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# Investigating Failure of a Road Section Due to Frost Heave

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Introduction

The Pennsylvania Slag Producers (PSP) who are members of The National Slag Association (NSA) are presenting comments regarding a Penn DOT new plan note that restricts the use of slag in unbound aggregate base applications when the absorption exceeds 3.5%. This plan note was applied to Penn DOT Project 2260 in District 8 where the unbound aggregate base was used under concrete. This plan note was also subsequently applied to SR 65 in District 1 requiring 26,000 tons of base aggregate on a main line pavement and is now being more widely used by Penn DOT on other projects.

The initiation of the plan note stems from an incident on SR0022 in District 9 specifically related to frost heave that resulted in pavement failure. Subsequent investigation conducted by Penn DOT included subbase boring at SR0022. It was noted that the core holes quickly filled up with water and it was inferred that water entrained in the subbase material is responsible for the frost heave. It has also been established that the particular section of roadway that failed was open to traffic although still under construction and awaiting placement of a surface wearing course layer. It was determined that the subbase was a mixture of steel slag and blast furnace slag and the subgrade was clay. To adequately address the actual cause of road failure and the proposed new absorption limit which will prevent future use of steel slag in unbound aggregate base it is important to first review frost action in compacted soils and how it leads to heave and subsequent pavement failure.

Understanding Frost Action in Compacted Soils

The actual amount of frost heaving is generally much more than an increase in volume due to the expansion of water within the soil itself. The formation of horizontal layers or lenses of ice distributed throughout the depth of frost penetration cause the additional change in volume and has been well studied and documented by various researchers including Taber (1929, 1930), Hilf (1975), Penner and Ueda (1977), Penner (1986), Horiguchi (1987) and Konrad (1989). Frost action includes thawing as well as heaving when the ground thaws, the water released from the ice lenses causes localized oversaturation until the excess water can leave the thawed zone. Since thawing commences from the surface and progresses downward, the frozen zone underlying the initially thawed zone acts as an impervious diaphragm tending to trap the excess water in this upper layer (Osler, 1966). Soils susceptible to frost action are those with pores of certain sizes. Silty and sandy clays tend to be frost susceptible. Coarse soils with large pore sizes are not affected. Soils with very small voids can develop high frost heaving pressures, but because of low permeability the volume of water available to form ice lenses is limited (Hilf, 1975). Even with susceptible soils, a water supply must exist in order for frost action to occur, and the amount of water ordinarily contained within a soil is not enough to cause a significant problem. This water supply is often in the form in contact with a silty soil (Åke and Spencer, 2005) in which the water is carried continually by capillary action into the frost zone (Miller 1977; Loch and Kay, 1978) to feed the growing ice crystals as shown in Figure 1.

