⊙ **Technical Paper**

Laboratory and In-Situ Study of the Effect of Additives on the Compaction Strength of Snow

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積雪의 다짐강도에 대한 附加物의 效果에 관한 實驗 및 實際的인 考察

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초 록

적설의 다짐강도에 대한 부가물의 효과를 고찰하기 위한 연구가 수행되었다. 본 연구의 목적은 본 연구에서 얻은 결과를 토대로 적설의 압착과정을 촉진시키고 나아가서 남극의 설상로나 설상활주로 눈의 다짐강도를 증진시키는 데 있다. 실험실에서의 실험결과에 의하면 처리된 눈에 소량의 톱밥을 섞었을 때 더 큰 강도를 얻을 수 있다는 것을 알 수 있었으며, 이 방법은 남극과 McMurdo 설상로에 있는 시험도에서 실제 적용되었다. 현지 실험에서 얻은 자료를 분석한 결과 적설의 고결은 일반적으로 예측되는 극한 환경에서 보다 빨리 진행되었으며, 궁극적으로 큰 지장없이 육중한 운송장비를 지지할 수 있는 충분한 다짐강도를 얻을 수 있다는 것을 알 수 있었다.

1. Introduction

Compaction of snow has been a common method of constructing roads and passageways in areas having a prolonged snowcover on the ground. However, it is a relatively recent effort that more systematic methods have been applied to the problem based on scientific and engineering knowledge. Such a development is probably the result of having to meet the need to operate heavy vehicles on the snow roads and also the aircraft on the snow covered airstrips. The snow compaction technology has become an important subject[1~11].

During the last two decades, much effort has been put into the development of snow compaction technology by several research groups. These techniques are based on knowledge of the behavior and properties of snow such as its sintering and age hardening process. For instance, it is well known that snow sinters and hardens at a faster rate than the normal metamorphic process when it is disturbed by agitation or disaggregation[2,12~15].

This property may be used effectively to construct a hard snowroad by disaggregation snow by

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suitable equipment, for instance, a rotary snow-plow, followed by compaction into a smooth surface. It is also known that small quantities of additives mixed with processed snow can accelerate the sintering process and increase compaction strength. Sawdust or wood chips have been studied as additives for this purpose[16].

It is not well understood how these additives promote sintering of snow. In order to investigae the physical processes which are responsible for this phenomenon, it is desirable to obtain experimental data under as many different conditions as possible. Such a study was conducted in a laboratory experiment which was then followed by in-situ field experiments in Antarctica.

2. Laboratory Studies on Additives

A number of confind compression tests were made in the laboratory in order to evaluate the effect of additives on the mechanical properties of snow.

In the first series of tests, sawdust and polystyrene beads were used as the two additives. Tests were run on these two snow mixtures for snow/additive volume ratios of 4:1, 3:4, 2:5, and 1:0. The purpose of these tests was to first determine the relative effectiveness of these two additives. A second purpose was to determine if there existed an optimum ratio of snow and additive. The samples were initially mixed and then placed in cylindrical tubes and compacted manually by the standard free weight drop technique used in soil-mechanics. The total compactive effort for each specimen was 12,375 *lb-ft*(16,700*N·m*). The samples were allowed to sinter for one day at −14°*C* before testing. The tests were all done in confined compression at a constant crosshead speed. Fig. 1 and 2 show a typical result for snow/sawdust mixtures. These test results were initially not very informative, other than to demonstrate that polystyrene beads were definitely counter productive in increasing strength. The sawdust, however, showed increased strength for the lowest ratio

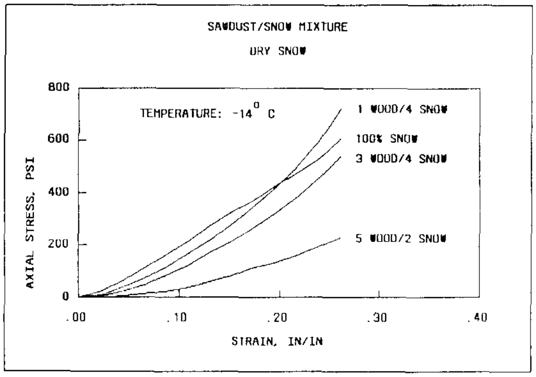

Fig. 1 Stress-strain curves for various volume ratios of sawdust mixed with dry snow

