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Field Experiments for Reducing Frost Susceptibility Using Recycled Tire Powder

폐타이어 파우더 혼합이 동상억제에 미치는 영향에 관한 야외실험 연구

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요 지

본 연구에서는 새로운 동상 억제제로서 폐타이어 파우더의 활용가능성을 검토하기 위해 폐타이어 분말 혼합토와 미혼합토를 대상으로 3년간 일본 토마코마이에서 야외실험 수행하였다. 야외실험 결과, 폐타이어 파우더를 20% 혼합함에 의해 현저한 동상억제 효과가 발생함을 확인하였으며, 관련 동상억제 효과를 동상량, 동상율, 열전도율, 투수성, segregation potential 이론 등을 중심으로 정량적으로 검토하였다.

Abstract

Three years of frost heave field experiments were conducted to evaluate a method for reducing heave using a recycled tire powder-soil mixture. By mixing Tomakomai soil with 20% recycled tire powder, frost heave amount was drastically decreased. The results of the field experiment confirm that recycled tire powder is an excellent material for use in controlling the total amount of heave. The restraining effect of a recycled tire powder-soil mixture is qualitatively analyzed based on amount of frost heave, frost heave ratio, thermal conductivity, permeability and segregation potential theory.

Keywords : Freezing index, Frost heave, Permeability, Recycled tire powder, Segregation potential theory, Thermal conductivity

1. Introduction

In cold regions, the ground is subjected to severe winter temperatures and freezes from the soil surface to a certain depth. During soil freezing, frost heave tends to occur in specific soil types under particular ground conditions. More specifically, frost heave results from the formation of successive ice lenses in subgrade soils. Roads, buildings, railways, pipelines, and other infrastructures are designed to prevent damage from frost heave; however, due to frost action, roads are often damaged by upheaval of the surface. The most common method of protecting roads from frost heave is to replace frost susceptible materials with non-susceptible soils.

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In some areas it is rather difficult to obtain an adequate supply of sandy materials from local resources which, in turn, makes road construction in areas with cold winters expensive. In attempts to find alternatives, several different materials have been added to on-site frost-susceptible soil to make the road frost tolerant. Fukuda et al. (1991) added ordinary cement to silty soil. Thompson (1973) and Ono et al. (2005) also report similar applications. Other methods include installing geotextiles (Henry, 1990; Tuchiya, 1998) or embedding thermal insulating material into the subgrade (Dunphy, 1973).

There are some common disadvantages among these applications that make their practical use difficult. First, the cost of the materials employed is higher than that of non-frost-susceptible soil. Second, new machinery and techniques for installation or mixing on site remain undeveloped. Third, the duration of these methods' effectiveness has not been determined. Even considering these disadvantages, there is still a demand for new applications from industry and society to improve the performance of roads during winter conditions.

Huge numbers of tires are being discarded every year due to rapid modernization throughout the world. The recycling rate for discarded tires is low, and a great many used tires are being discarded into landfills or open stockpiles. Therefore, a variety of methods handling these tires are urgently needed. One popular use of discarded tires is to embed them as insulation layers in road subgrades as mentioned above to limit the depth of frost penetration (Robert, 1994). However, embedded tire layers cannot support the stress surcharge derived from heavy vehicles, giving rise to large settlement. The authors propose a novel method to overcome these disadvantages. A frost-susceptible soil is mixed with granulated rubber powder at a fixed soil-to-powder ratio. The authors firmly believe that using a soil-powder mixture, not only reduces total heave, but enables to recycle many waste tires. With reduced frost heave, the operational life of engineering structures.

The present study evaluates the effectiveness of tire powders in reducing frost heave and the total heave reduction efficiency achievable with the application of tire powder-soil mixtures. The evaluation focuses on frost heave ratio, thermal conductivity, permeability and segregation potential parameters, based on the results of field tests conducted over three winter seasons.

2. Testing Conditions

The authors conducted a field experiment using powdered tires in Tomakomai, which is located about 50 km south of Sapporo, Hokkaido. The area is situated at the bottom of a small basin where temperatures are quite low in clear weather. The daily mean air temperature drops to 0℃ starting in late November, and does not rise above 0℃ again until mid-March every year.

The freezing index and daily mean air temperature in the winter of 1996-1997 are shown in Fig. 1 as an example of the field conditions. The total freezing index amounted to 367℃·days that winter. The monthly mean air temperature was 3.2℃ in November, -1.6℃ in December, -3.5℃ in January, -3.7℃ in February, -0.5℃ in March, and 4.9℃ in April. The minimum air temperature was -8.5℃ on January 25, 1997.

To eliminate extraneous effects, the field test was carried out in a waterproof concrete basin measuring 5 m long, 5 m wide, and 1.75 m deep (Fig. 2).

