AGE HARDENING OF SNOW AT THE SOUTH POLE

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Abstract. The age hardening of artificially and naturally compacted snow has been investigated at the South Pole. Results show that the age-hardening process is greatly retarded at low temperatures. Artificially compacted samples of density 0·55 g./cm.³ attained a compressive strength of less than 3·0 kg./cm.² after one year's ageing at −49° C. Exposure to solar radiation accelerated the age hardening. Irradiated samples attained a strength of 6·0 kg./cm.² after 100 hr., increasing to a virtual maximum of 8·0 kg./cm.² at the end of 600 hr. Compressive strengths increased with decrease in snow-particle size and with increasing angularity of the particles. Below 3 m. the strength of naturally compacted snow was found to increase rapidly with increase in density. Naturally compacted snow of density 0·55 g./cm.³ possessed considerably greater strength than any of the age-hardened samples of artificially compacted snow of the same density. Thin-section studies show that age hardening can be correlated with the formation and growth of intergranular bonds, and that bond growth falls off rapidly with decreasing temperature. In view of the low strengths found in both naturally compacted snows near the surface and in artificially compacted snow at the South Pole, "cut-and-cover" under-snow camp construction may not prove too practical at the South Pole.

Résumé. La cohésion en fonction du vieillissement de la neige tassée artificiellement et naturellement a été étudiée au pôle Sud. Les résultats montrent que le processus de variation de cohésion en fonction du vieillissement est grandement retardé aux basses températures. Des échantillons artificiellement tassés de densité 0,55 g/cm³, ont atteint une résistance à la compression de moins de 3,0 kg/cm², après une période de 1 an à −49° C.

L'exposition à la radiation solaire accélère la cohésion en fonction du vieillissement. Des échantillons irradiés ont atteint une résistance de 6 kg/cm² après 100 heures croissant jusqu'à un maximum virtuel de 8 kg/cm² après 600 heures. La résistance à la compression croît avec la décroissance de la dimension des particules de neige et avec l'angularité croissante des particules. En-dessous de 3 mètres, la résistance de neige naturellement tassée croît rapidement avec l'accroissement de densité. Une neige tassée naturellement d'une densité 0,55 g/cm³ possède une résistance considérablement plus grande que tous les échantillons vieillis de neige artificiellement tassée ayant même densité. Des études de lames minces montrent que la variation de cohésion avec l'âge peut être reliée à une formation de liaisons intergranulaires et que cette croissance des liaisons diminue rapidement avec une température décroissante.

Par suite des faibles résistances trouvées à la fois dans les neiges naturellement tassées près de la surface et dans la neige artificiellement tassée au pôle Sud, la construction d'un camp sous la neige par la technique de "couper et couvrir" peut ne pas être très efficace au pôle Sud.

Zusammenfassung. Es wurde die durch Alterung hervorgerufene Verfestigung von künstlich und natürlich verdichtetem Schnee am Südpol untersucht. Die Ergebnisse zeigen, dass der Prozess der Altersverfestigung bei niedrigen Temperaturen stark verzögert ist. Künstlich verdichtete Proben der Dichte 0,55 g/cm³ erreichten nach einem Jahr Alterung bei −49° C eine Kompressions-festigkeit von weniger als 3,0 kg/cm². Sonnenstrahlung beschleunigte die Altersverfestigung. Bestrahlte Proben erreichten nach 100 Stunden eine Festigkeit von 6,0 kg/cm², die nach 600 Stunden einem virtuellen Maximum von 8,0 kg/cm² zustrebte. Die Kompressionsfestigkeit stieg an mit abnehmender Grösse und mit zunehmender Eckigkeit der Schnee-Teilchen. Es wurde gefunden, dass unterhalb 3 m die Festigkeit von natürlich verdichtetem Schnee mit zunehemender Dichte rasch anwächst. Natürlich verdichteter Schnee der Dichte 0,55 g/cm³ besass eine beträchtlich grössere Festigkeit als irgendeine der durch Alterung verfestigten Proben von künstlich verdichtetem Schnee derselben Dichte. Dünnschnittstudien zeigen, dass die Altersverfestigung mit der Bildung und dem Wachstum von Bindungen zwischen den Teilchen in Beziehung gebracht werden kann, und dass das Wachstum der Bindung mit abnehmender Temperatur rasch nachlässt. Im Hinblick auf die niedrigen Festigkeiten, wie sie sowohl in dem oberflächennahen natürlich verdichteten als auch in dem küstlich verdichteten Schnee am Südpol gefunden wurden, mag sich die "cut-and-cover" Bauweise von Lagern unter dem Schnee am Südpol als nicht zu praktisch erweisen.

Introduction

The object of this paper is to present the results of some recent studies of the age hardening of artificially and naturally compacted snows at the South Pole. Prior to this study very little was known as to the rate of age hardening, or the ultimate strength of snow at very low temperatures. In view of the proposed construction of a new camp under the snow at the South Pole, such data became most desirable. Under-snow construction was successfully accomplished by the U.S. Army in Greenland, and it is hoped that the same methods can be applied in the Antarctic. In the present investigations, therefore, an attempt was made to prepare snow samples which simulated, in density and grain size, the disaggregated snow produced by the Peter snow miller and used extensively in under-snow camp construction. Of particular interest was to evaluate the effect of the very low temperatures at the South Pole on the age-hardening process. The effects of solar radiation, grain size and grain shape on the age hardening of snow were also investigated. These investigations were supplemented by thin-section studies to determine changes in the structure of the snow as it aged.

Previous Work

Extensive tests on the strength properties of snow have been made by Butkovich (1956). These investigations conducted primarily on old snow that had reached its maximum strength over a long period of time showed that the compressive strength of the snow increased linearly with density. Studies of age hardening (the increase of strength of disaggregated snow with time) by Bender (1957) indicated that the strength of bonds between grains in test samples

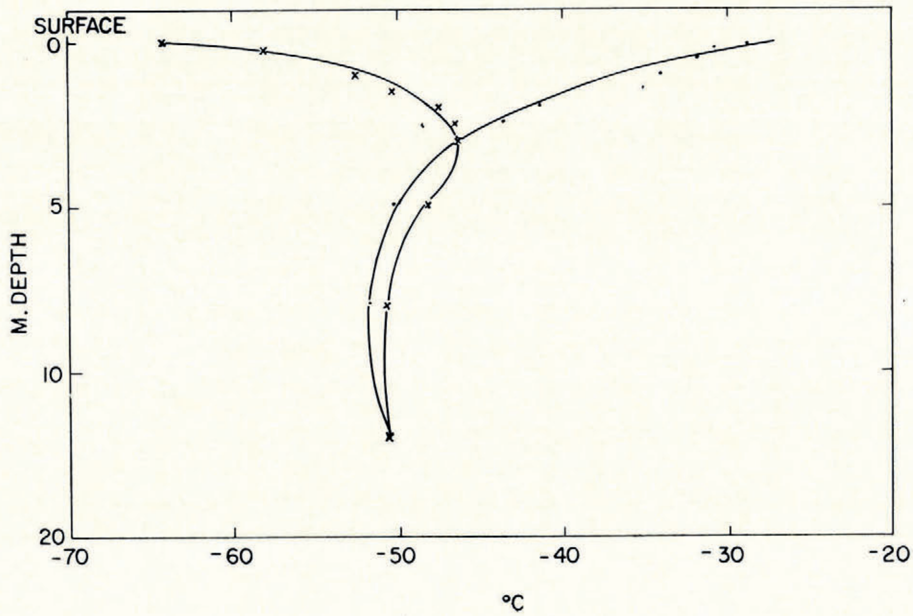

Fig. 1. Snow temperature profiles at the South Pole (after Giovinetto, 1960). Points · correspond to 3 February 1958; points × correspond to 5 April 1958