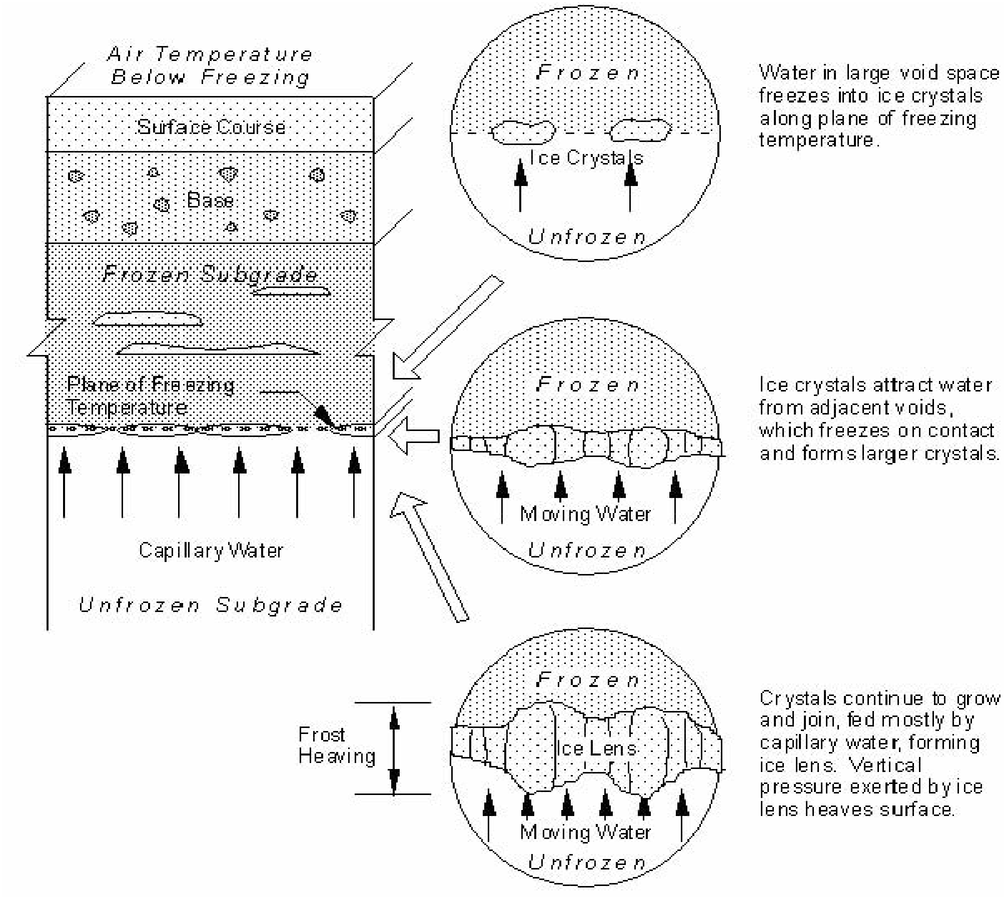



**Figure 1 Illustration of Ice Lens Formation**

Designs to prevent the effects of frost action include:

- Use of soils that are not susceptible to frost action;
- Controlling the water supply and height of capillary rise;
- Insulating against frost penetration;
- Excavation of soils to the depth of frost penetration and replacing them with clean granular material;
- Provide adequate surface drainage and lower the water table so that the water level or zone of capillary rise will not fall within the zone of frost penetration;
- Use intercepting ditches to collect ground water and eliminate perched water conditions.

<u>Review of SR0022 Incident</u>

The subbase coring taken at SR0022 revealed that water was present in significant amounts within the subbase, and the question is, where was this water coming from. Figure 2 below shows the core that was made in the roadway and the material removed from it. The requirement of limiting aggregates absorption to less than 3.5% implies that it is the absorbed water that is responsible for the pavement failure but as noted in earlier discussions water ordinarily contained within a soil is typically not sufficient enough to cause a significant problem. Furthermore coarse soils with large pore spaces are not considered as soils susceptible to frost heave. The fact that water was quickly able to fill the hole left from coring as shown in Figure 3 shown below indicates that there is not adequate drainage within this layer a condition necessary for the prevention of frost heave. The material that was utilized at SR0022 as subbase is slag, and it appears that Penn DOT is of the opinion that slag is the culprit material responsible for the pavement failure due to its absorption potential. Although the absorption potential of slag varies, to date this material has been used extensively in similar applications with no previous incidents of the occurrence of frost heave. An intensive literature search has been unable to yield any conclusive relationship between absorption and heave from frost or ice lens growth and therefore we feel it is inappropriate to conclude that the absorption potential of an aggregate such as steel slag and blast furnace slag is an indicator of its susceptibility to the frost heave phenomenon. Before proceeding any further, we feel that a discussion on the physical characteristics of slag is warranted in order to highlight those qualities that make slag such an excellent construction aggregate especially as a base or sub-base in road construction.

**Figure 2 Core Made in Roadway**

**Figure 3 Water Infiltration**

Slag

Slag comprising both steel slag and blast furnace slag, have been identified as superior construction aggregates primarily in granular base applications that include gradation, compacted density, friction angle, bearing capacity, freeze-thaw resistance, weathering, durability, hardness and impact resistance, abrasion, and drainage characteristics. This material is easily processed to meet the gradation requirements as specified under AASHTO M147. Slag is very stable and as an aggregate it has a high angle of internal friction (40° to 45°) and a high bearing capacity with a California Bearing Ratio (CBR) of over 100% that can reach as high as 300%. Ironically its slightly elevated absorption capacity is essential for its cementitious behavior (Muhmood et al., 2009) a highly desirable property in construction. Slag is also very durable, free draining and is known for its resistance to weathering and erosion particularly from phenomenon such as freeze-thaw. The performance record of these materials in construction applications is well documented (USDOT, 2010) and it has been shown that when properly selected, processed and built within specified guidelines, slag is an excellent material in applications such as road bases or subbases with a resilient modulus that exceeds those of traditional granular materials (Luciana et al., 2003). Quality control similar to those applied on conventional aggregates is recommended for slag where standard field and laboratory test methods including AASHTO T191, T205, T238, and T239 are employed. One of the criteria required in road construction is limiting the quantity of fines. An inspection of the core taken from SR0022 see Figure 4 below shows coarse and fine material. The significance of fines content and how varying amounts can impact quality will be discussed further.