First, non-frost-susceptible soil (sand) was backfilled and tamped into the bottom of the basin to a depth of 35 cm to maintain a uniform water distribution. Then a 100-cm deep layer of silty soil was added. Above this

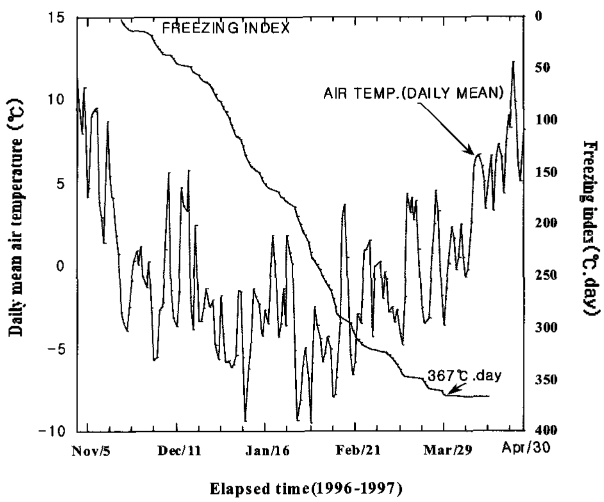


Fig. 1. Field test thermal and frost conditions

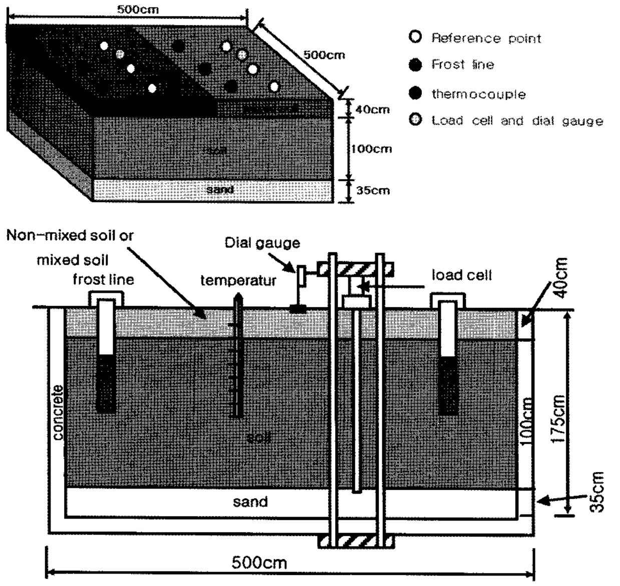


Fig. 2. Schematic diagram of field test installation (not to scale)

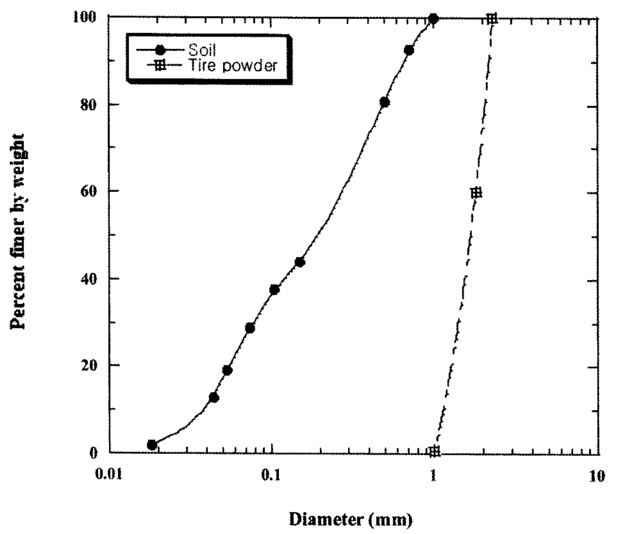


Fig. 3. The particle size distribution of soil and recycled tire powder

second layer, the apparatus was divided into two sections. One was a non-mixed section filled with silty soil, while the other contained silty soil mixed with 20% tire powder by weight. The third layer in both sections was 40 cm deep. After each soil layer was placed in the basin, it was compacted using a vibrating ram. The maximum frost penetration depth was estimated to be about 40 cm.

To obtain the maximum freezing effect, snow was cleared from the site to eliminate the insulating effect of a snow cover. The soil used in the test is frost susceptible and is classified as SC. Fig. 3 shows the particle size distribution of soil and recycled tire powder. The specific surface area is 54 m^2/g and the specific gravity is 2.66. The plastic limit is 38% and the liquid limit is 46%. The granulated rubber powders used were uniformly graded and had a nominal maximum size of 2.1 mm and a minimum size of 1.1 mm. The granules were irregular in shape and were made using a cooling crusher after maintaining tire chips at -120℃ for 15 min. The specific gravity of the powder is 1.22.

3. Measurements

In the test layer, a variety of sensors and instruments were installed to measure temperature profiles in each layer, the water level in the pool and the amount of frost heave. Water content profiles were also analyzed by core sampling using a boring machine. The measurement methods employed are described below.

