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Résumé

Les auteurs présentent des données sur la salinité, la masse volumique, la granulométrie et la morphologie, la résistance à la compression uniaxiale et le module de rupture d'échantillons de vieille glace de mer et de glace saumâtre, prélevés sur la plate-forme de glace Ward Hunt de l'île Ellesmere au Canada. La salinité moyenne de la glace saumâtre (0,3 $^{0}/00$) est inférieure d'un ordre de grandeur à celle de la glace de mer (1,59 $^{0}/00$) et la structure de la glace saumâtre est beaucoup plus variable que celle de la glace de mer. À une vitesse de déformation nominale de $1 \times 10^{-5} s^{-1}$, la résistance de la glace et le module de rupture varient respectivement de 1,7 à 8,9 MPa et de 0,9 à 2,6 GPa. À une vitesse de déformation nominale de $1 \times 10^{-3} s^{-1}$, la résistance de la glace et le module de rupture varient respectivement de 3,8 à 15,0 MPa et de 1,1 à 8,3 GPa. Les échantillons de glace de mer présentent des valeurs de résistance plus élevées que les échantillons de glace saumâtre, et la résistance ainsi que le module de rupture de la vieille glace semblent peu différer de ceux de la glace «moderne». Les propriétés physiques et structurales de la glace de mer et de la glace saumâtre sont discutées en rapport avec leurs propriétés mécaniques distinctes et avec la validité de la comparaison de glaces d'âges sensiblement différentes.

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INITIAL MECHANICAL AND PHYSICAL-STRUCTURAL PROPERTY MEASUREMENTS OF OLD SEA AND BRACKISH ICE FROM WARD HUNT ICE SHELF, CANADA

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ABSTRACT

Data are presented on ice salinity, density, grain size and morphology, uniaxial compressive strength and failure modulus for old sea and brackish ice specimens from Ward Hunt Ice Shelf, Ellesmere Island, Canada. Brackish ice mean salinity (0.3°/₀₀) is an order of magnitude less than that of sea ice (1.59°/₀₀), and brackish ice structure is much more variable than sea ice. At a nominal strain rate of 1×10^{-5} s^{-1} ice strength and failure modulus range from 1.7 to 8.9 MPa and 0.9 to 2.6 GPa respectively. At a nominal strain rate of 1×10^{-3} s^{-1} ice strength and failure modulus range from 3.8 to 15.0 MPa and 1.1 to 8.3 GPa respectively. The sea ice specimens have higher strength values than the brackish ice specimens, and the ice strength and failure modulus do not appear to differ significantly from "modern" ice. The physical-structural properties of the sea and brackish ice are discussed with respect to their differing mechanical properties, and the validity of comparing ice that differs significantly in age.

INTRODUCTION

The fast ice fringe along the north coast of Ellesmere Island, NWT, Canada, comprises ice shelves and multiyear landfast sea. Occasional calvings from the fast ice produce thick sea ice floes and ice islands (tabular icebergs). The ice islands are of particular interest, since they are the most massive ice features in the Arctic Ocean. Though they are relatively rare, their drift with the pack ice in the Beaufort Gyre takes them into the coastal waters of the Beaufort Sea where they are recognized as a potential hazard to bottom-founded offshore structures.

A frequent source of ice islands during the last 25 years has been the Ward Hunt Ice Shelf (83°N, 74°W). The ice shelf is 40-50 m thick, about 440 km^2 in area, and it has a complex structure of iced-firn, fresh, brackish and sea ice (Lyons et al., 1971; Jeffries et al., 1988a). Though the physical and structural properties of ice in Ward Hunt Ice Shelf are quite well documented, there have been no measurements of ice mechanical properties. Elsewhere in this conference proceedings, Frederking et al. (1988) report the first mechanical property measurements of iced-firn from an ice island, i.e., "Hobson's Choice" ice island that calved from Ward Hunt Ice Shelf in 1982-83. Here, we report the first mechanical property measurements on old, undeformed sea and brackish ice from Ward Hunt Ice Shelf.

SPECIMEN ACQUISITION, PREPARATION AND TESTING

In March 1986 a 10.28 m long, 76mm diameter ice core was drilled from Ward Hunt Ice Shelf, in an area where sea and brackish ice had been previously identified (Lyons et al., 1971). The core was drilled in temperatures <-40°C using a CRREL-type ice coring auger. All specimens were packed and sealed in polythene bags, and subsequently shipped to Resolute Bay and stored at -18°C.