**Figure 4 Slag From Coring**

**Tube City IMS (TCIMS) Forensic Investigation**

***Materials:***

In order to investigate the effects of conditions the construction materials that were involved in the actual road construction were subjected to during the period of time when the SR 0022 roadway heaved, TCIMS investigators conducted sampling and testing of these materials. Material sampling of an Indigenous Clay below the road surface and shoulder near a drainage culvert was carried out approximately 3-5 feet below the road surface, and fines in the clay subgrade is believed to be material that can impact quality. Steel Slag from the TCIMS Parkhill Site was also sampled from a current approved Penn DOT 2A stockpile. Limestone used as conventional aggregate was also included for comparison purposes.

***Procedure:***

Various configurations were tested to simulate and allow for a comparison of the actual composition or physical make up of the SR0022 roadway in question. A cross section of the compacted material in the mold would simulate a bottom layer of clay which represents the sub grade and a top layer of 2A material (either 2A Steel Slag or Limestone) which represents the subbase of the roadway. Each of the materials 2A Steel Slag, Limestone, and Indigenous Clay were also tested separately to establish a baseline comparison of the expansion potential.

Round #1: The 2A Steel Slag and Indigenous Clay were graded, a representative 14 lbs. sample of each, based on their gradations, were compacted into 6” molds as per ASTM D-1557 Modified Proctor. A 2:1 configuration of Steel Slag (top 2/3 of mold) and Indigenous Clay (bottom 1/3 of mold) was also compacted in the same manner. A swell plate along with a 10 lbs. surcharge was placed on top of the compacted material in the mold; this was then placed in a Stainless Steel tank.

Round #2: Testing in Round #2 was conducted on representative 14 lbs. samples of 2A Limestone, and Indigenous Clay. A 2:1 configuration of 2A Limestone (top 2/3 of mold) and Indigenous Clay (bottom 1/3 of mold) was prepared and also tested.

Round #3: Testing in Round #3 was conducted on a representative 50/50 configuration of 2A Steel Slag (top 1/2 of mold) and Indigenous Clay (bottom 1/2 of mold) as well as a 50/50 configuration of 2A Limestone (top 1/2 of mold) and Indigenous Clay (bottom 1/2 of mold).