3.1 Soil Temperature

Soil temperatures were measured at the center of each test section using thermocouples which were attached to the external surface of a 3-cm diameter vinyl pipe at 5 or 10 cm intervals from the soil surface to a depth of 200 cm. The pipe was inserted into a 3-cm diameter hole in the soil. Though the pipe rose together with the heaving of the ground surface, the spacing of the thermocouples did not change throughout the measurement period. Temperatures measured by the thermocouples were recorded in 4-hour intervals with a digital data acquisition system.

3.2 Frost Penetration

Frost penetration was determined using a thin transparent tube filled with a 0.01% methylene blue dye solution in each test section. This frost tube was sheathed from above and suspended down into another open topped pipe with a slightly larger diameter, which was embedded vertically in the soil with its top protruding from the ground surface. The frozen depth was measured once a week.

3.3 Surface Frost Heave

The amount of surface heave was measured using an engineer's level and a dial gauge. Measurements using the level were carried out once a week and the displacement detector recorded data every 4-hour during the freezing period.

3.4 Groundwater Level

The water level in the basin was measured by reading the level of a buoy floating in a pipe connected to and placed close by the basin. No water from outside the basin was added after the soil began to freeze.

4. Results of the Field Experiment

4.1 Frost Heave Characteristics

The data observed during the test for frost heave, penetration of freezing front, frozen depth and groundwater level for the mixed and non-mixed sections, along with the elapsed time in the three successive winter seasons from 1996 to 1999 are summarized in Figs. 3 to 5. The freezing index of the first season was a little warmer (367℃·days) than the following two seasons, 513℃·days and 539℃·days, respectively.

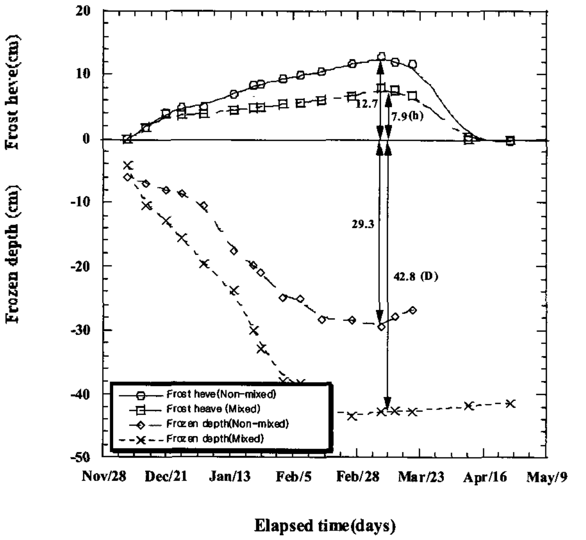


Fig. 4. Results of observation in the field during the winter of 1996-1997

For the 1996 to 1997 season, ground freezing began around the end of November. After that, the ground surface continued to rise and reached its highest point of 7.9 cm in the mixed section and 12.7 cm in the non-mixed section on March 10, 1997 (Fig. 4). By that time the measured maximum depth of frost penetration in the non-mixed section was 42 cm and the depth of frost penetration in the mixed section was 50.7 cm. The freezing front continued to penetrate into the ground until February 28, 1997 and became nearly stationary thereafter. On March 10, 1997 the freezing front reached its deepest level of 42.8 cm (mixed section) and 29.3 cm (non-mixed section). The frost heave ratios of the mixed and non-mixed sections, (maximum frost heave height divided by maximum frozen depth) were 18.5 and 46.9% respectively. The heave ratio of the mixed section was less than half that of the non-mixed section.

For the 1997 to 1998 season (initial groundwater level 10 cm below the ground surface), ground freezing began around December 15. The maximum measured heaves were 5.8 cm in the mixed section on March 16 and 13.3 cm in the non-mixed section on February 24. The maximum frozen depths were 42.4 cm (mixed) and 27.6 cm (non-mixed) yielding heave ratios of 13.7% (mixed) and 48.9% (non-mixed). Complete melting occurred on April 27. The ground water table continued to fall considerably as heaving progressed, reaching the tank bottom (175 cm below the initial ground surface) on February 17 and rising suddenly with the onset of thawing after March 24 (Fig. 5).

The mean heaving rate was about 2.1 mm/day from December 15 to February 17 (non-mixed) and 0.63 mm/day from December 15 to March 17 (mixed). The heaving process in the mixed section was much slower than that in the non-mixed section, while the frost penetrated deeper in the mixed soil than that in the non-mixed soil.

For the 1998 to 1999 season (initial groundwater level 35 cm below the ground surface), ground freezing began around December 15. The maximum heave heights were 9.6 cm (mixed) on March 1 and 23.3 cm (non-mixed) on February 12. The maximum frozen depths were 37.6 cm (mixed) and 17.1 cm (non-mixed). The heave ratios were 24.2% (mixed) and 59.1% (non-mixed). Complete melting occurred on April 26. The groundwater table rose due to ground surface thawing between December 7 and December 14. It then proceeded to fall considerably as heaving progressed, reaching a depth of 130 cm below the initial ground surface on February 14 after which it remained stable then suddenly rose as thawing began after March 26 (Fig. 6).