increased very rapidly during the first four days and attained close to maximum strength in ten days. In 1957 Jellinek carried out more detailed studies of the compressive strength of artificially compacted snow cylinders as a function of age of the snow, snow-particle size and amount of age hardening. His results show that young snow hardens (strengthens) more rapidly than old snow under the same conditions of ageing, and that the ultimate strength diminishes with decrease in grain size. Field studies on the changes in snow structures with ageing have been reported by Fuchs (1959, 1960), Butkovich (1962) and Wuori (in press). All these studies indicate that age hardening of snow involves the formation of bonds between grains, and that the strength of the snow seems to be determined very largely by the number and size of intergranular bonds. Koch and Wegener (1930) used this principle in their north Greenland expedition in 1913. They mixed ice chips with snow to build bridges across crevasses which could be crossed by horses and sledges the following day. Recently, Kingery (1960) and Kuroiwa (1961) have compared the kinetics of the freezing together of ice particles (and the resultant formation of bonds) with those derived from sintering phenomena. All the above studies were performed at temperatures varying from −7° C. to −20° C., and the object of the present study was to extend current knowledge of age hardening to the low-temperature conditions prevailing at the South Pole.

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Experimental Methods

Cylindrical snow samples used in the age-hardening studies were all prepared from a standard mixture of disaggregated snow. A 4 m. pit was dug for this purpose on 6 December 1960. A preliminary study of the pit stratigraphy showed that snow now buried to a depth of

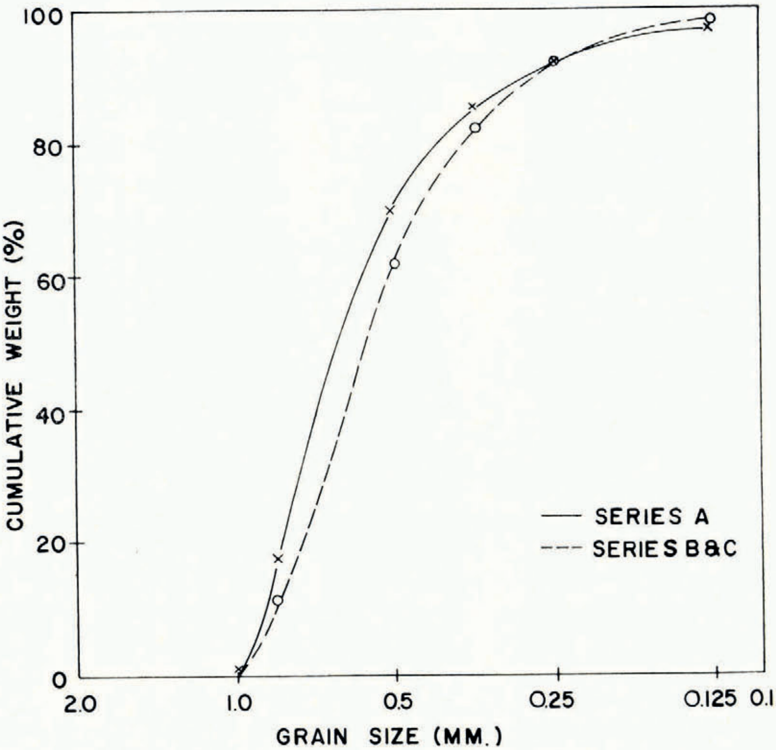

Fig. 2. Grain-size analyses of disaggregated snow

4 m. was deposited at the surface 21 yr. ago. This gives an accumulation rate of about 7·4 cm. of water per year. Densities vary considerably from layer to layer. The density in the first meter averaged 0·36 g./cm.^{3} and increased to 0·42 g./cm.^{3} at 4 m. depth. The temperature varied from −30° C. in the surface layers to −47° C. at 4 m. Temperature profiles for the late summer and fall from the surface to 10 m. are given in Figure 1.

Blocks of snow were cut in continuous vertical sequence from one wall of the pit and disaggregated on a large sieve of 1·0 mm. mesh. All grains larger than 1·0 mm. were discarded and the remainder were thoroughly mixed to form the standard sample material. Results of sieve analyses of two arbitrary samples from this snow mixture are given in Figure 2.

These curves compare rather closely with the size distributions observed in well-sorted, medium- to coarse-grained sands.

The compaction apparatus for making the snow test cylinders consisted of two half cylinders of aluminum coated on the inside with "Teflon". The two half cylinders were assembled and mounted on a circular base plate, and the snow was added in small amounts and tamped periodically with an aluminum plunger. After compaction the two half cylinders were disconnected, and the artificially compressed snow cylinder (diameter 5·7 cm., length 20·0 cm.) was carefully removed. With this method it was possible to prepare test samples of almost constant density (0·554 ± 0·005 g./cm.³) at a rate of about 40 cylinders per hour. Several series of snow cylinders were prepared and subjected to ageing under varied conditions. Each series consisted of 8 to 13 groups of samples, and each group contained 8 to 10 samples.

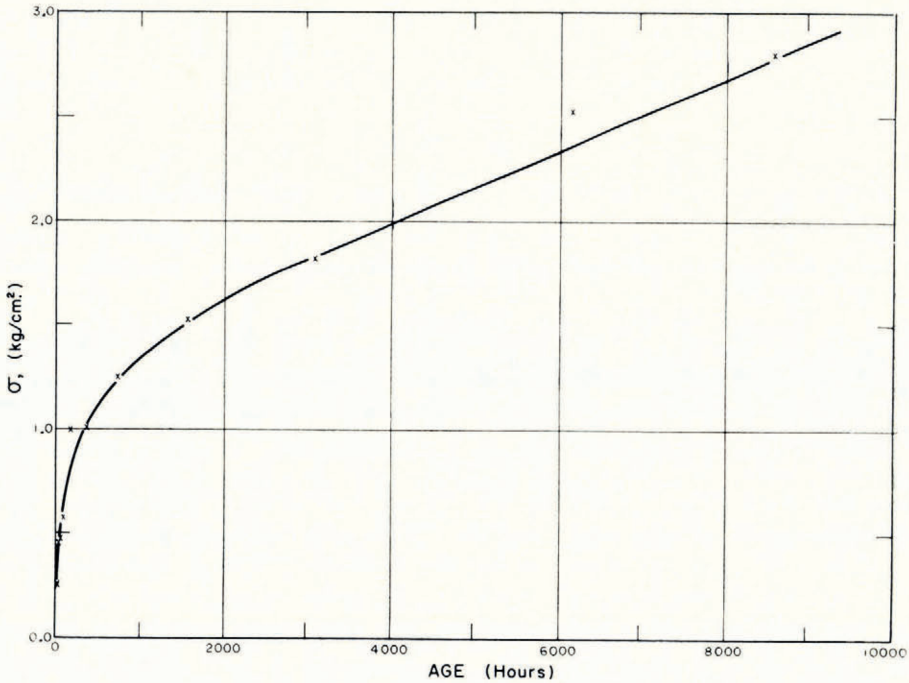

Fig. 3. Unconfined compressive strength of snow cylinders as a function of the age of the cylinders at −49° C. Each point represents the average of ten tests in Series A

At intervals throughout the ageing process, groups of samples were crushed in unconfined compression, on a "Soiltest" press with a 2,000 lb. (900 kg.) load capacity. The upper plate of the press could be swivelled through an angle of about 5 degrees to accommodate slight irregularities in the bearing surface of the snow cylinder. The force required to crush a sample was read from a dial gauge mounted on the proving ring. The load was applied manually at a rate of about 10·5 kg./cm.² sec. The cylinder usually fractured into three pieces in the manner described by Butkovich (1956). However, many of the low-strength samples (those aged for a short period of time) tended to crumble rather than fracture. All samples used in the present study were processed during December 1960 and most of the tests were completed before the authors left the South Pole in late January 1961. However, extra samples were prepared in December 1960 to permit continuation of some of the low-temperature tests during the winter of 1961. The authors are indebted to Mr. James Burnham, ionospheric physicist at the South Pole in 1961, for conducting these additional tests on the Series A samples.