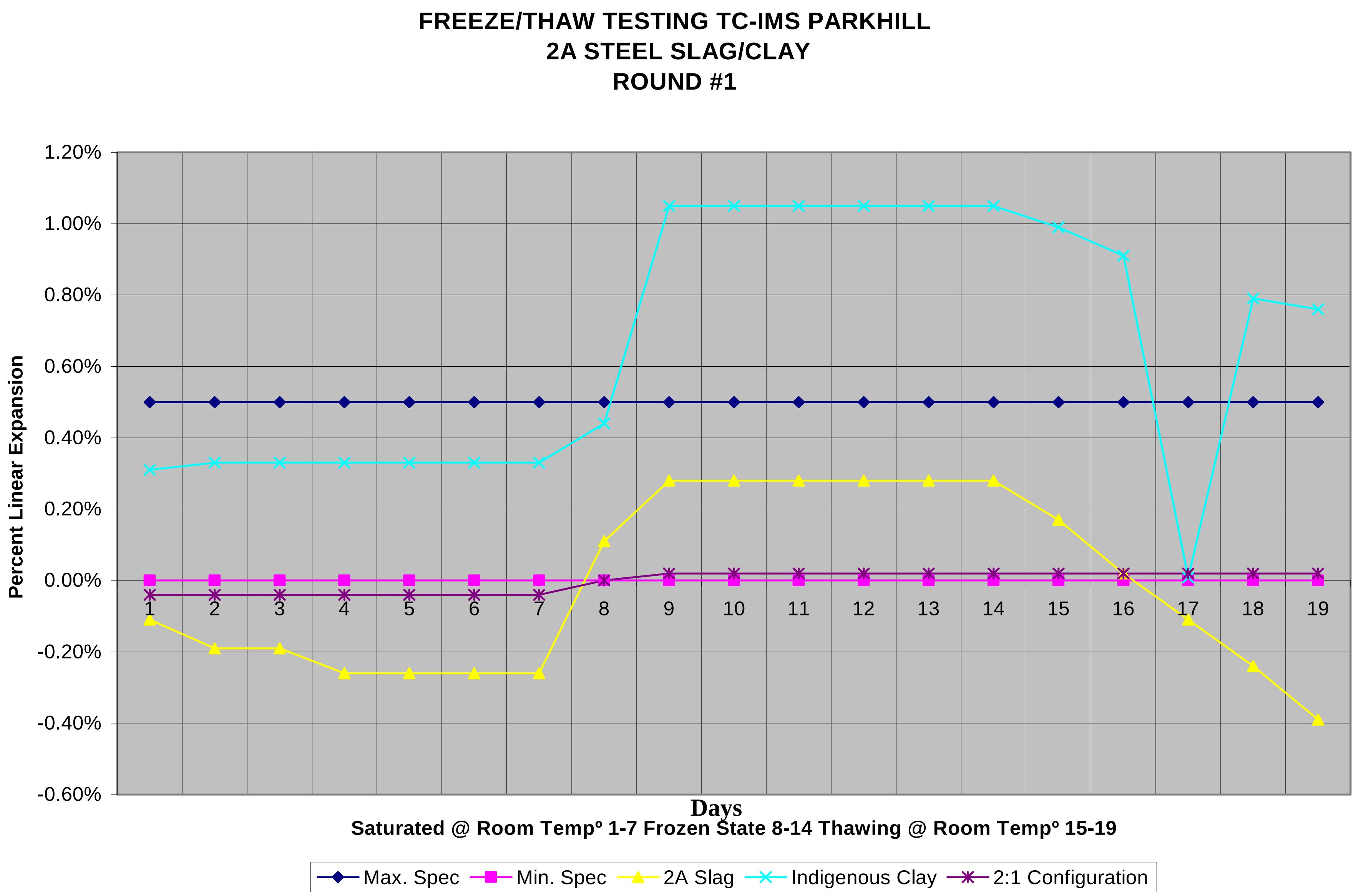
In order to replicate the natural environmental conditions that the roadway would encounter over the change of seasons in Western Pennsylvania, the test molds were subjected to the following 3 stages:

*Saturated State:*
Each mold containing the compacted materials and appropriate surcharges were placed in stainless steel tanks and filled with tap water until the level of the water reached the brim of the mold. This was completed to assure that the entire volume of the compacted material would be saturated. A tripod with a dial indicator was affixed to the mold and the amount of linear expansion at room temp° was monitored and documented daily for a period of 7 days.