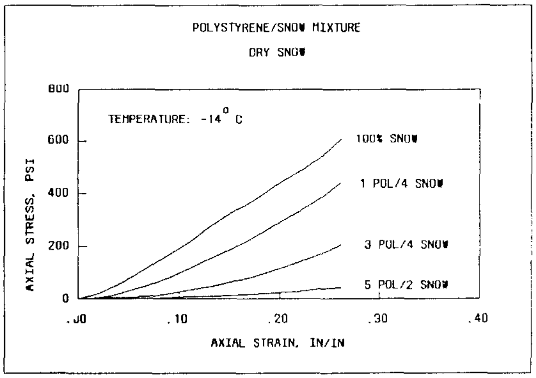

Fig. 2 Stress-strain curves for various ratios by volume of polystyrene beads mixed with snow

tested (1 part wood/4 parts snow). However, no conclusions regarding an optimum ratio of sawdust to snow could be arrived at with the use of these test results. Note, however, the relative curves of the 100% snow and the 1 wood/4 snow mixtures. The 100% snow sample initially showed a higher strength but was substantially lower in ultimate strength. This will be discussed later.

The second set of laboratory tests were more comprehensive. In this case a computer operated servo hydraulic testing machine with higher crosshead speed capability was used. Samples were again prepared by mixing snow and sawdust in prescribed ratios (0, 2.5%, and 10% by volume sawdust). These ratios were used, since the earlier tests indicated higher proportions of sawdust did not enhance strength. After mixing, the snow mixture was placed in waxed concrete sample holders with a diameter of ten inches. These samples were then place in the testing machine and compressed at a rate of 0.1″/s(2.54mm/s) until a load of 2500 lb (0.2 MPa stress) was reached. This stress was then held constant for ten seconds and then released. All samples were prepared in this method. They were all aged for 27 days and then tested. Prior to testing the sample was cut from its sample holder, cut down to an 8″ (203.2mm) diameter and placed in an instrumented aluminum cylinder for the confined compression tests. The crosshead speeds were either 1″/s(25.4mm/s) or 0.1″/s(2.54mm/s), and the test temperature was −14°C.

The results are shown in Fig. 3~5. In these figures the data are shown as stress-strain curves. Fig. 3 demonstrates the rate dependency of snow, which shows an increased stress response with strain rate. The mean density was 532 $kg/m^3 \pm 7kg/m^3$ for the two tests illustrated. This trend was found to also hold for the samples containing sawdust.

Fig. 4 and 5 demonstrate the relative stress-strain curves for the snow mixtures of 0%, 2.5%, and 10% sawdust.

Fig. 4 is for the slow rate(0.1″/s) and Fig. 5 is for the high rate (1.0″/s). Both figures indicate the 10% sawdust mixture gives the greatest strength. The 100% snow had the lowest ultimate strength for strains taken to 24%. However, note that the 100% snow samples had the highest initial stiffness and continued to have the higher strength until strains approaching 15% were reached. This