In June 1986 ice samples were taken for salinity and stable isotope analysis (for analytical methods see Jeffries et al., 1988a) and bulk density was measured by weighing in air on a triple beam balance. The remaining core specimens were stored in Resolute Bay until November 1987 when 15 specimens were shipped to Ottawa. Some melting occurred on the outer parts of the specimens, but it is believed not to have significantly altered the ice properties. In December 1987, mechanical property measurements were made, as were further physical property measurements.

A horizontal thin section of each specimen was prepared and photographed in polarized light, and bulk density was measured prior to testing. Fourteen test specimens were prepared on a lathe and reduced to diameters in the range 58.6 to 69.6 mm. The ends of the specimens were finished with a band-saw and emery paper. Eight specimens had length-diameter ratios exceeding 2, the remainder were <2. Uniaxial compression tests were performed using a 100 kN capacity "Instron" model TTDM-L test machine with a swivel-head platen. Specimens were mounted vertically with respect to the ice shelf surface, and 100 mm guage length extensometers were fitted for specimen deformation measurements. Six specimens were tested at a nominal strain rate of 1×10^{-3} s^{-1} and one at 1×10^{-4} s^{-1}, the other seven were at 1×10^{-5} s^{-1}, at -10°C. After the tests were complete, some vertical thin sections were prepared and photographed in polarized light. Also, ice samples were taken for additional salinity and stable isotope analysis.

RESULTS

Brackish ice grows from water with a salinity of 1-24.7°/₀₀, and sea ice grows from water with a salinity >24.7°/₀₀. In the case of Ward Hunt Ice Shelf stable isotopes can be used to determine the salinity of the water from which ice has grown. The results of the stable isotope analysis of core 86-8 are not presented here, but the application of stable isotope measurements to the recognition of fresh, brackish and sea ice is discussed elsewhere (Jeffries et al., 1988b). According to the stable isotope measurements ice core 86-8 comprises 73% brackish ice, 24.3% sea ice and 2.7% fresh ice. The sea ice and brackish ice occur in alternating layers, with the sea ice being found in two thin layers at 2.2-2.5 m and 5.25-6.5 m (Fig. 1a). It is apparent from the ice salinity profile that the sea ice is more saline than the brackish ice (Fig. 1a). The salinity and density of sea and brackish ice are summarized in Table 1. There is very little difference in the density of each ice type, but sea ice is an order of magnitude more saline than brackish ice.

The test specimens for this study are quite representative of the entire ice core (Fig. 1a). Eleven (77%) specimens are brackish ice and three (23%) specimens are sea ice. Salinity, density and grain size data for the test specimens are summarized in Table 2. The salinity and density data from the test program are very similar to the data obtained in June 1986; this suggests that the ice properties remained largely