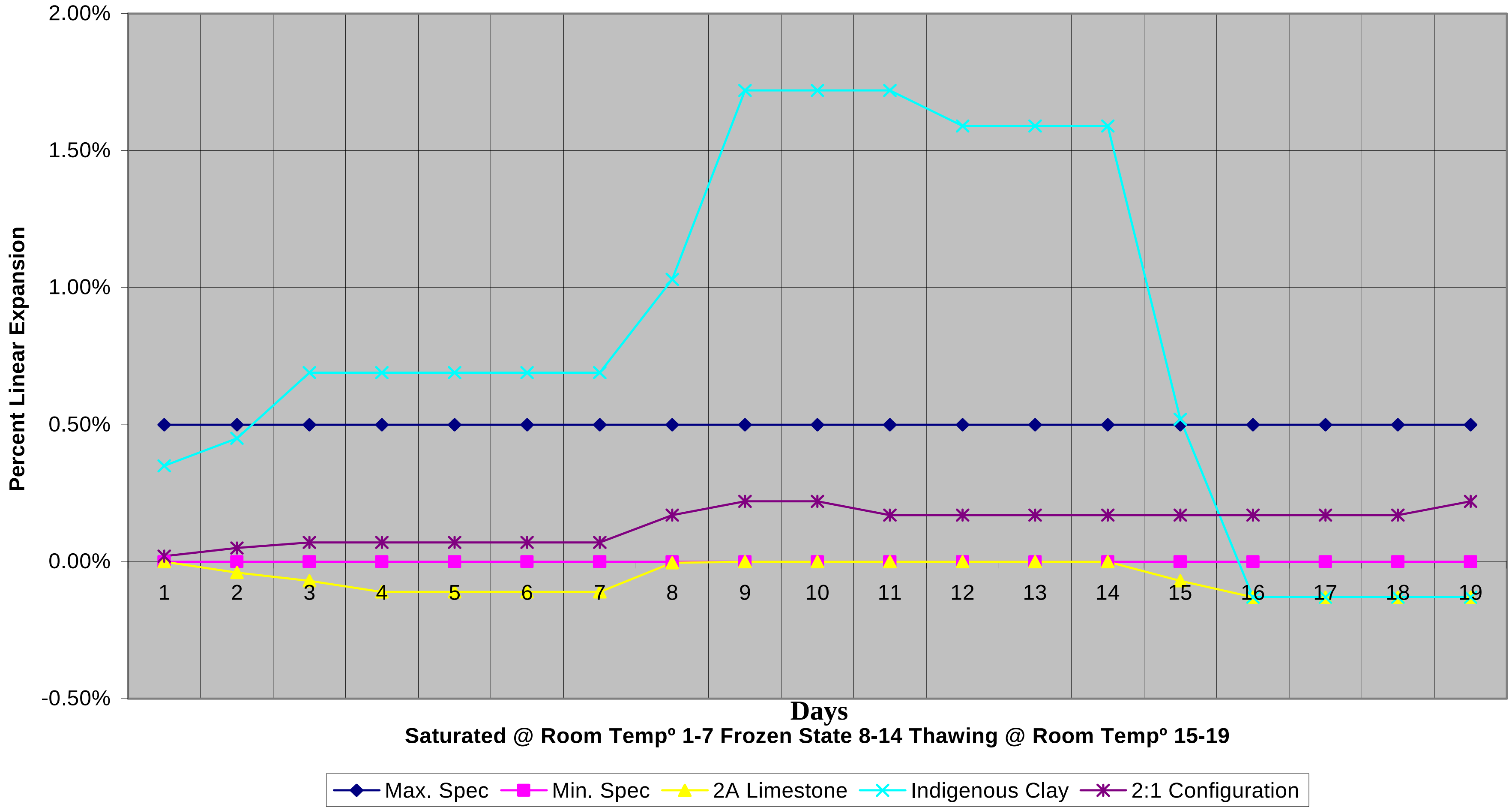
*Frozen State:*
At the conclusion of 7th day of the saturated stage, the sample was then placed in a chest freezer and allowed to freeze at a temperature of minus 4° F. The percent of linear expansion was monitored and documented for a period of 7 days.