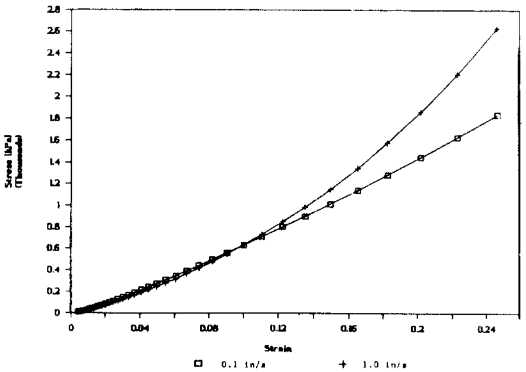

Fig. 3 Stress-strain curves for various crosshead speeds

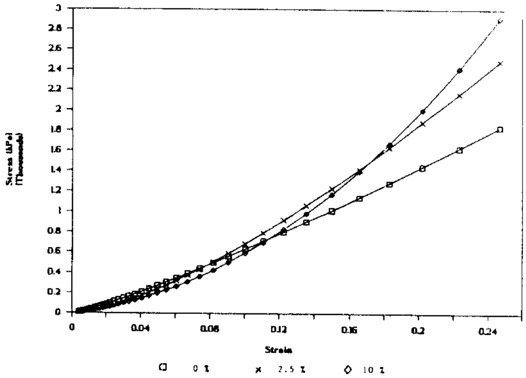

Fig. 4 Stress-strain curves for various sawdust concentrations with crosshead speed of 0.1 in/s(2.54mm/s)

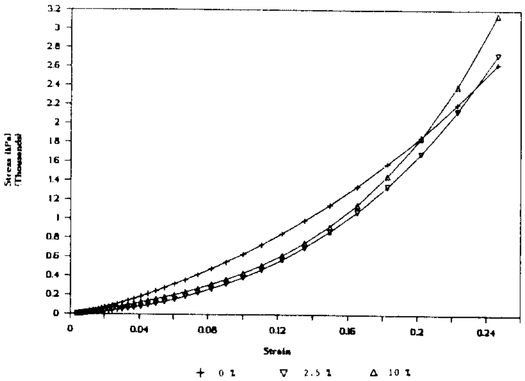

Fig. 5 Stress-strain curves for various sawdust concentrations with crosshead speed of 1.0 in/s(25.4mm/s)

is consistent with the earlier tests shown in Fig. 1.

The higher initial strength of the pure snow may partially be explained in terms of sintering and adhesion processes. Apparently after mixing, sintering between the ice particles takes place at a higher than adhesion between the sawdust and ice particle, After the 27-day sintering period the interparticle bounding was more fully developed in the pure snow samples, since all particle contacts were between ice particles. Upon starting the deformation, the superior intergranular (or interparticle) bounding in for the 100% snow results with higher initial stresses. As the deformation proceeds the intergranular bounding breaks down due to fracture of the bounds (both between the ice particles and between the ice and wood particles). As this proceeds, the greater strength of the wood, its elastic behavior, and more complicated geometrical shape of the wood chips combine to increase the strength of the mixtures above that of the pure snow.

Fig. 6 and 7 illustrate the effect of the addition of sawdust on the initial stiffness of the mixtures. The figures illustrate the change in initial Young's modulus E(here given as change of stress) as the strain is increased to 24%. As can be seen, E decreases significantly as the sawdust content increases. The values of E was calculated by making a numerical differentiation of the stress-strain curves.

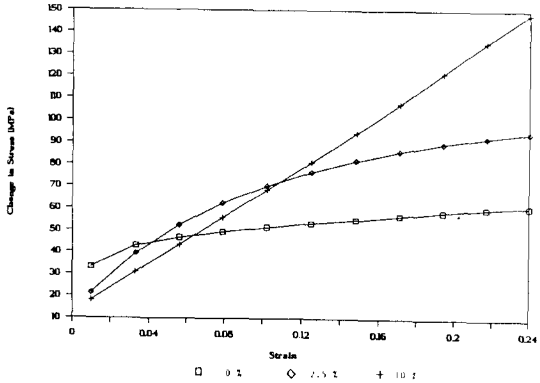

Fig. 6 Change in stress-strain curves for various sawdust concentrations with crosshead speed of 0.1*in/s*

