded cobbles at the Huygens landing site, and in 100-km-long streambeds [2], suggests that some Titan materials may be tough but somewhat ductile – deforming plastically rather than breaking in a brittle manner.

Test Methodology: We froze ~150ml cylindrical samples of standard laboratory solvents in liquid nitrogen. To obtain a semiquantitative measure of hardness (specifically the Young's modulus) we impacted the samples with an impulse hammer or penetrometer apparatus. This device (Figure 2) has a weighted ~10cm arm that is raised to a fixed stop and falls under gravity onto the sample: this measurement takes only seconds to perform, so can be performed at laboratory temperatures before the sample has time to warm up. A spherical indentor (a 12.7mm diameter steel ball bearing) on the underside of the arm impacts the sample, and the impact load pulse is recorded by a piezoelectric accelerometer (Endevco 2255) on the arm, the signal (typically a 0.5ms pulse) being recorded by a portable digital storage oscilloscope. The pulse height, indicating the peak deceleration, is proportional to $E^{2/5}$, where E is the Young's modulus. Relative results are indicated in Figure 1. Additionally, we performed some simple scratch tests, analogous to the Mohs hardness test familiar to field geologists, and report some simple observations.

Observations : The frozen texture of many of these materials was distinctive – see Figure 2. We did not anneal our water ice samples, thus they were typically crazed with cracks from expansion during freezing. As has been observed before, frozen ammonia solution looked glassy, with regular polygonal cracks at a spacing of roughly 1cm. All the hydrocarbons and nitriles studied formed white solids, sometimes waxy in appearance. Methanol was more transparent, with ~2-3mm wide needle-like crystals.

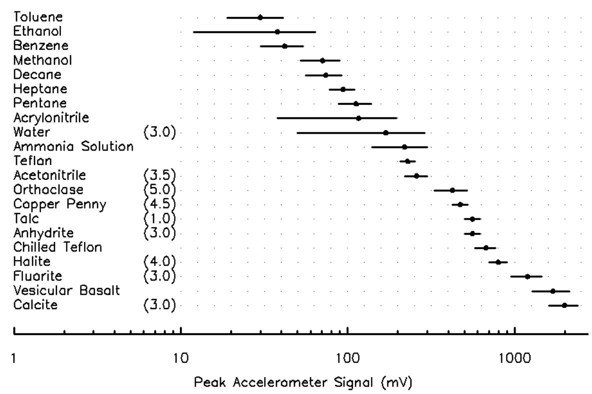

Figure 1: Results showing the relative impact hardness of materials (softest at the left). Bars show variation among typically ~5 tests: the Mohs scale values for known materials are listed in parentheses.

We did not conduct any experiments in this campaign on condensed gases, but we record here the observation that in preparing hydrogen cyanide for a previous spectroscopic study, at ~80K it has mechanical properties resembling those of stiff molasses. While acetonitrile has a Young's modulus that is modest compared with hard terrestrial rocks such as basalt, we noted that it is more or less impossible to crush bulk acetonitrile in a mortar and pestle (whereas the 'harder' rocks are straightforward to grind up with some effort). This presumably reflects the different measures of strength – acetonitrile is hard enough to resist elastic or plastic deformation under pestle loads, but does not fracture as easily as stiffer materials. In this connection, we have separately cast a small (4cm diameter, 1 cm thick) ingot of phenanthrene (a polycyclic aromatic hydrocarbon $C_{14}H_{10}$: this three-ring compound arguably may be somewhat representative of Titan's dune-forming materials). This slab (formed by melting granules at 375K) after immersion in liquid nitrogen could be scratched by water ice, and could be easily crushed by a pestle. Paraffin wax similarly cast became opaque and very brittle in liquid nitrogen - readily crumbling when agitated by a magnetic stirrer.

Results: Because the organic ices would melt on contact, comparison materials had to be chilled for scratching. We therefore also established that the Mohs hardness of comparison ('terrestrial') materials chilled to liquid nitrogen temperatures were the same as for room temperature (the ratio of ambient temperature to melting point being low in either case). We found that acetonitrile can be scratched by a steel knife blade, and by apatite (5). Cold fluorite (4) and acetonitrile can scratch each other. Acetonitrile can scratch cold calcite (3), but not a copper penny (3.5). These slightly discrepant data suggest a Mohs hardness of 3 to 4 for acetonitrile. Water ice can be scratched by a knife blade, fluorite and even a fingernail, suggesting a hardness of 2 or less. Separately, we obtained a small sample of tholin (pieces of a brittle orange film, about 0.7cm long, and less than 1mm thick) but it proved impossible to perform a scratch test without fracturing it.