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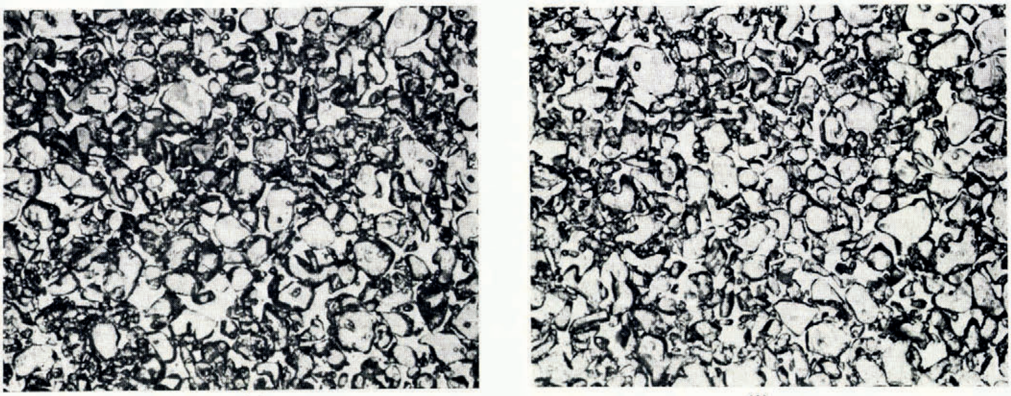
Changes in structure of snow with ageing were investigated in thin sections. The aniline method for the preparation of thin sections as described by Kinosita and Wakahama (1960) was used. Thin sections were cut to a thickness of about 0·1 mm. on a Leitz sledge microtome, and photomicrographs were obtained in transmitted light between crossed polaroids with a Bausch and Lomb extension camera.

EXPERIMENTAL RESULTS

Series A: The samples for Series A were prepared and aged in a 27·5 m. snow mine at a temperature of $-49 \cdot 4 \pm 0 \cdot 2°$C. Each point in Figure 3 represents the average unconfined compressive strength of ten samples. Two photographs of structures in thin section are given in Figure 4.



(a) (b)

Fig. 4. Thin-section photographs of age-hardened structure in Series A samples after (a) 768 hr. and (b) 1 yr. 6× magnification. Note how weakly developed the bonding is even after one year's ageing

Series B: The samples in Series B were aged at the snow surface, i.e. subjected to solar radiation at the ambient air temperature (Fig. 5). Results are presented in Figure 6 and thin-

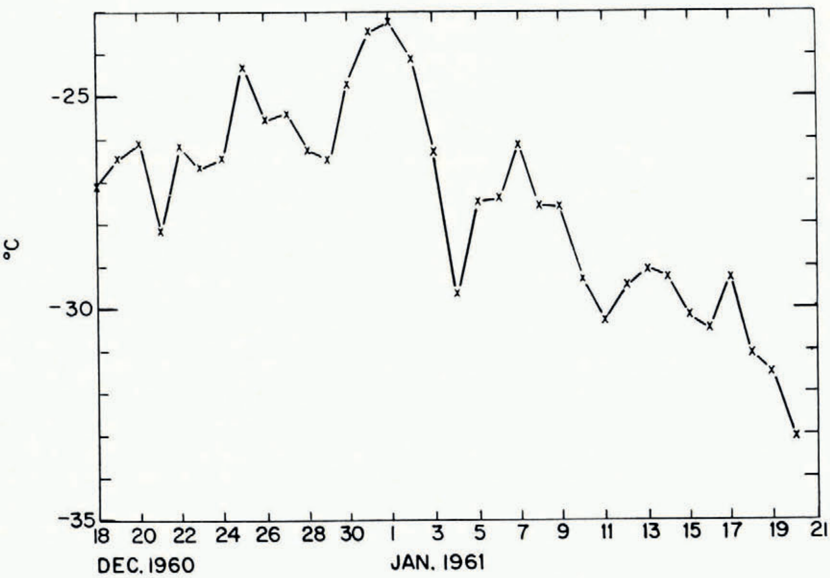


Fig. 5. Plot of daily average ambient air temperatures 3 ft. (0·9 m.) above the snow surface from 18 December 1960 to 20 January 1961 at the South Pole