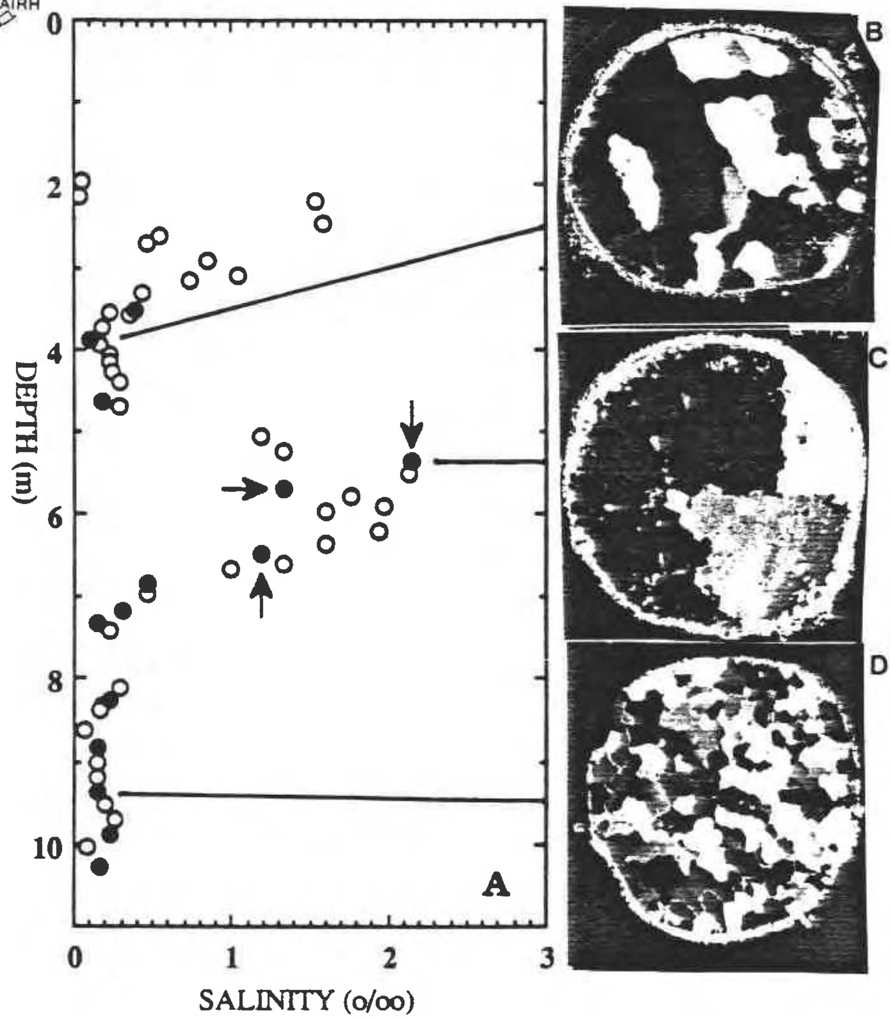

Figure 1. A: Salinity profile of ice core 86-8 (solid circles and arrows denote test specimens and sea ice specimens respectively). B: Horizontal thin section of brackish ice, Specimen #1721. C: Horizontal thin section of sea ice, Specimen #1734. D: Horizontal thin section of brackish ice, Specimen #1760. Major sub-divisions on the scale measure 10 mm.

Table 1. Summary of ice salinity and ice density of sea and brackish ice in ice core 86-8.

		Brackish Ice	Sea Ice
Salinity	Range	0.03 to 1.19	0.46 to 2.15
(°/oo)	Mean	0.3 ± 0.27 (n = 28)	1.59 ± 0.5 (n = 9)
Density	Range	890 to 919	891 to 926
(kg/m^3)	Mean	912 ± 8 (n = 18)	914 ± 10 (n = 7)

Table 2. Salinity, density and grain size of test specimens. (B: brackish ice, S: sea ice).

Specimen No.	Depth (m)	Salinity (‰)	Density (kg/m^3)	Mean Grain Diameter (mm)
1716	3.53	0.38 B	908	16.0
1721	3.90	0.10 B	908	13.3
1728	4.63	0.18 B	908	7.7
1734	5.27	2.15 S	912	41.6
1736	5.70	1.33 S	887	24.0
1743	6.48	1.19 S	902	26.8
1746	6.83	0.46 B	910	10.3
1748	7.16	0.30 B	912	13.5
1749	7.32	0.15 B	912	12.3
1752	8.26	0.22 B	908	8.4
1757	8.83	0.15 B	909	9.7
1760	9.38	0.15 B	907	7.2
1764	9.88	0.23 B	907	6.4
1766	10.28	0.16 B	896	10.6

unchanged during storage and transportation. Structurally the sea ice has a larger grain size than the brackish ice (Table 2). The large sea ice grains have sutured, interlocking grain boundaries (Fig. 1c), and the grains are massive, long columns (exceeding specimen length) in vertical section. The brackish specimens have a more variable structure than the sea ice specimens; brackish ice structures vary from those close to sea ice, to those that closely resemble freshwater ice, and from fine to coarse grained. Two freshwater ice-like specimens are shown in Figs 1b and 1d; the boundaries are slightly irregular and there is some interlocking of the equi-axed (Fig. 1d) and the elongate (Fig. 1b) crystals. In vertical section the brackish ice has a quasi-columnar structure of grains with length-width ratios of 4-5, maximum length of 50mm, and slightly irregular grain boundaries. In the sea ice specimens there was evidence of a platelet sub-structure, but it consisted of discrete brine inclusions with few inter-connections. There were few inclusions in brackish ice, and no evidence of a platelet sub-structure. Lyons (personal communication) found the brackish ice from this part of Ward Hunt Ice Shelf to be columnar with irregular grain boundaries, and it did not have the platelet sub-structure that is so characteristic of sea ice (Lyons et al., 1971).