The mean heaving rates were about 4.2 mm/day from November 22 to February 15 (non-mixed) and 1.3 mm/day from November 22 to March 1 (mixed).

The heaving rate from the onset of winter to the middle of December this season was very high due to the intensive growth of an ice column at the ground surface. The ice column, which was observed in the field, was 2 cm thick in the mixed section and 6 cm thick in the non-mixed section. The frost front of the mixed section penetrated deeper than that of the non-mixed section. Such a difference of freezing front shows that the volumetric water content decrease caused by the granulated rubber powder-soil mixture has an effect on the latent heat caused by ice segregation.

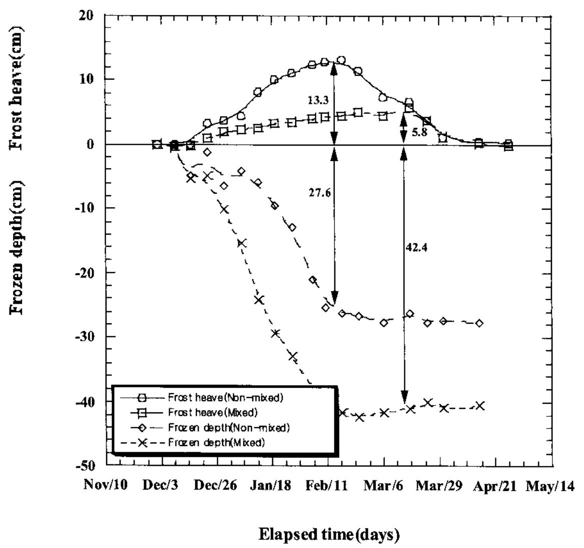


Fig. 5. 1997-1998 winter field observations

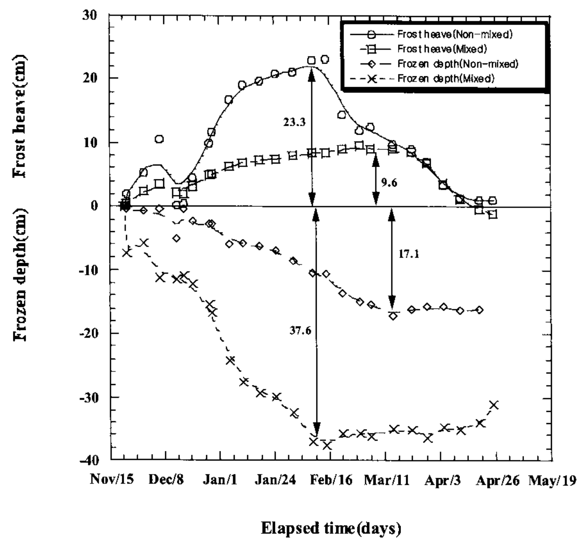


Fig. 6. 1998-1999 winter field observations

4.2 Thermal Characteristics

The maximum frozen depth, defined as the thickness from the original ground surface before frost heave to the freezing front for the 1996-1997, 1997-1998 and 1998-1999 winters is shown in Fig. 7. The frozen depth beneath the mixed section ranged from 37.6 cm to 42.8 cm. On the other hand, the frozen thickness beneath the non-mixed section ranged from 17.1 to 29.3 cm. The addition of the granulated rubber powder increased the frozen depth of the mixed section about 66% compared to the non-mixed section. This indicates that the granulated rubber powder is not effective in reducing the frozen depth and that the decrease of the heave achieved by mixing the rubber powder in is not produced by an insulation effect but some other factor.

A comparison of the freezing front, representing the boundary between the frozen and unfrozen zones in both sections is shown in Fig. 8 (1996-1997 season). The freezing front in the non-mixed and mixed sections reached levels

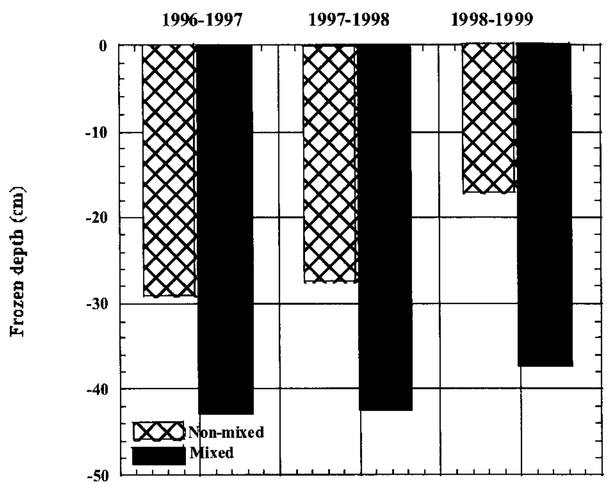


Fig. 7. Maximum frozen depth

of 42 and 50.7 cm, respectively, below the ground surface on March 10. The freezing front in the mixed section penetrated more rapidly than in the non-mixed section until the beginning of the spring thaw in both sections. However, the results shown in Figs. 6 and 7 are quite different from Humphrey's result (Humphrey, 1995, 1998). This is thought to arise from a diminution of latent heat due to the water-repellent properties of the tire material and the decrease of unfrozen water content in the mixed soil. It is also clear that if tire powder is mixed with a soil, the rubber powder does not function as an insulator, even though the thermal conductivity of rubber is much lower than that of soil.