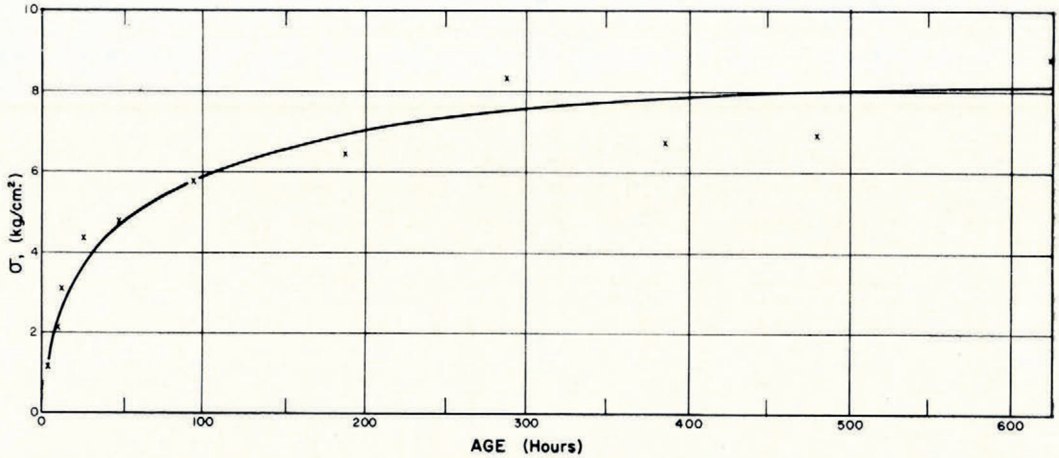
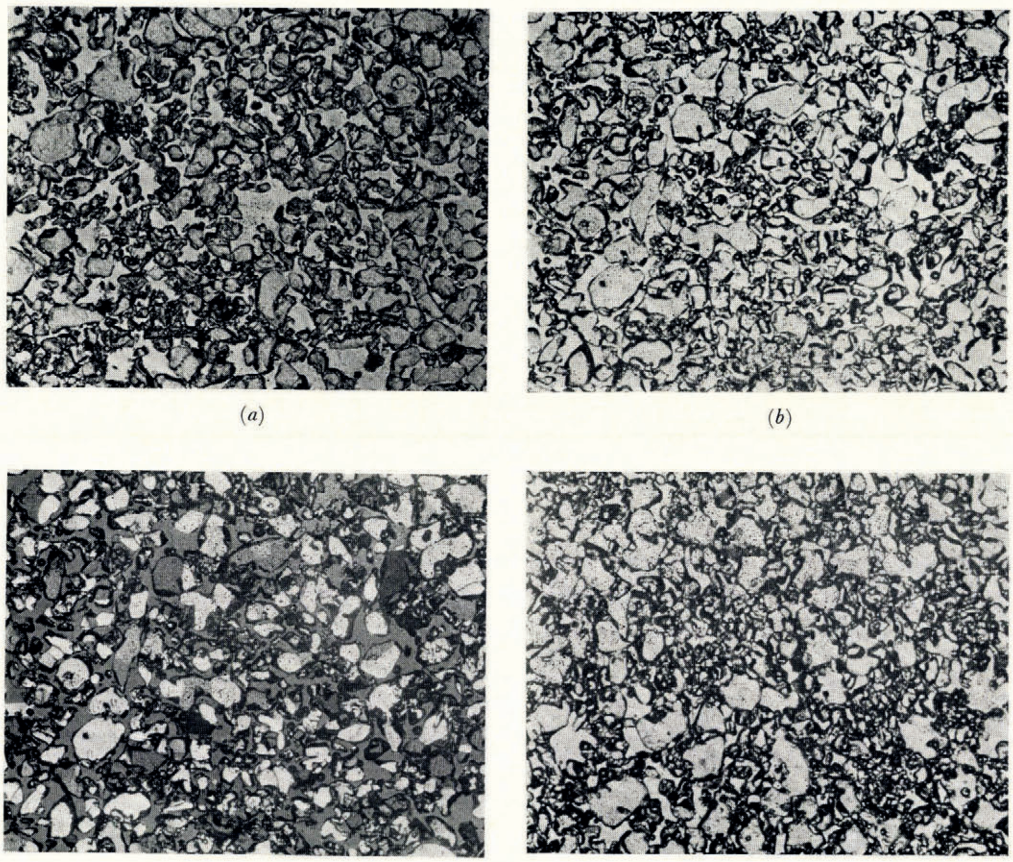


Fig. 6. Unconfined compressive strengths of snow cylinders of Series B. Each point represents the average of ten tests



(*a*) (*b*) (*c*) (*d*)

Fig. 7. Thin-section photographs of age-hardened structure in Series B samples after (*a*) *48 hr.,* (*b*) *and* (*c*) *96 hr., and* (*d*) *624 hr. 6× magnification. Photograph* (*c*) *shows the same area as* (*b*) *but is taken with the sample between crossed polaroids*

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section photographs are given in Figure 7. During ageing, the Series B samples underwent progressive sublimation. In Figure 8 sublimation is shown in terms of cross-sectional area loss plotted against time for both Series B and C.

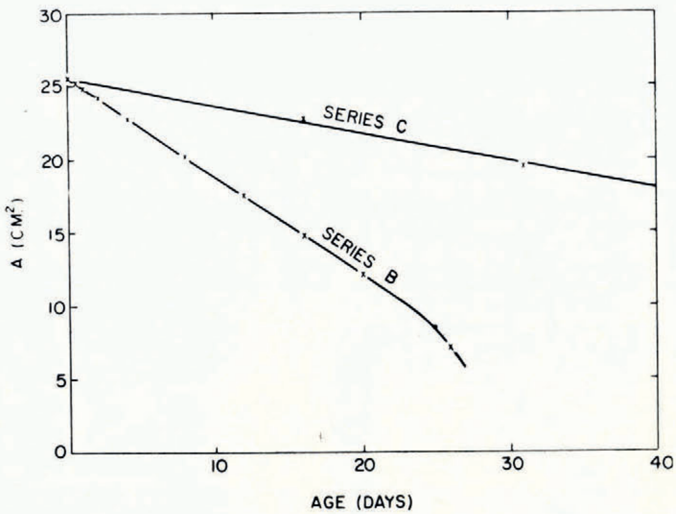


Fig. 8. Cross-sectional area loss by sublimation of snow cylinders in Series B and Series C

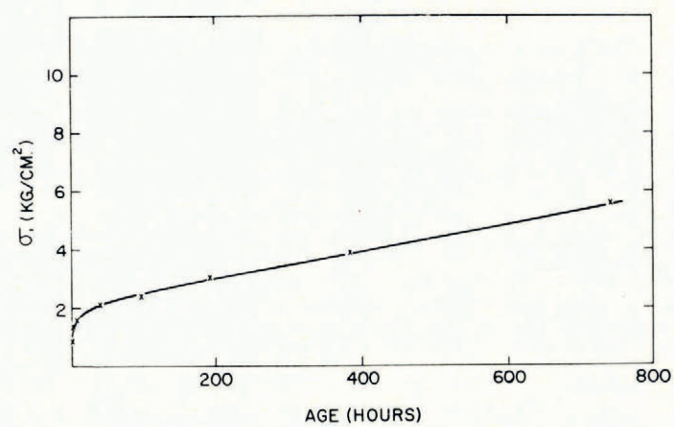


Fig. 9. Unconfined compressive strengths of snow cylinders in Series C. Each point represents the average of eight tests

Series C: This series was also aged at the ambient air temperature but the samples were placed in a ventilated box to eliminate the effects of solar radiation. It can be seen from Figure 8 that the Series C samples underwent much less sublimation than did the samples in Series B. Results of compressive strength tests are given in Figure 9 and thin-section structures are shown in Figure 10.