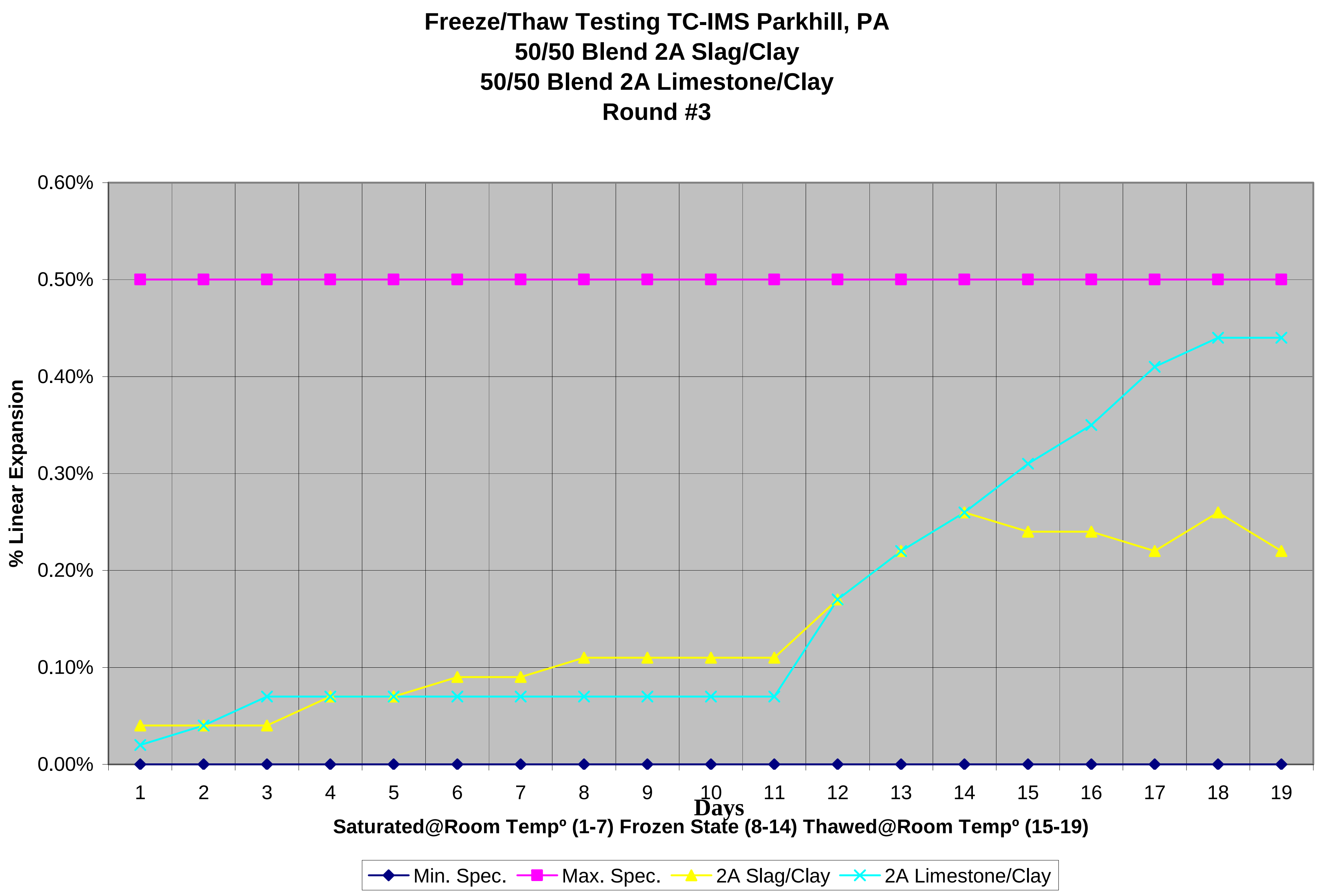
*Thawed State:*
At the conclusion of the Frozen Phase, which would be the 14th day, the then frozen sample was allowed to thaw at room temp for a period of 5 days while the amount of linear expansion was monitored and documented daily.

This testing regimen was devised to demonstrate the adverse hydraulic effects that could possibly occur to a saturated sub base material due to freezing, as well as the expansive characteristics of clay, which we believe is included in the make of the sub-grade of the site in question. A graphical representation of the results is presented in the following figures:


FREEZE/THAW TESTING TC-IMS PARKHILL
2A STEEL SLAG/CLAY
ROUND #1
Percent Linear Expansion
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Days
Saturated @ Room Tempº 1-7 Frozen State 8-14 Thawing @ Room Tempº 15-19
Max. Spec
Min. Spec
2A Slag
Indigenous Clay
2:1 Configuration

**FREEZE/THAW TESTING**
**TC-IMS PARKHILL 2A LIMESTONE/INDIGENOUS CLAY**
**ROUND#2**





Freeze/Thaw Testing TC-IMS Parkhill, PA
50/50 Blend 2A Slag/Clay
50/50 Blend 2A Limestone/Clay
Round #3
% Linear Expansion
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Days
Saturated@Room Tempº (1-7) Frozen State (8-14) Thawed@Room Tempº (15-19)
Min. Spec.
Max. Spec.
2A Slag/Clay
2A Limestone/Clay

***Analysis***:

After 7 days in the saturated state at room temp both the 2A Steel Slag and the 2A Limestone actually exhibited a reduction in linear movement of the compacted material in the mold as expressed by the dial indicator. Conversely the sample of Indigenous Clay material began to moderately expand from day 1 of the saturation phase.

During the Frozen State each sample expressed a degree of expansion. The 2A Limestone expanded at a minimum, the 2A Steel Slag expanded, but did not exceed the maximum allowable percent of expansion for a sub base material as specified in the PTM 130 Expansion Testing. The Indigenous Clay demonstrated the most extreme amount of expansion when frozen in this saturated state.

Almost every sample demonstrated some reduction of linear movement during the Room Temp Thaw phase. Both the 2A Steel Slag in Round #1 and the 2A Limestone in Round #2 showed a reduction in the amount of expansion when thawed at room temp. The clay samples are very perplexing because the sample in Round #2 returned to a level actually below its' starting point, where in Round #1 the clay sample only showed a slight reduction in linear expansion during the thaw phase. The exception to this observation was the 50/50 configuration of Limestone/Clay in Round #3. This particular sample expressed no reduction in the rate of expansion during the thaw phase.