4.3 Volumetric Water Content Analysis

Core samples 5 cm in diameter, extending from the ground surface to about 100 cm deep, were taken from both sections on March 5, 1998 and March 5, 1999 (during freezing), using a boring machine with a high-speed rotating edge. The samples were examined to investigate their layered structures. Slices were taken at intervals of 2.5 and 5.0 cm. The volumetric water content (θ) of each frozen sample was obtained by calculating its wet density (ρ_t), using the difference between its weights in air and kerosene, its water content(w) and the density of water (ρ_w); $\theta=\rho_t \cdot w/(\rho_w(1+w))$. The samples' volumetric water

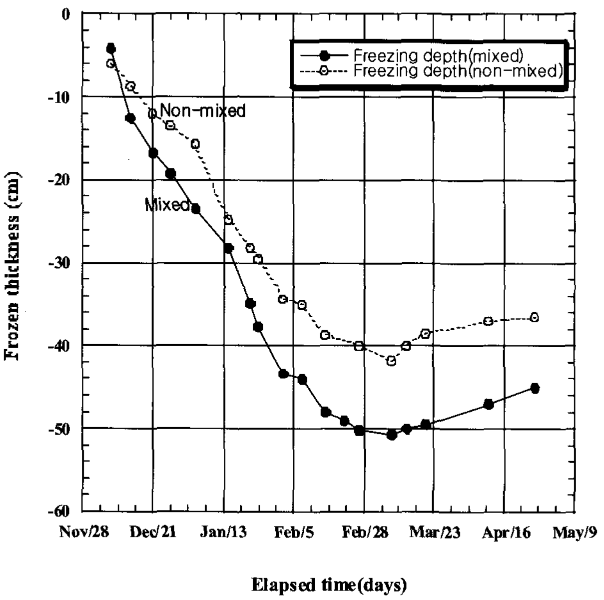


Fig. 8. Frost front depth comparison, 1996-1997 season

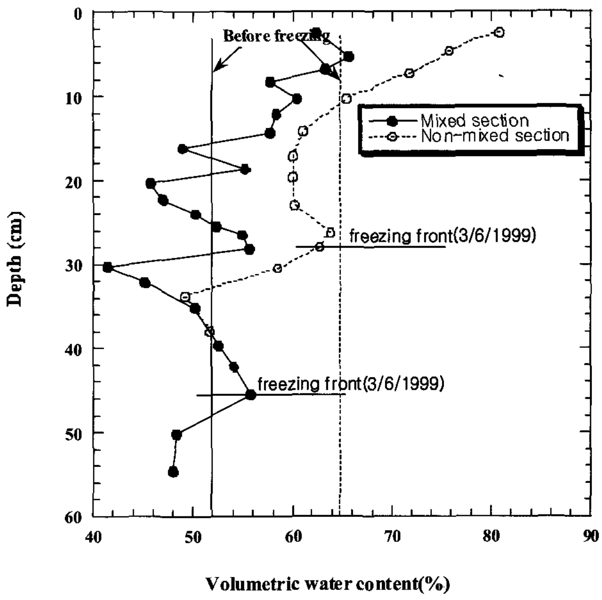
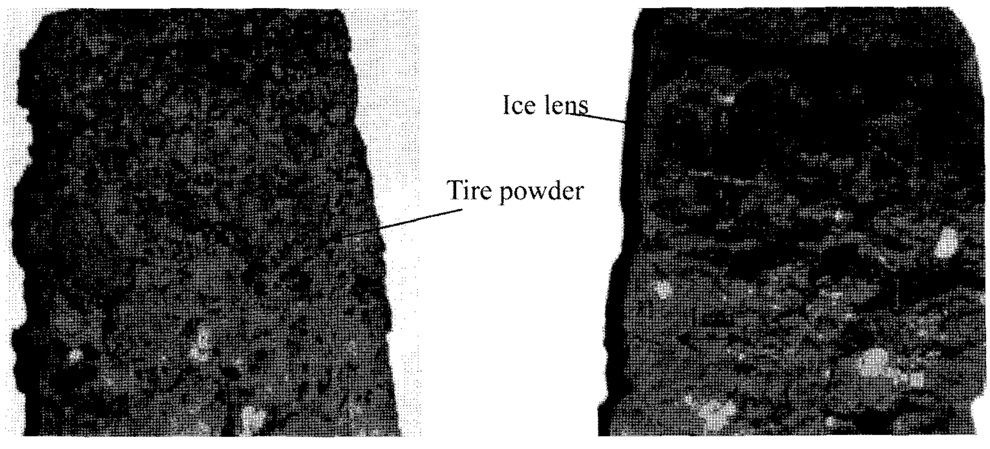


Fig. 9. Vertical distribution of volumetric water content



(a) Mixed section

(b) Non-mixed section

Photo. 1. Occurrence of ice lenses in mixed and non-mixed soil content is shown in Fig. 9.