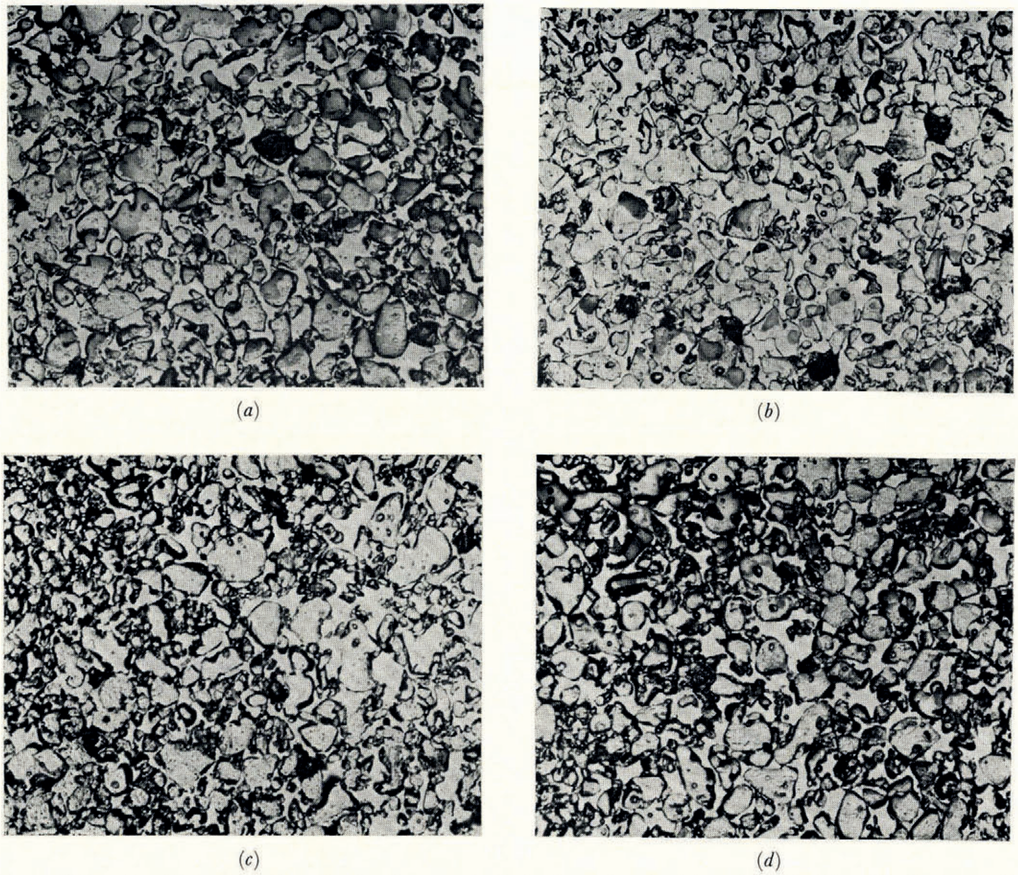


Fig. 10. Thin-section photographs of age-hardened structure in Series C samples after (a) 24 hr., (b) 48 hr., (c) 384 hr., and (d) 768 hr. 6× magnification

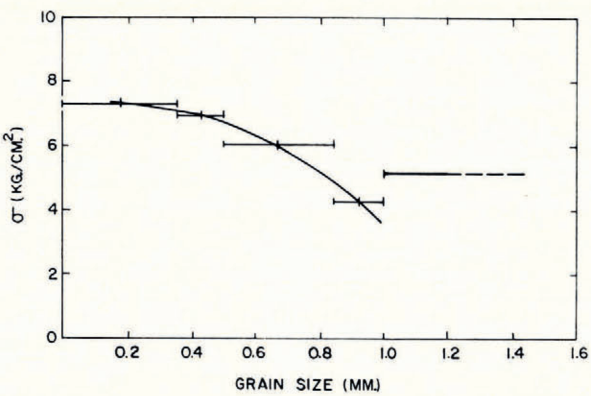
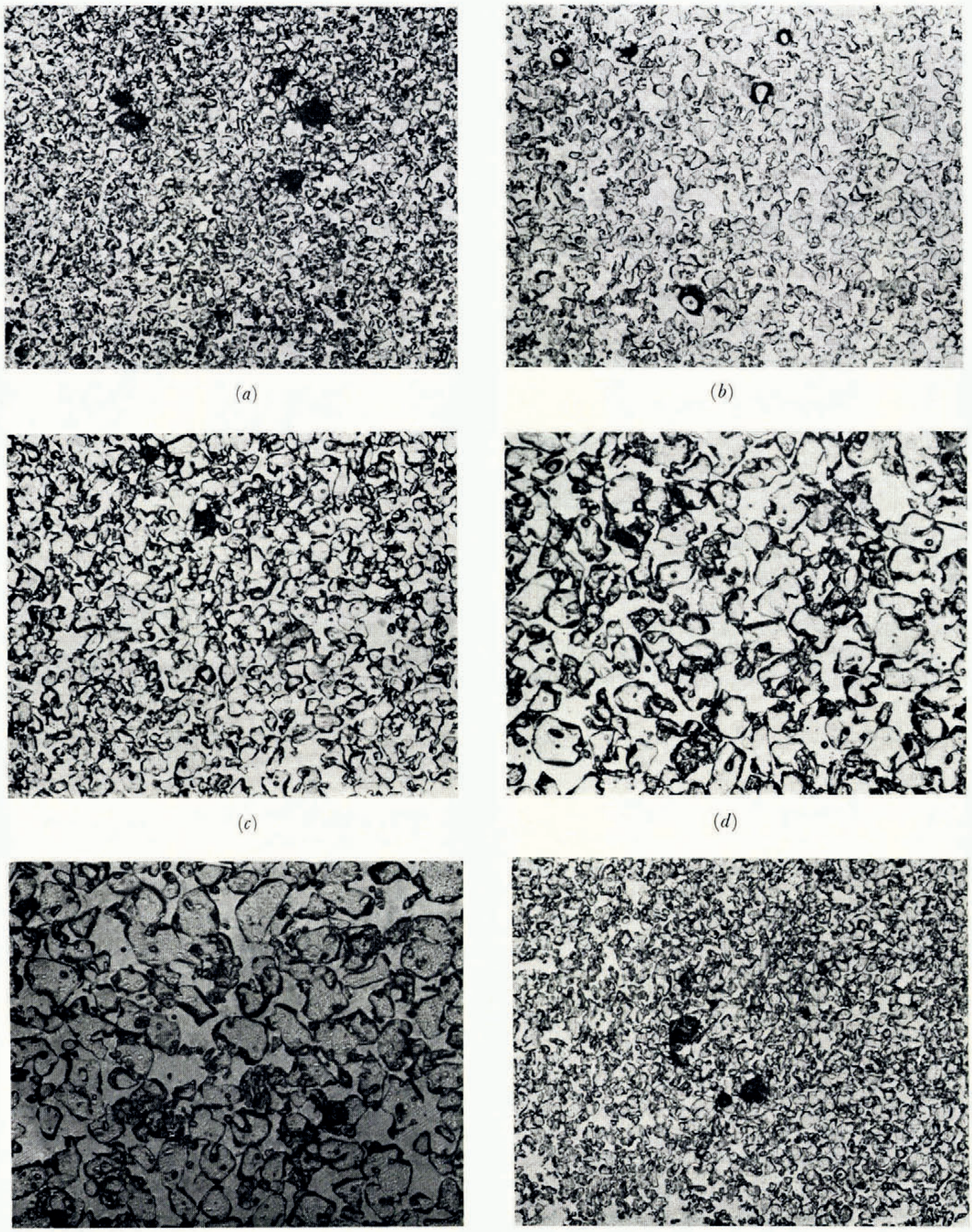


Fig. 11. Compressive strength as a function of particle size for Series D samples. All samples were aged for 384 hr. Each point represents the average of five tests

Series D: These samples were aged for 384 hr. under approximately the same conditions as for Series C: i.e. at ambient air temperatures and protected from solar radiation. Figure 11 gives the compressive strength values as a function of particle size for the snow cylinders in Series D; each data point represents the average of 5 tests. The horizontal line drawn through each point indicates the range of grain sizes within a group of samples. Two samples from each



(*a*) (*b*) (*c*) (*d*) (*e*) (*f*)

Fig. 12 (*continued overleaf*)