These tests show that any expansion associated with the aggregates by themselves as used within this study are well within the allowable expansion parameters specified in PTM 130. Not surprisingly the expansive nature of the Indigenous Clay is expected and on its own has the potential to cause heave problems associated with frost. The combination of aggregate and Indigenous Clay to simulate the subbase, and subgrade respectively shows insignificant linear expansion that is well within the allowable tolerance levels.

## Discussion

It is important to note that slag combined with lime has actually been shown to increase the strength and mitigate the effects of frost heave in frost susceptible soils. Kawabata and Kamiya (1997) concluded that slag and lime stabilized soils increased their long term strength significantly in addition to reducing frost heave and the frost penetration depth. A study by Tester and Gaskin (1996) on crushed limestone with varying fines content acting as base and sub-base under a pavement showed that there was a linear increase in frost heave with increased fines, although the bearing strength was not significantly affected by freezing and thawing. The result implied that if a road base has slightly more fines than permitted, there would be a slight increase in frost heave.

As previously mentioned there has been very little investigation on water absorption and its relationship to frost heave phenomenon since it had already been established by researchers such as Taber (1929) that frost heave is not due to the expansion on freezing of water already contained within a material, since there is usually sufficient air void space to enable this to take place without causing appreciable change in volume. Perhaps the most convincing evidence that such expansion is not a major factor in frost heaving, when freezing takes place in open systems, is obtained by substituting for water other liquids which solidify with decrease in volume as demonstrated by Taber (1932) where he was able to induce heave in specimens containing nitrobenzene. The induced heave did not occur from absorbed liquid but from external forces.

The slightly elevated water absorption of slag is due to its vesicular nature. Note however that the physical properties of slag including good adhesion and good abrasion resistance offers advantages compared to other aggregates. The fact that slag lacks clay and organic ingredients mitigates the capillary action responsible for frost heave. A study by Kettle and Williams (1976) on 29 samples of burnt and unburnt colliery shales from 19 different collieries looked at frost heave in relation to particle size, sedimentation and absorption. Specimen preparation and freezing procedure were based on the test requirements of LR 90 as prescribed by Croney and Jacobs (1967). The specimens were compacted statically in a constant volume mould, immediately extruded, wrapped in waterproof paper and positioned in the frost heave trolley. Sand fill provided lateral insulation so that the freezing front would subsequently move vertically downwards thus simulating conditions in a road, but the sand was not specified in detail. A high water table was created by supporting the individual specimens on porous ceramic discs, the upper faces of which were in water maintained at + 4° C throughout the freezing period. After a pretest conditioning period of 24 hours at room temperature, the trolley was wheeled into a cold room operating at -17° C the push rod system having been zeroed so as to allow subsequent heave to be determined during the 250-hour freezing period (Kettle and Williams, 1976).

The study by Kettle and Williams (1976) comparing burnt and unburnt shales with similar absorption values in excess of 7.5% showed significantly less heave in the unburnt shale as opposed to the burnt shale. This was attributed to the higher proportion of fine material in the unburnt shales and to particle crushing in specimen preparation which reduces the role of the coarse particles with the behavior of the clay colloids becoming more important (Kettle and Williams, 1976). Fines as described in this study refer to particles less than 200 mesh (75 microns). With Penn DOT 2A aggregate the amount of fines less than 200 mesh allowable is 0 to 10%. Kettle and Williams (1976) state that colliery shale can be considered as a two-phase material containing porous particles embedded in a matrix of fine material and this provides a basis for further examination of the differences between the freezing behavior of the two types of shale. Their findings suggest that for shales with less than 10% of fine material, the relationship between heave and absorption is essentially linear and, for coarsely grained shales, is consistent with generally accepted concepts. In support of this, it was found that the water uptake during the 24 hour soaking period was appreciable in such shales with high absorption values and this would increase subsequent flow to the freezing front. For shales with greater than 20% of fine material flow through the matrix tends to dominate in this type of material and heave is not greatly influenced by absorption. In such materials the permeability is low and so much of free energy will be used for water transport rather than for uplift and heave. For shales with between 10 and 20 % of fine material, heave increases with an increase in absorption with the shales with an absorption capacity in excess of about 6 % developing substantial heave. The moisture flow in the shales with low absorption is largely through the matrix and the permeability will be reduced by the suction forces. In shales with high absorption, there will also be appreciable moisture flow through individual particles so that, particularly in the burnt shales, permeability is less affected by the suction forces. Thus the mass transport of water is relatively unimpeded resulting in an increased rate, and amount, of heave (Kettle and Williams, 1976). Interestingly enough the authors also acknowledge that earlier studies by Croney and Jacobs (1967) found no correlation between heave and absorption even with the inclusion of burnt shale in their investigations.