It is notable that acetonitrile was appreciably tougher than ice (Figure 1). The alkanes and aromatics behaved as waxy, plastic solids, and were rather soft. All the ices investigated were colorless or white. Given the observed dark colour of Titan's sand seas, it is likely they are a more complex, carbon-rich composition.

Conclusions: Our macro-scale results are broadly consistent with recent nanoscale indentation experiments [3] which showed that tholin had a hardness and Young's modulus about an order of magnitude smaller than quartz sand and similar to gypsum; compounds intermediate in molecular weight between our frozen solvents and tholin, e.g. naphthalene and phenanthrene, had a hardness about an order of magnitude lower than tholin. While the materials studied so far are soft indeed compared with many terrestrial rocks, it should be remembered that the driving energies behind processes on Titan are commensurately smaller, owing to the low temperature and solar flux available, and the lower gravity. The generation of a similar landscape on Titan to that of the earth can therefore be understood, but is no less wonderful.

References: [1] Cordier, D., et al. (2016) Icarus, 270, 41 [2] Le Gall, A., et al. (2010) Icarus, 207, 948 [3] Yu, X. et al. (2018) LPSC IL Abstract 1786.

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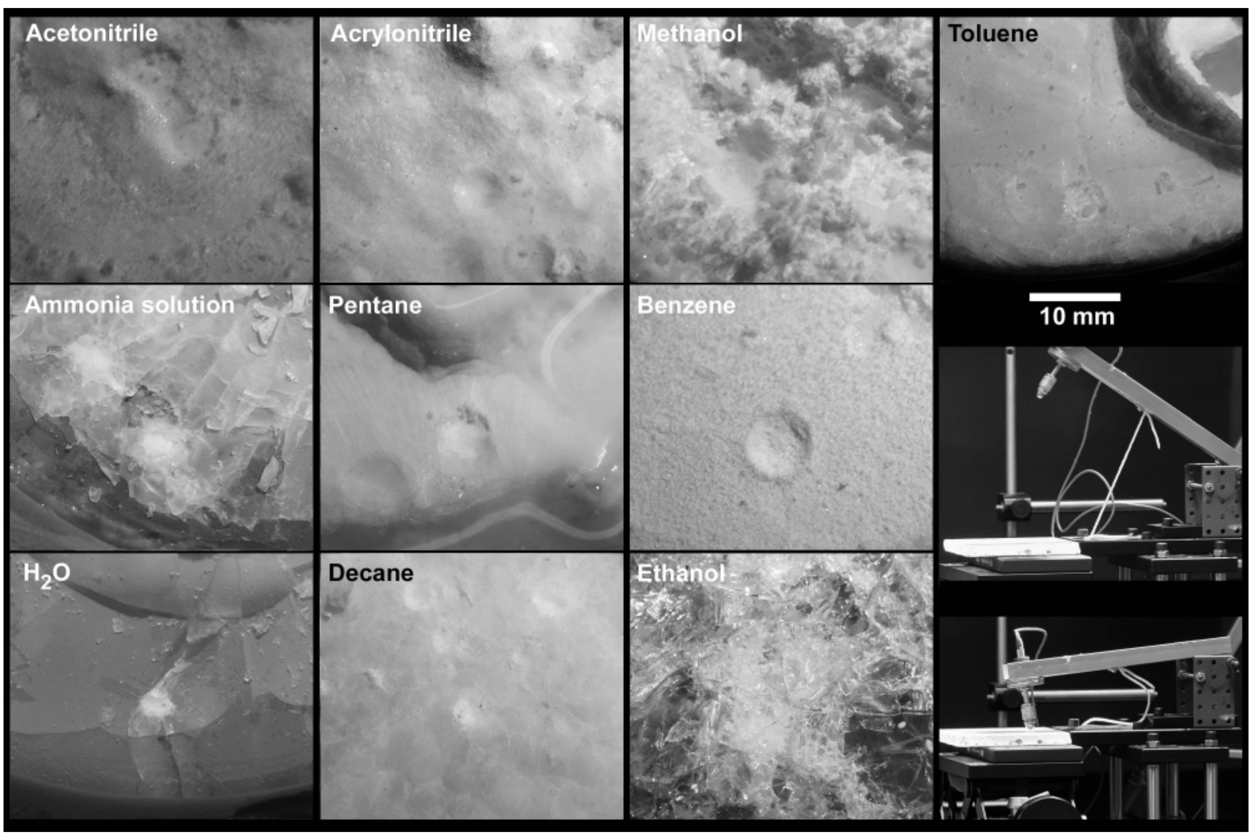

Figure 2: The different textures of the materials tested. The indenter apparatus is seen at lower right (not at the same scale as the closeup textures to which the scale bar applies). Alkanes, benzene and toluene appear waxy and deform rather plastically; the nitriles were appreciably harder. Water and water-ammonia ices experienced brittle failure, as did the alcohols.