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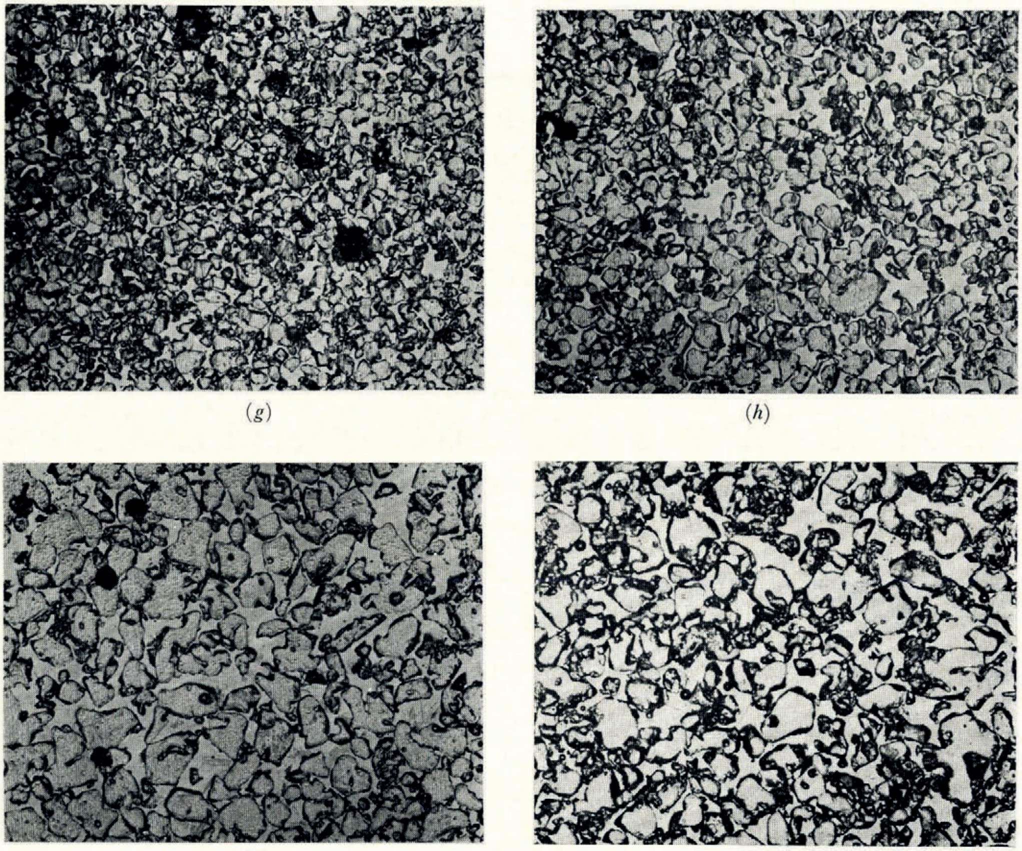

(*g*) (*h*)

(*i*) (*j*)

Fig. 12. Thin-section photographs of age-hardened structure at the end of 384 hr. (a–e) and after one year (f–j) in Series D samples. Grain-size ranges are as follows: (a) and (f), 0·35 mm. and less; (b) and (g), 0·35–0·50 mm.; (c) and (h), 0·50–0·84 mm.; (d) and (i), 0·84–1·00 mm.; (e) and (j), 1·00 mm. and larger. 6× magnification

group in Series D were retained unbroken and deposited in the snow mine with samples from Series A. These will be crushed after two years ageing to determine the effect of a constant low temperature on structure and subsequent strength. Thin-section photographs of the age-hardened snow structure after 384 hr. and at the end of one year are given in Figure 12.

Series E: During the winter of 1957, a snow mine was excavated to a depth of 27·5 m. below the surface at the South Pole. The following year, M. Giovinetto (1960) systematically cored one wall of the snow mine to obtain samples for density and pollen analyses at different depths. Most of the cores were replaced in the original drill holes, and a large number of these cores were used for measuring compressive strengths of naturally compacted snow at depths from 7·5 to 27·5 m. below the surface. Above 7·5 m., Giovinetto's cores had not been replaced so fresh cores were cut to within 4·5 m. of the surface with a standard 3 in. (7·6 cm.) coring auger. Because of the excessive accumulation near the portal, it was not possible to obtain undisturbed samples in the first 4 m. in the mine. These shallow samples were taken from the 4 m. pit. Since the snow in the pit lacked the cohesion of the deeper deposits the 3 in. coring auger could not be used and samples were obtained with standard SIPRE snow tubes. All samples were trimmed to 19·8 cm. length and crushed in unconfined compression at −49° C. A 5,000 lb. (2,250 kg.) proving ring was required to measure the crushing

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strengths of the high density samples from near the bottom of the snow mine. A plot of the crushing strength versus density is shown in Figure 13. Some average values obtained by Butkovich (1956) at Site 2, Greenland are included for comparison. Thin-section photographs in Figure 14 illustrate the changes in structure with increasing depth of burial in snow and firn at the South Pole.

DISCUSSION

That the process of age hardening is strongly dependent on temperature can be readily appreciated if we compare the low temperature studies at the South Pole with results obtained by Jellinek (1957) on the age hardening of snow at −10° C. Jellinek found that artificially compacted snow attained a near maximum strength of 10 kg./cm.² after about 100 hr. at −10° C. In the Series A tests at −49° C., the samples had acquired a strength of less than 0·8 kg./cm.² after 100 hr., i.e. about 8 per cent of the strength attained at −10° C. After

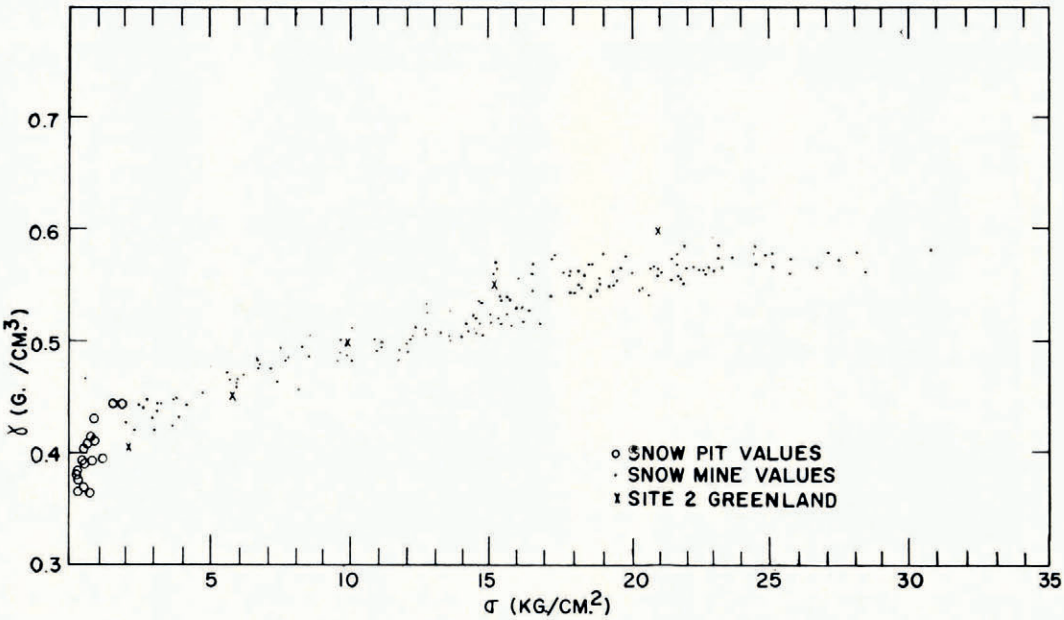
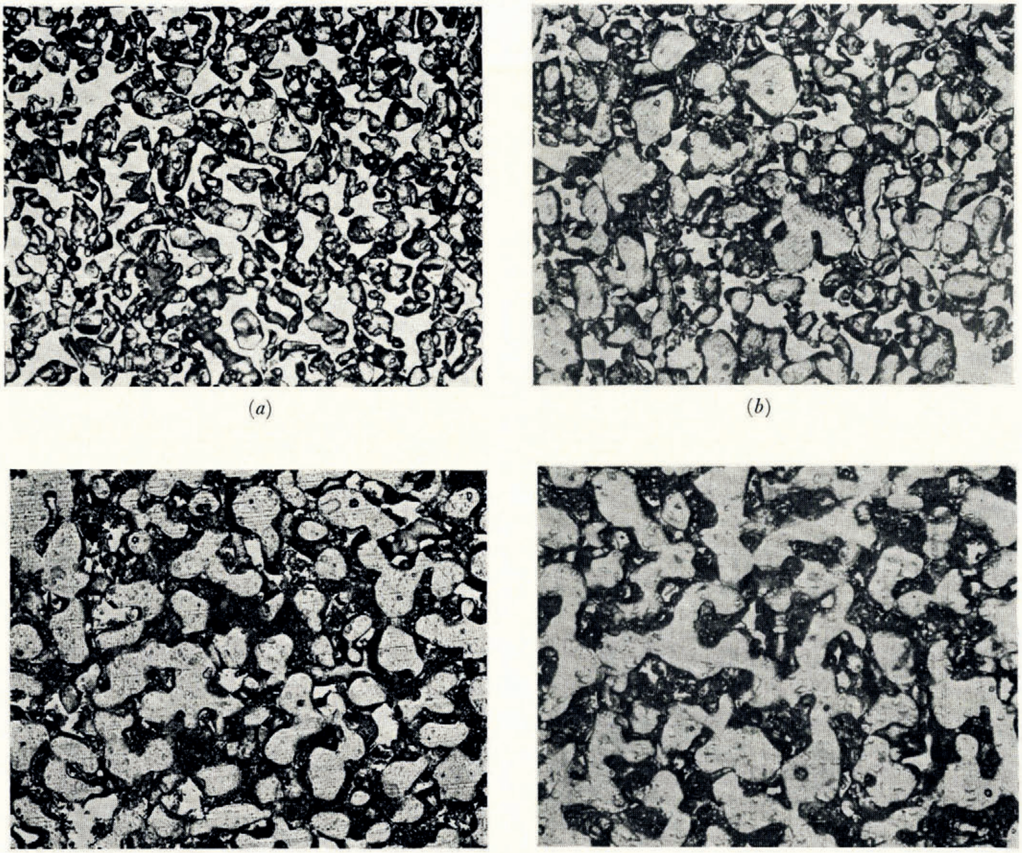