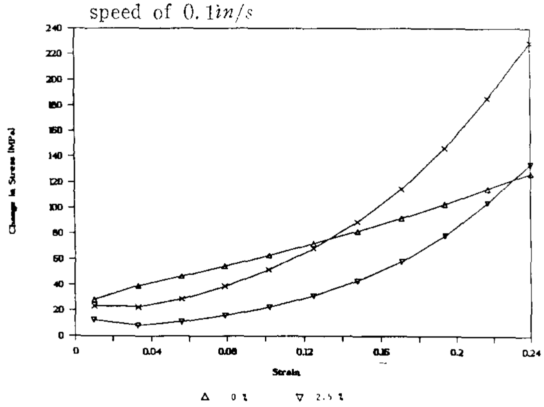

Fig. 7 Change in stress-strain curves for various sawdust concentrations with crosshead speed of 1.0 *in/s*

A least squares fit to the equation

$$\sigma = \exp[A + B\varepsilon + C\varepsilon^2 + D\varepsilon^3]$$

was used to fit the stress-strain curves to actual data. The initial values of E calculated from these equations were higher than those found from numerical differentiation and shown in Fig. 6 and 7, probably because of the poor resolution of the data acquisition system at low stress levels. However the relative values of E for the different samples were the same.

The values of E are much lower than would be found from the more acceptable technique of dynamic testing. However, this data does give a good measure of the relative value of Young's modulus E for the various sawdust contents. As can also be seen in these figures, the Young's modulus remains larger for the pure snow until strains in excess of 5% are reached both the slow rate tests (Fig. 6) and the high rate tests (Fig. 7).

These results clearly demonstrate that ice bonds more slowly to wood than it does to itself. However, it is possible that the eventual adhesive strength between wood and ice could be high.

3. Field Experiments in Antartica

The effectiveness of sawdust as an additive to promote snow sintering was investigated in the cold and dry environment of Antarctica. Test sections were constructed at McMurdo and the South Pole stations and the progress was monitored during the austral summer seasons of 1986~87 and 1987~88.

The general construction procedure was to excavate undisturbed snow with a bulldozer tractor to a depth of three feet where there was a layer of dense snow-ice, probably from the thaw-freeze cycle of the preceding year. The trench was then filled to within two feet of the surface with snow placed and compacted with a bulldozer, sheepsfoot roller and drag. Six inch (152.4*mm*) lifts of snow were then blown into the trench using a small driveway-type rotary snow blower. This was followed by fifteen compaction coverages of the bulldozer tracks. This procedure continued until the test sections were filled to final grade and leveled by backblading.

A) McMurdo-Williams Field Road

Four test sections were constructed adjacent to the Williams Field Road. each of the dimension twenty feet by forty feet. The first test section was filled with snow and compacted by the bulldozer to within six inchs of grade. The remaining six inches of trench was then filled with snow blown in by the rotary blower and compacted and backbladed with the bulldozer. The second test section was constructed as described the general procedure, all snow blown in six-inch lifts. The third section was constructed as described by the general procedure except that with each lift a measured amount of wood sawdust was spread on each lift and reprocessed or mixed into the snow with the snow blower so that the top two feet (0.61*m*) resulted in a layer of snow/sawdust mixture of 20/1 by volume. The fourth section was the same except that the amount of sawdust was doubled resulting in a snow/sawdust mixture of 10/1 by volume (7.58*m*).

B) Williams Field Taxiway

These test sections were constructed in the same manner as in A) except that their dimensions were smaller: thirty feet (9.09*m*)by twenty five feet (7.58*m*).

C) South Pole Cargo Berm

Two test sections were constructed near the cargo berm, an area of snow already compacted by traffic of construction equipment. These test sections were similar to the second and third sections of the McMurdo-Williams Field Road test sections described in A).

D) South Pole Taxiway

Three sections were constructed which were similar to the second through fourth sections of the McMurdo-Williams Field Road test sections described in A).

3.1 Field Test Results

Monitoring of the test sections was conducted throughout the 1986~87 season and for one week during January, 1988. Temperature and density profiles, Rammsonde penetrometer readings and Clegg surface impact data were obtained from these test sections. In addition, subjective observations were made to take note of any unusual deterioration of the integrity of the road and taxiway. The present report summarizes the density data obtained from these test sections.