Fig. 9 shows that the volumetric water content near the surface in the mixed section was 52%, compared to 65% in the non-mixed section before freezing. It increased to 68% (non-mixed) and 81% (mixed) including an ice column that developed at the surface, but was smaller in an unfrozen layer immediately below the freezing front. The increase of the volumetric water content in the frozen layer corresponds to the presence of ice lenses. Ice lenses 2 to 3 mm thick were detected in the frozen core of the non-mixed section, but hardly any ice lenses were visible in the frozen core of the mixed section, as shown in Photo. 1.

5. Discussion

There are several mechanisms by which frost heave may be reduced when granulated rubber powder is mixed with soil. In order to understand which mechanisms are responsible for the reduction, we investigate frost heave considering thermal conductivity, and the permeability of the tire powder-soil mixture, Then, in the last part of this chapter, we analyze the effect of the addition of tire granules to the soil based on segregation potential theory.

5.1 Evaluation of the Tire Powder Mixture Using Frost Heave Ratio

Frost heave ratio is usually defined as the ratio of frost heave height to maximum frozen depth (See Fig. 4 h/D). The calculated frost heave ratios for the three winters of the study are shown in Table 1. The difference in frost heave ratio between a mixed medium and a non-mixed medium is clearly shown in Table 1. In our 3-year field experiment, the frost heave ratio decreased by about 64% as a result of mixing tire powder with surface soil.

The thermal and hydraulic properties of a soil material affect the degree of its frost susceptibility. The thermal conductivity of tire powder-soil mixtures was measured for various mixing ratios. In Fig. 10, the thermal conductivities of these tire powder-soil mixtures are plotted for both frozen and unfrozen conditions as a function of mixing ratio (tire powder to dry soil by weight). When frozen, thermal conductivities decrease slightly as mixing ratio increases. This implies that frozen depths may be shallower for a mixed soil than for soil with a higher value of thermal conductivity such as an non-mixed soil. Differences in frozen layer thickness between the two test conditions, both of which have the same freezing index, might be caused by this property.

The permeability of soils in their unfrozen state was measured for different tire powder/soil mixing ratios. The results are shown in Fig. 11. The permeability of samples with tire powder added is twice to three times that of non-mixed soil.

In general, soils with higher frost susceptibility have higher permeabilities. This result implies that soil permeability is not the determining factor for frost heave if the values differ only by a factor of 2 to 3.

The comparisons of thermal conductivity and permeability between tire powder-mixed and non-mixed soils do not appear to conclusively explain the mechanism whereby frost heave is reduced. To try to discover the factor responsible for the reduction in frost heave achieved by

Table 1. Frost heave ratios in mixed and non-mixed sections (%)

Year	1996-1997	1997-1998	1998-1999	Mean
Mixed site	18.5	13.7	24.2	18.8
Non-mixed site	46.9	48.2	59.1	51.4

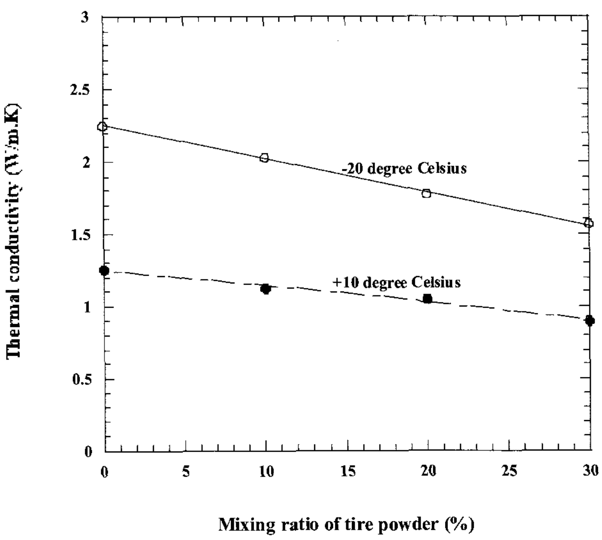


Fig. 10. Relationship of thermal conductivity to tire powder mixing ratio

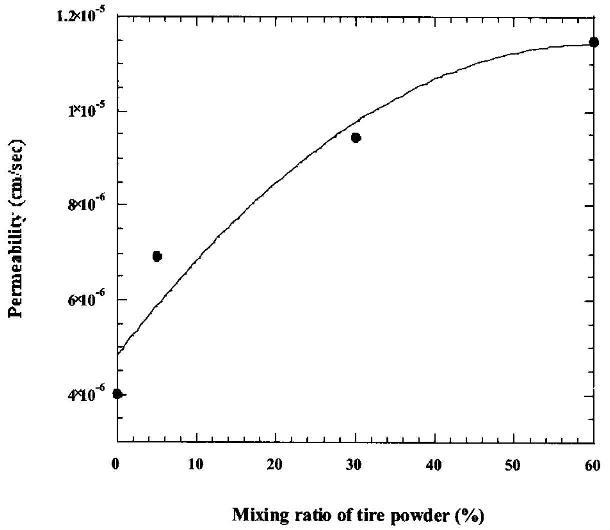


Fig. 11. Permeability as function of tire powder mixing ratio (unfrozen state)