Fig. 13. Strength σ plotted against density γ of naturally compacted snow at the South Pole. Each point represents the unconfined compressive strength of a single sample

768 hr. of ageing the Series A samples had acquired a strength of 1·25 kg./cm.² increasing to 1·5 kg./cm.² at 1,500 hr. and becoming 1·8 kg./cm.² after 3,000 hr. Additional tests of the Series A samples show that they are still gaining in strength at an approximately constant but very slow rate (Fig. 3).

By comparison we find that the naturally compacted snow in Series E at the same density (0·55 g./cm.³) has a strength of about 20 kg./cm.². Nakaya and Waterhouse (personal communication) have been able to correlate an increase in Young's Modulus with increasing strength in Greenland snow, and according to Nakaya (1962) the Young's modulus (and hence the strength) of disaggregated snow at Site 2, Greenland, exceeded that of naturally compacted snow after only one year's ageing. Such a rate of age hardening does not occur at the low temperatures experienced at the South Pole. Results from Series A show that it would take a very long time for artificially compacted snow of density 0·55 g./cm.³ at a temperature of −49° C. even to approach the strength of naturally compacted snow of the same density.



(a) (b) (c) (d)

Fig. 14. Thin-section photographs of the grain structure of naturally compacted snow at the South Pole: (a) at 0·6 m. depth, density 0·37 g./cm.³, (b) at 6·0 m. depth, density 0·45 g./cm.³, (c) at 20·0 m. depth, density 0·55 g./cm.³, (d) at 48·0 m. depth, density 0·65 g./cm.³. The dark areas in (c) and (d) are pore spaces filled with partially melted aniline. 6× magnification

Furthermore, age hardening in naturally compacted and artificially compacted snow are not strictly comparable processes. It should be realized that naturally compacted snow of density 0·55 g./cm.³ (19 m. depth) at the South Pole has passed through a long history (more than 100 yr.) of recrystallization and structural changes. These changes have occurred under conditions of very low temperature and slowly applied overburden pressure. On the other hand the Series A samples were compacted very rapidly to a density of 0·55 g./cm.³ and then aged.

In Series C where the samples were aged at the ambient air temperature which averaged 26° C. for the duration of the studies, the rate of age hardening was much higher than for Series A. After 100 hr., the strength had exceeded 2·5 kg./cm.². Thereafter, the rate of increase remained constant, reaching a strength of about 6·0 kg./cm.² after 800 hr.

The samples in Series B were also maintained at ambient air temperature, but the rapid increase in strength can be attributed to exposure to solar radiation. After 100 hr., the strength had reached 6·0 kg./cm.². With additional ageing, the strength increased at a much reduced rate, reaching 8·0 kg./cm.² after 600 hr.

Studies of the effect of particle size on the compressive strength of artificially compacted snow (Series D) showed that the strength decreased appreciably with increase in grain size. It was observed however that the fine-grained particles were generally more angular than the coarser particles, so that the apparent correlation between strength and grain size may be in part a function of grain shape. In contrast to the present result, Jellinek (1957) found the strength of artificially compacted snow to increase with increasing grain size. Jellinek also noted that the coarse-grained samples required much more work of compaction to be compressed to a density of 0·55 g./cm.^{3} than did the finer-grained samples. He attributed the somewhat greater strength of coarse-grained samples to recrystallization and firmer bond formation in the more highly stressed grains of the coarse-grained samples. However, it is possible that during compaction, many of the coarser grains (consisting in large part of crystal aggregates) were broken, causing a resultant overall reduction of grain size and changes in grain shape. It would seem that the shape of grains is just as important as their size in determining the number of contacts between grains, and hence the potential number of bonds and ultimate strength of an artificially compacted aggregate. As already mentioned in the section on experimental methods, it proved possible to prepare samples of almost constant density—0·554 ± 0·005 g./cm.^{3}, equivalent to 39–40 per cent porosity. Redetermination of densities just prior to testing revealed no significant changes, even after considerable ageing. Thus, apart from the growth of bonds in the contact areas of grains, low-temperature age hardening results in negligible changes in the bulk structure of a moderately compacted aggregate.

The plot of crushing strength versus density for Series E (Fig. 13) shows that strength increases very rapidly with density. Although there is a large variation in strength for the 4 m. pit samples, the strength of snow from the mine increases linearly at densities above 0·42 g./cm.^{3}, but for one distinct break at a density of 0·55 g./cm.^{3}.

Conclusions

Age hardening at the South Pole at low temperatures is very slow. Exposing samples to solar radiation greatly accelerated the process. However, an artificially compacted snow cover would not gain strength as rapidly as the Series B snow cylinders because of the difference in the amount of direct solar radiation received. Because of the low angle of incidence of the sun's radiation at the South Pole (less than 23° during December and January) the snow surface would absorb considerably less solar energy than the test samples which were set up vertically on the surface. In the particular case of snow processed for engineering purposes a thin layer of artificially compacted snow would probably not gain in strength at a rate much faster than that found for the Series C samples (protected from solar radiation). A thicker layer would not strengthen uniformly because of the fairly rapid decrease in temperatures with depth in the layer.