1986~1987 season

A) McMurdo-Williams Field Road

10/1 snow/wood	0.85 *gm/cc* near surface to 0.65@70 *cm*
20/1 snow/wood	0.70 *gm/cc* near surface to 0.75@70 *cm*
Processed snow	0.65 *gm/cc* near surface to 0.70@70 *cm*
Top processed	0.60 *gm/cc* near surface to 0.60@70 *cm*

B) WilliamsField Taxiway

10/1 snow/wood	0.70 *gm/cc* near surface to 0.80@50 *cm*
20/1 snow/wood	0.74 *gm/cc* near surface to 0.65@50 *cm*
Processed snow	0.62 *gm/cc* near surface to 0.62@50 *cm*

C) South Pole Cargo Berm

20/1 snow/wood	0.62 *gm/cc* near surface to 0.66@40 *cm*
Processed snow	0.64 *gm/cc* near surface to 0.69@40 *cm*

D) South Pole Taxiway

10/1 snow/wood	0.58 *gm/cc* near surface to 0.59@40 *cm*
20/1 snow/wood	0.61 *gm/cc* near surface to 0.50@40 *cm*
Processed snow	0.58 *gm/cc* near surface to 0.5@540 *cm*

1987~88 Season

A) McMurdo-Williams Field Road

10/1 snow/wood	0.87 *gm/cc* near surface to 0.66@55 *cm*
20/1 snow/wood	0.86 *gm/cc* near surface to 0.66@55 *cm*
Processed snow	0.79 *gm/cc* near surface to 0.59@55 *cm*
Top processed	0.38 *gm/cc* near surface to 0.60@55 *cm*

B) Williams Field Taxiway

No data was obtained as the test sections had too much snow drift on the surface to make the data useful.

C) South Pole Cargo Berm

No data was obtained as the test sections had a thick layer of compacted snow by the construction and maintenance equipment.

D) SouthPole Taxiway

10/1 snow/wood	0.47 *gm/cc* near surface to 0.54@40 *cm*
20/1 snow/wood	0.49 *gm/cc* near surface to 0.54@50 *cm*
Processed snow	0.53 *gm/cc* near surface to 0.50@50 *cm*

It should be noted that, due to inadequate equipment used, the mixing of wood additives and snow was not uniform. As a result, layering of sawdust at various depth was noted from the snow core samples that were taken during the 1988 season. The density profiles listed above have some range of inaccuracies that would not have resulted had the mixing been done more thoroughly.

4. Conclusion

It can be seen from the data that wood sawdust used as additives are effective in increasing density of processed snow. These wood additives used in concentrations of 5% to 10% by volume and mixed well into the snow while processing or disaggregating the snow will result in producing a road or airstrip of higher strength than using processed snow only. The strengthening effect was greater at McMurdo than at South Pole. It appears that the sawdust is more effective as a binder material at higher ambient and snow temperatures especially when direct solar radiation can bring the snow/wood mixture to or close to the melting point. Note, for example, the ambient and snow temperatures of $-5°C$ to $-10°C$ and $-5°C$ to $-15°C$, respectively, at McMurdo as compared to the corresponding temperatures of $-30°C$ to $-40°C$ and $-30°C$ to $-49°C$, respectively at South Pole during the test section construction. The field tests confirm the results indicated by the laboratory experiments that sawdust can significantly increase snow strength.

The processes which affect the strength of sawdust/snow mixtures are complicated, and more study is needed to quantitatively determine their importance. For instance, the snow mixtures at McMurdo experienced greater strengthening than at South Pole. This coud be due to the dependence of sintering rates on temperature, the effect of temperature on the compressibility of the material at the time of processing, or the increased degree of the melt-freeze process due to the warmer temperatures at McMurdo. In addition, it is evident that the sawdust/snow mixture properties depend on the properties of each constituent, the sintering and adhesion properties, and the inter granular deformation mechanisms once bonding has been destroyed. More accurate means of discribing these processes and their effects are currently under investigaton.

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