The results of the mechanical property measurements are summarized in Table 3. The method used to correct the nominal strain rate, and definitions of time to failure, strength, failure modulus, etc. are given in a companion paper at this Symposium (Frederking et al., 1988). The effect of making the strain rate correction is quite significant, reaching a full order of magnitude, particularly at the higher strain rates (Table 3).

Table 3. Results of Mechanical Property Measurements of Sea and Brackish Ice Specimens at -10°C.

Specimen Number	Time to Failure(s)	σ (MPa)	E_f (GPa)	$\dot{\epsilon}_{nom.}$ ($1x10^{-5}$ s^{-1})	$\dot{\epsilon}_{corr.}$ ($1x10^{-5}$ s^{-1})	$\Delta\dot{\epsilon}$ ($1x10^{-5}$ s^{-1})
1716	390	1.7	1.0	0.9	0.50	0.40
1734	690	8.9	-	1.5	1.15	0.35
1736	660	5.8	2.2	1.1	0.84	0.26
1748	440	3.5	2.6	1.0	0.61	0.39
1752	300	4.1	-	1.5	0.61	0.89
1760	400	2.4	1.2	1.1	0.60	0.50
1766	450	1.9	0.9	0.9	0.55	0.35
				($1x10^{-3}$ s^{-1})	($1x10^{-3}$ s^{-1})	($1x10^{-3}$ s^{-1})
1721	52.0	3.8	-	0.15	0.05	0.10
1728	6.6	7.3	1.1	0.85	0.43	0.42
1743	10.5	15.0	-	1.50	0.46	1.04
1746	7.1	11.2	8.3	1.43	0.49	0.94
1749	6.4	6.7	-	1.41	0.49	0.92
1757	6.9	8.7	1.3	0.97	0.44	0.53
1764	7.4	7.3	3.4	1.13	0.43	0.70

Ice strength data are plotted versus the corrected strain rate in Fig. 2. Ice strength varies from 1.7 to 8.9 MPa, and from 3.8 to 15.03 MPa at the low (10^{-5}) and high (10^{-3}) strain rates respectively (Fig. 2, Table 3). At both low and high strain rates the sea ice, which is more saline and has larger grains than brackish ice, is also stronger than brackish ice (Fig. 3a, 3b). No trend is apparent in the relationship between ice strength and density for both ice types at high and low strain rates, and this is not illustrated.

Values for failure modulus are not available for all specimens; those that are range from 0.9 to 8.3 GPa (Table 3). The relatively wide range of failure modulus values is plotted against corrected strain rate (Fig. 4), and there is the suggestion of a trend of increasing modulus with increasing strain rate.