Jellinek (1957) was able satisfactorily to fit his age-hardening curves of −10° C. with the equation

$$\frac{S_f - S_t}{S_f - S_0} = e^{-kt}$$

where S_0 and S_f are the initial and final compressive strengths respectively, S_t is the compressive strength at time t, and k is a rate constant. An attempt has been made to apply the same equation to the results from the South Pole and also to data obtained by Butkovich (1962) and Wuori (1962) with artificially processed snow. The constants used to construct the curves in Figure 15 are listed in Table I. It should be noted however that Jellinek was able to estimate S_f very closely because his samples had attained almost maximum strength after 100 hr. This was not the case at the South Pole where the results showed that samples were still gaining in strength at the end of the tests—approximately 700 hr. for the field tests.

To facilitate the calculations, the value assigned to S_f was that strength attained after approximately 700 hr. ageing. It can be seen in Figure 15 that all the calculated curves with the exception of the Series A tests at $-49°$ C. deviate considerably from the experimentally

TABLE I. PARAMETERS USED TO FIT DATA

T °C.	S_0 kg./cm.^{2}	S_f kg./cm.^{2}	k /hr. $\times 10^{-3}$	*Density* g./cm.^{3}
−7	3·63	11·25	12·3	0·49
−10	1·50	11·00	17·73	0·55
−20	0·35	10·35	5·52	0·50
−26	0·60	8·1	9·83	0·55
−26	0·70	5·2	3·81	0·55
−49	0·02	1·2	5·66	0·55

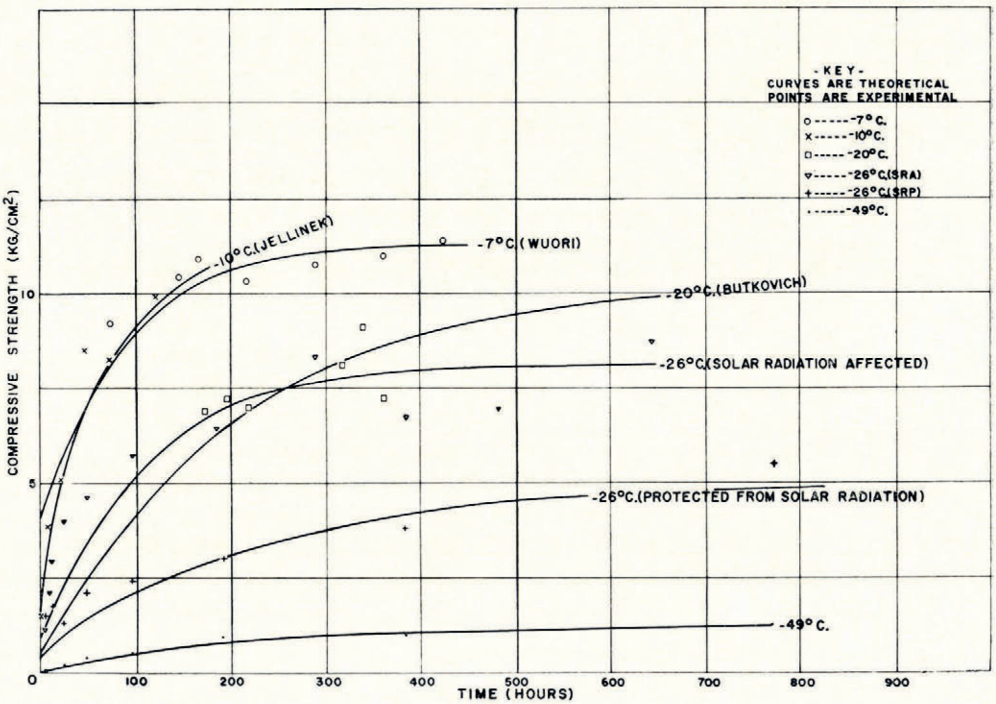


Fig. 15. Age-hardening curves, calculated from the equation

$$\frac{S_f - S_t}{S_f - S_0} = e^{-kt}$$

where S_f and S_0 are the final and initial compressive strengths, S_t is the compressive strength at time t, and k is a rate constant

determined values, especially in the early stages of age-hardening. The non-uniform conditions under which some of the tests were conducted may be partly responsible. For instance, the Series B and Series C samples at the South Pole were aged at the average ambient temperature which, as indicated in Figure 5, fluctuated from day to day. Similarly the processed snow used by Butkovich and Wuori had also been subjected to natural variations in solar radiation and temperature. The very significant effect of solar radiation on the age-hardening process can be readily seen in the $-26°$ C. tests at the South Pole. However, it also appears that our estimates of S_f were too low. Long term testing of the Series A samples has shown that the average strength has increased almost linearly from 1·2 kg./cm.^{2} (S_f at 700 hr.) to nearly 3·0 kg./cm.^{2} after one year's ageing. A constant rate of increase was also noted in the Series C samples after the first 100 hr. of ageing, and this would suggest that at least for low temperature tests the age-hardening process cannot be expressed entirely satisfactorily in terms of the equation

$$\frac{S_f - S_t}{S_f - S_0} = e^{-kt}.$$

At least on the basis of the present analysis, it is rather difficult to find a direct relationship between the rate constant k and temperature. Of immediate interest would be further laboratory tests with the same type of snow to determine strength as a function of temperature. If the results of such tests can be accommodated in the first-order reaction equation suggested by Jellinek then it would be possible to derive an energy of activation for age hardening in snow.

Compressive strengths were found to increase with decreasing particle size and with increasing angularity of the particles. The fact that fine-grained samples could be compacted to the test density of 0·55 g./cm.^{3} much more readily than coarse-grained snow clearly reflects the influence of particle shape and size distribution on the packing of particles in the compacted aggregate. The effects of these variables and also of variable degrees of compaction on the age-hardening properties of snow warrant further study. Results up to the present suggest that optimum strengthening would be obtained with a fine-grained but poorly sorted aggregate composed of angular particles. In nature these conditions are perhaps most closely approached in certain wind-compacted layers—fine grained wind slabs.

Naturally compacted snow acquires considerable strength at depth. Near-surface snows (density less than 0·42 g./cm.^{3}) possess rather low strength. The rate of increase of strength with density is essentially linear for densities between 0·42 and 0·55 g./cm.^{3}. Above 0·55 g./cm.^{3} the strength appears to increase at an even greater rate.

Thin-section studies show that age hardening can be correlated with the formation and growth of bonds between grains. This occurs more rapidly at higher temperatures and the whole process is essentially one of sintering. The relatively rapid initial strengthening in an artificially compacted snow sample can be attributed to the widespread formation of bonds at grain contacts. Subsequent age hardening at a diminishing rate probably reflects the continued growth of these early-formed intergranular bridges, plus growth of some new bonds. The process is obviously retarded at lower temperatures as evidenced by the tendency for the samples at −49° C. to crumble rather than fracture in unconfined compression even after considerable ageing. In naturally compacted snow at the South Pole, the process is facilitated by diffusion, sublimation and recrystallization under conditions of slowly increasing overburden pressure.

Since this work was performed at the South Pole a new under-snow camp has been successfully constructed at Byrd Station. However, in view of the low strength found in artificially compacted snow and in naturally compacted snow near the surface at the South Pole, the current "cut-and-cover" method of under-snow construction may not prove the most practical means of rebuilding the South Pole Station. Other methods are now being considered (Mellor, unpublished; Ramseier, unpublished).

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