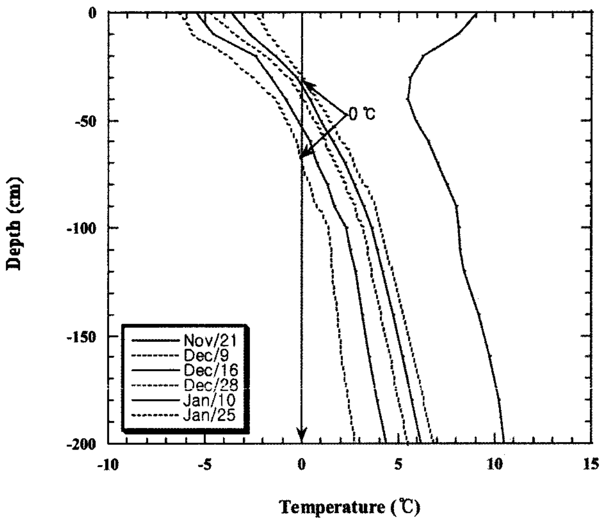


Fig. 12. Test section temperature profiles for 1997-1998

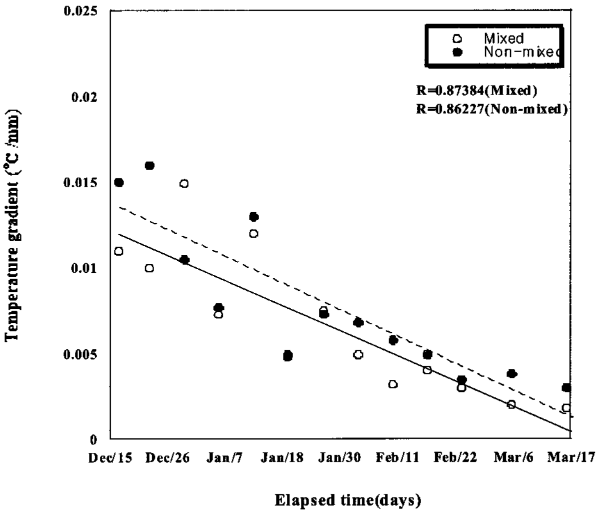


Fig. 13. Temperature gradients for the 1997-1998 winter season

mixing powdered tires into soil, the results of the field experiment were examined based on the so-called segregation potential (SP) theory proposed by Konrad (1980, 1982). The results of this analysis are given in the next section.

5.2 Evaluation of the Tire Powder Mixture Effect Using the SP Theory

According to the SP theory, an ice lens grows somewhere inside frozen soil, slightly behind the freezing front, which is the warmest isotherm at which ice can exist in the soil pores. The growth of the ice lens depends mainly upon the temperature gradient in its vicinity. In the simplest form of the model, the segregation potential is given by:

$$V = SP \cdot gardT \tag{1}$$

where V is the velocity of water intake (mm/s) and gardT is the temperature gradient adjacent to the growing ice lens (℃/mm).

5.2.1 Temperature Gradient Near Frozen Fringe

An example of a soil temperature profile observed during the field experiment is shown in Fig. 12. Each temperature in the profile was calculated using mean daily temperatures recorded at 4-hour intervals.

In this study, we assume the space between the location where the temperature is 0℃ and the nearest upper thermocouple to be the frozen fringe, and calculate temperature gradients using temperature data at these points during the freezing period. The slope of the temperature profile then becomes the temperature gradient near the frozen fringe because of temperature profile interpolation. The relationship between daily temperature gradients and elapsed time for both sections is shown in Fig. 13. Fitting the data to the plots, we obtain values for the time-dependent function grad(t)=A-B(t), where grad(t) is the temperature gradient in the frozen fringe, t is elapsed time (days), and A and B are constants. The temperature gradient of both soils tended to decrease gradually as temperatures fell starting in the middle of December, although individual temperature gradients for both test conditions varied considerably within a range of 0.015-0.003℃/mm.