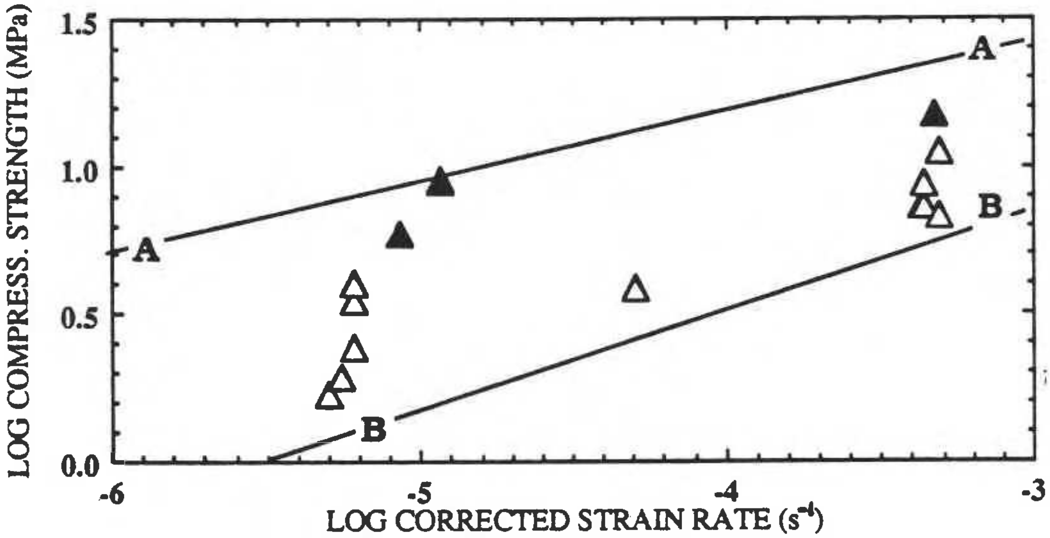

Figure 2. Scatter plot of the log of ice strength versus the log of corrected strain rate (solid triangles denote sea ice specimens). Line A-A represents data for vertically oriented columnar sea ice (Sinha, 1983); line B-B represents data for horizontally oriented fine-grained frazil sea ice (Sinha, 1986).

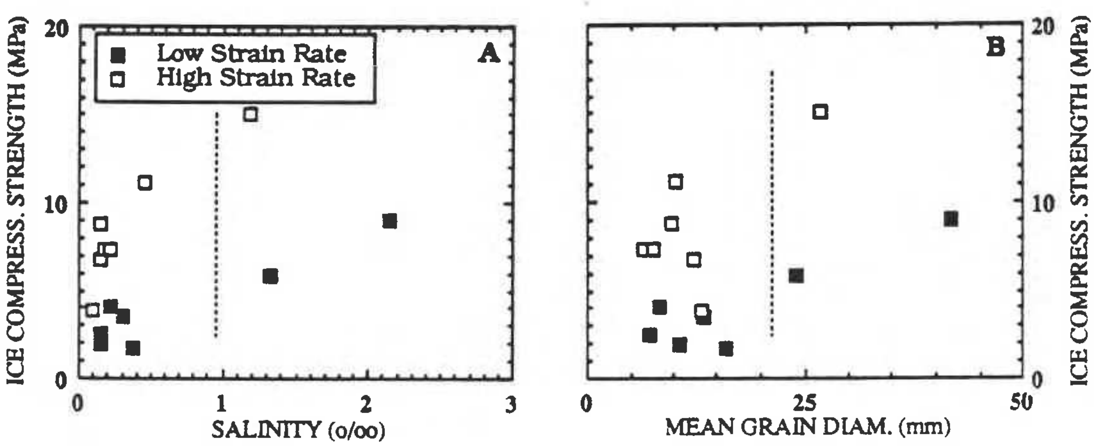

Figure 3. A: Scatter plot of ice strength versus ice salinity at low and high strain rates. B: Scatter plot of ice strength versus mean grain diameter at low and high strain rates The dashed lines separate the brackish ice specimens from the sea ice specimens.

DISCUSSION

Ice core 86-8 was drilled from an area of Ward Hunt Ice Shelf where it is almost 50 m thick (Lyons et al., 1971), and where the ice accreting at the bottom of the ice shelf takes as much as 500 years to reach the surface (Crary, 1960). Thus, the physical and mechanical property data

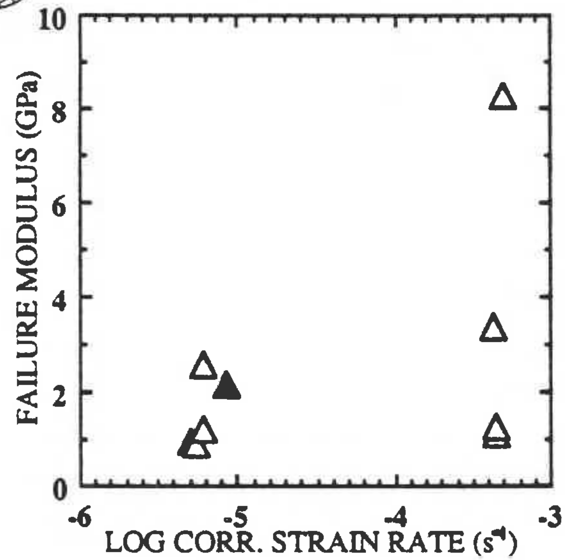

Figure 4. Scatter plot of failure modulus (E_f) versus the log of corrected strain rate (solid triangle denotes sea ice).

obtained in this study are for ice that is probably 400-500 years old. With the exception of some measurements of the mechanical properties of specimens from deep ice cores in Greenland and Antarctica (e.g., Pimienta et al., 1988) there have been few studies of ice of this age, particularly ice of marine origin.