We earlier stated that slag as a particle is vesicular in nature, and this property which amounts to an increase in surface area is what enables it to have the larger absorption capacity not typical of other aggregate materials. To understand this assertion, a slag particle can be compared to a dimpled golf ball the major difference being that the dimples in slag penetrate the particle more. The characterization of the slag particle as porous is not entirely accurate and it is better to characterize the physical structure of slag as containing irregular pores that terminate inside the matrix. These pores are not interconnected and this is best illustrated in Figure 5 which shows a schematic of pores within a slag particle. The blue shaded area in Figure 5 represents pore water absorbed within the matrix. As you can see from this illustration the pore water absorbed within the matrix has room to expand, but more importantly this water is not available as capillary water required to grow the ice lenses required for frost heave. If you recall in Figure 1 we discussed ice lens growth responsible for frost heave as being facilitated by capillary flow within a soil structure. The pore structures illustrated in Figure 5 are not interconnected and therefore there is no path from the bottom unfrozen zone as is required for capillary flow action to occur. This also helps explain why the Kettle and Williams (1976) study showed in some cases a relationship between heave and absorption. The colliery shale is a porous structure with interconnected pores that can allow for the flow through of water within the structures matrix. However for most aggregates such as slag any pore that may exist within its matrix does not create flow through channels.

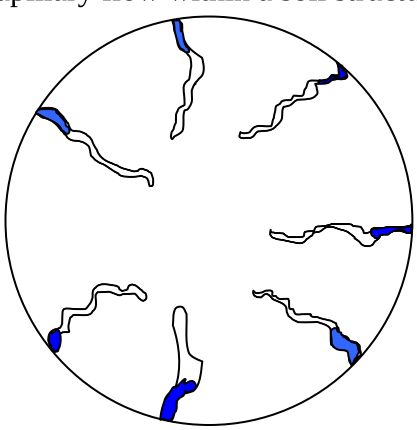


**Figure 5. Illustration of Vesicular Nature of Slag Particle with Absorbed Water.**

<u>Conclusions</u>

1. Researchers such as Yilmaz and Karasahin (2009) have shown that the physical properties of slag particularly, the LA and CBR values and high frost resistance, qualify slag as aggregate suitable for pavement layers.
2. Studies such as those of Croney and Jacobs (1967) show that there is no correlation between heave and absorption.

3. The TCIMS study confirmed Yilmaz and Karasahin's findings and demonstrated success under a worst case scenario that included exposing the entire slag and clay blended sample to both saturated and freezing conditions. The frost heave absorption studied carried out by TCIMS investigators on slag and clay blends showed that any expansion that occurred was well within the allowable limits.
4. Slag particles characterized by irregular pores that terminate inside its matrix do not enable capillary flow from the unfrozen zone to the frozen layer, and therefore act as a barrier to ice lens formation that results in frost heave.
5. Absorbed water within a slag particle has adequate room for expansion within its pore structure and does not contribute to the overall expansion under a pavement.
6. The proper placement of slag or any other aggregate in a road building application is crucial to achieving the desired performance.
7. The potential of heave due to frost action can be further avoided by providing adequate drainage and constructing well above the water table to minimize the supply of water necessary for frost heave.

Over the last ten (10) years alone companies such as Tube City IMS, Lafarge and Beaver Valley Slag have supplied Penn DOT and others well over 4 million tons of construction aggregate for road projects. Attached is a sampling of the Penn DOT and other construction projects that have used slag as a construction aggregate. The historical use of slag within the Commonwealth of Pennsylvania dates several decades and there has never been an issue with frost heave resulting from its use. The decision to limit the absorption capacity of a construction aggregate to <3.5% is unfounded, and would greatly impact the utilization of slag in Pennsylvania. In light of the evidence presented here please reconsider-your decision to impose absorption capacity limits and restrictions on the use of slag as a construction aggregate.

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