5.2.2 Velocity of Frost Heave and Velocity of Water Intake

Equation (1) shows that the velocity of water intake and temperature gradient are proportional to the SP value for a soil. The relationship between velocity of frost heave and velocity of water intake can be described by:

$$V = (1/1.09)\times dh/dt \tag{2}$$

where dh/dt is the frost heave velocity. By substituting Eq. (1) into Eq. (2), the velocity of frost heave can be expressed as follows:

$$dh/dt = 1.09 \cdot SP \cdot gradT \tag{3}$$

Thus the result that differentiated frost heave amount measured in 7 day interval by time (Fig. 5) becomes the velocity of frost heave. Similarly ground surface frost heave rates calculated for both test sections plotted against elapsed time are shown in Fig. 14. The relationship between elapsed time to heave rate was then obtained by fitting data to f(t)= C-D(t) where C and D are constant. In the early stages, the frost heave rate of both soils was very high, then generally decreased as time passed.

5.2.3 SP Comparison of Mixed and Non-mixed Soil

Based on the procedures outlined in sections 5.2.1 and 5.2.2, SP was calculated by substituting the temperature gradient and velocity of frost heave into Eq. (3). The one to one correspondence of temperature gradients and frost heave velocities calculated for the same points in time are shown in Fig. 15. Calculated SP and the results of a simple linear regression on mixed and non-mixed soil for three winters from 1996-1999 are shown in Table 2 and Fig. 15.

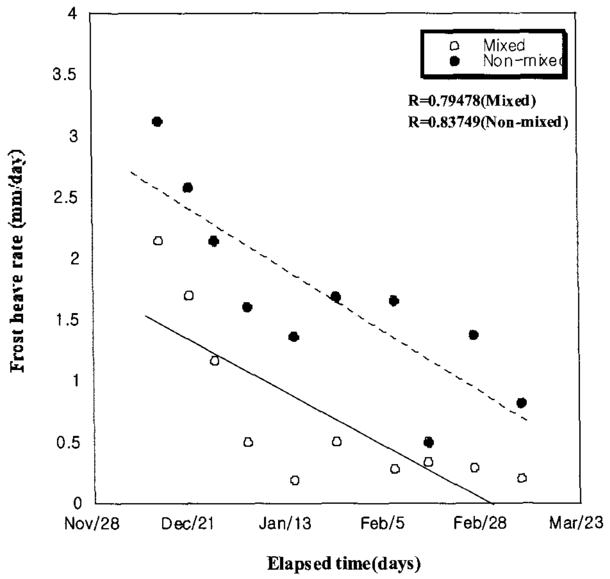


Fig. 14. Frost heave rates for a winter season of 1997-1998

The difference in frost susceptibility between the tire powder-mixed and non-mixed soil is clearly visible using SP values. The SP value of a soil depends on soil type and two other external conditions, overburden pressure and pore water pressure at the frost front. In our field experiments, these conditions are the same in the mixed and non-mixed sections throughout the whole freezing periods as both sections are located in one waterproof pool. SP differences depend solely on soil characteristics or properties other than thermal conductivity and permeability.

6. Conclusion

Field trials were conducted over three winters (1996-

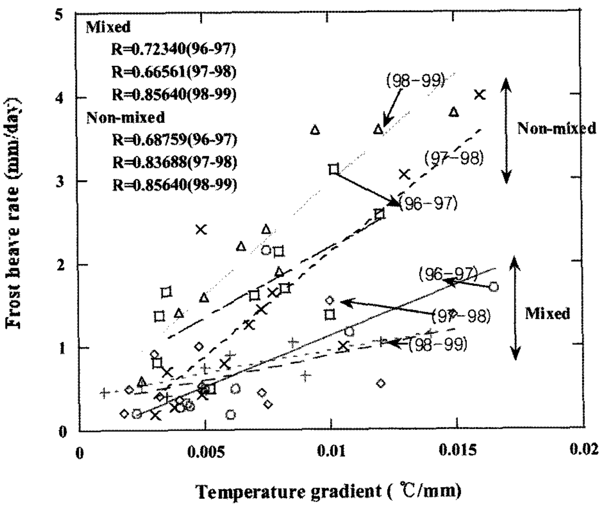


Fig. 15. Relationship between frost heave rate and temperature gradient

Table 2. SP values obtained by linear regression for the 3 winters from 1996-1999 (units: $mm^2/s \cdot day$)

Type	1996-1997	1997-1998	1998-1999	Mean
Non-mixed section	167	249	264	225
Mixed section	121	59	54	78

1999) to investigate the effect of granulated rubber powder as a new frost heave restraint material. The following conclusions can be drawn from the results of the research:

(1) The frost heave reductions achieved by mixing powdered tires into soil were not due to the insulating effect of rubber.
(2) The frost front in the mixed section penetrated deeper than in the non-mixed section. This may be a latent heat diminution effect caused by water-repellent properties of the rubber and decreased specific surface area in the mixed soil.
(3) Our 3-year field experiment found that mixing soil with granulated tires (20% by weight) reduced the frost heave ratio by about 75%.
(4) The segregation potential (SP) value of the soil decreased 65% by mixing 20% tire powder by weight into the soil. This large SP difference explains how the frost heave of mixed soil is restrained by the addition of powdered tires.

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