Despite its age the ice has retained a significant and measurable amount of brine. In the sea ice specimens the brine is probably contained in the inclusions that are remnants of the original platelet sub-structure. Re-texturing during the 400-500 year passage from the bottom to the top of the ice shelf might account for changes in the sea ice sub-structure. The absence of a platelet sub-structure in brackish ice might also be attributed to re-texturing; however, no platelet sub-structure was found in young brackish ice near the base of the ice shelf (Lyons et al., 1971). The process of brine inclusion into brackish ice is not well understood, but it must be related to the nature of the ice-water interface and water salinity. In this regard, since brackish ice grows from lower salinity water than sea ice, there must be less brine available for inclusion in brackish ice; hence, brackish ice has a lower salinity than sea ice (Table 1).

Although the ice is very old, the ice strength data compare well with data for "modern" ice. In particular it is noted that the sea ice specimen strengths do not exceed those found in other tests on vertically oriented columnar sea ice (Sinha, 1983; Line A-A, Fig. 2). The modulus data also compare quite well with "modern" ice values, including the trend of increasing failure modulus with increasing strain rate (Sinha, 1986). The patterns observed in Fig. 2 are also similar to those observed in recent studies of the mechanical properties of multiyear ice (Cox et al., 1984). In the study by Cox et al., as in other studies, the scatter in ice strength values has been attributed to variations in the physical-structural properties of the ice. The observed physical-structural properties of the sea and brackish ice specimens are related to, 1) the original growth conditions and processes at the base of the ice shelf, and 2) changes that have occurred as the ice has aged and passed from the base to the surface of the ice shelf. Neither of these factors is well known or understood, but they are likely to be different from those below annual or multiyear ice. Also, the aging process has probably involved some kind of temperature gradient metamorphism, particularly in the uppermost 10 m where seasonal temperature changes occur. These factors must be remembered when the ice strength of 400-500 year old sea and brackish ice is compared with "modern" ice.

Rather than compare strength data for ice types that differ significantly in age, it is more appropriate to compare the sea ice with the brackish ice. Perhaps the most significant of the ice properties with regard to ice strength are the massive, long columnar grains of the sea ice. When loaded vertically, the columnar structure of a sea ice specimen presents grain boundaries that are not oriented for easy occurrence of internal cracking. The interlocking grain boundaries of the sea ice (Fig. 1c) probably also contribute to the high strength. Unlike the sea ice grains the brackish ice grains are smaller in horizontal and vertical section, with less irregular grain boundaries; hence, internal cracking will occur more easily and the strength of brackish ice will be lower than that of sea ice (Fig. 3b). In sea ice failure planes frequently coincide with the salt inclusions between ice platelets (Schwarz and Weeks, 1977). In the sea ice studied here, although a significant amount of brine is retained in the ice, it is evident that the platelet sub-structure has been altered by age and temperature cycles. This alteration would have decreased the number of potential failure surfaces, hence the high strength values. As for the brackish ice, too little is known of its original or altered substructure to suggest its affect on ice strength.

CONCLUSION

Preliminary mechanical property measurements on sea and brackish ice from Ward Hunt Ice Shelf suggest that it does not differ substantially from other types of ice found in nature. However, comparisons with "modern" ice might be inappropriate because the ice studied here is without doubt much older than any marine ice on which mechanical property measurements have been made to date. The ice has unusual physical-structural properties that probably owe their origin in part to growth conditions and processes at the base of the ice shelf, and in part to processes occurring as the ice has aged and passed from the base to the surface of the ice shelf. The data presented in this paper is the first of its kind and suggests the need for further work on the physical, structural and mechanical properties of the sea and brackish ice. Though this ice might be considered somewhat exotic, it should be remembered that this ice probably occurs in other arctic ice shelves, and a modern equivalent is common in the multiyear landfast sea ice in this region (Jeffries et al., 1988b). Thus, it will be found in thick sea floes and ice islands, for which extensive and systematic mechanical property measurements have yet to be done.

ACKNOWLEDGEMENTS

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