

# Soil Stabilization by Incipient Fusion

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A procedure is given for determination of the melt range of soil-additive mixtures using the phase equilibria approach, thus making possible the choice of a fluxing agent to bring the melt range of the mixtures within the capabilities of existing mobile down-draft heaters. The investigation includes the melt-temperature range of soils with respect to their composition, an analysis of soils representative of the various oxide combinations found in soil types comprising the surface of the earth, and the thermal stabilization of a soil by use of a common fluxing agent to lower the incipient fusion temperature.

The behavior of soils at high temperatures was investigated to predict phase changes and melt ranges for the mineral combinations existing in soils. A list of common clay and non-clay minerals is presented, including structural water contents, typical atomic proportions of dry melt, and melt-temperature ranges, and a method is described for estimating the full-melt temperatures of soils with these data. Some estimated and observed fusion ranges are given for soil aggregate material.

Mineralogy and oxide combinations of common soil types of the world are considered, and a list of representative soils is presented together with the soil mineral contents.

A typical soil from the Sierra Uplift was investigated for mineral content, and the reduction in soil full-melt temperature was estimated for increments of soda ash additive necessary to bring the temperature within usable range for practical thermal stabilization. Pyrometric cone tests, combining visual observation with thermo-electric recording, were used to determine the soil-additive incipient fusion temperatures.

Further research is needed on the effects of type and amount of fluxing agent on the properties of thermally stabilized soils.

•THE INITIAL investigation into high-temperature soil properties was undertaken because a space isotope power supply may eventually return to earth and become buried in a soil, and such a system is thermally very hot. The purpose of this investigation is to show how the approximate melt range of a soil may be determined using the phase equilibria approach, and to show how the soil melt range may be lowered by the addition of an appropriate fluxing agent to make possible the thermal stabilization of a typical soil for road construction with existing equipment.

## SOIL MINERAL COMPONENTS

The entire soil horizon consists of in-place weathered rock or transported material comprised of certain mineralogical suites, which are primarily determined by source material, climate, and topography. There are ordinarily two or three colloidal-size minerals that predominate in a soil depending on the weathering stage of the soil.

The silicate minerals that form the predominant portion of most soils, along with carbonates, sulfates, and oxides, may be described in terms of constituent oxides when considering the melt range of any soil complex. The composition of the crust of

the earth has been estimated to consist of approximately the following oxide percentages:  $\text{SiO}_2$ , 59.8;  $\text{Al}_2\text{O}_3$ , 14.9;  $\text{Fe}_2\text{O}_3$ , 2.7;  $\text{FeO}$ , 3.4;  $\text{MgO}$ , 3.7;  $\text{CaO}$ , 4.8;  $\text{Na}_2\text{O}$ , 3.2;  $\text{K}_2\text{O}$ , 3.0;  $\text{H}_2\text{O}$ , 2.0;  $\text{TiO}_2$ , 0.8;  $\text{CO}_2$ , 0.7;  $\text{P}_2\text{O}_5$ , 0.3; remainder, 0.7. These twelve oxides, which form the predominant portion of the earth's crust, vary in melt temperature from 0 C for  $\text{H}_2\text{O}$  to 2800 C for  $\text{MgO}$  but have an average melt range of about 1300 C.

Certain components of soils were first investigated during the latter part of the 19th century by ceramists to determine their fluxing properties. The soil components of primary interest to the ceramists were the clays and feldspars, especially kaolinite and microcline. During this time research was also conducted on the high-temperature physical characteristics of silica-alumina refractory bricks for use in metallurgical processes.

Most of the soil mineral investigations undertaken in agriculture and mineralogy have involved reactions at ambient temperatures. The study of the formation and alteration of rocks and minerals at high temperatures and pressures has been undertaken primarily in geochemistry and geophysics and is far from being complete. Much work has also been done with the high-temperature phase relations of metals, alloys, and oxides in metallurgy.

### SOLID PHASE REACTIONS

A soil mass consists of a network of solid particles enclosing voids filled with moisture and gas. The solid particles may consist of many different minerals, some of which contain water as an integral part of their crystal lattice structure (hydration compounds). Most solid particles also hold surface water layers by means of molecular attraction (adsorption). A soil mass may also contain carbonate and sulfate minerals which, when heated sufficiently, will degas with subsequent alterations in crystalline structure.

The clay minerals (hydrous layered silicates) may also contain layers of water that are bound to the clay mineral surfaces by the residual negative charges possessed by the clay mineral structures and the cations, such as  $\text{Ca}^{++}$  or  $\text{Na}^+$ , contained in the water. This "bound water" requires considerable heat energy to be separated from the solids. Many common soil minerals suffer a significant weight loss when the minerals are heated through their solid phase ranges. Nutting (1) and Grim (2) have given weight loss data for the more common clay minerals and the more common hydrous non-clay soil minerals.

When the temperature of the soil mass is first increased the free interstitial water is driven off, then the adsorbed water is driven off. The bound water held by the clay minerals may not be completely and irreversibly driven off until many of the hydrated soil minerals, such as gypsum, goethite, and gibbsite, are also dehydrated. As the soil mass is heated further the hydration water is driven off and new minerals are formed having different crystalline morphologies. Often several solid-state phase changes may ensue, with the hydration water being driven off in stages and then the anhydrous minerals going through several phase changes.

At higher temperatures the carbonate soil minerals, such as calcite and dolomite, begin to break down, the partial pressure of the carbon dioxide increases rapidly, even in calcite above 600 C, and at higher temperatures the solid-state phases of the oxides result (1, p. 216). The chlorides, sulfides, and sulfates are metastable when heated in air; the sulfides tend to become sulfates and the minerals melt without oxidizing when forming a predominant part of the soil mass. If a large part of the surface area of the soil mass is exposed to air the chlorides and sulfates will eventually oxidize with a resultant loss of chlorine and sulfur dioxide as the temperature is increased; however, the sulfates tend to be stable even in the molten state under some conditions. Of these chlorides and sulfates, halite and gypsum are the only two common soil minerals that are encountered in soils, and these minerals seldom comprise a predominant part of the soil masses except in hot arid playas, such as the bolsons of the southwest United States.



TABLE 2  
COMMON CLAY MINERALS

Mineral	Structural Water (%)	Typical Atomic Proportions of Dry Melt								Melt Point (deg C)		
		CaO	K <sub>2</sub> O	Na <sub>2</sub> O	FeO	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Estim.	Observed
<b>Kandites:</b>												
Kaolinite	14.3	—	—	—	—	—	—	—	0.460	0.540	1810	1785
Halloysite	17.4	—	0.006	—	—	—	—	—	0.456	0.538	1800	1775
<b>Smectites:</b>												
Montmorillonite	21.2	0.030	—	—	—	0.029	—	0.041	0.236	0.664	1490	—
Nontronite	22.4	0.029	—	—	—	0.380	—	—	0.071	0.520	1580	—
<b>Micas:</b>												
Muscovite	4.8	—	0.106	0.009	—	—	—	—	0.395	0.490	—	1255-1290
Phlogopite	3.1	—	0.098	—	0.048	0.031	0.016	0.231	0.158	0.418	1200	—
Biotite	2.3	—	0.086	—	0.186	0.056	0.038	0.094	0.153	0.387	—	1155-1240
<b>Others:</b>												
Illite	7.2	—	0.071	—	—	0.041	—	0.019	0.279	0.600	1590	—
Vermiculite	19.1	—	—	—	0.012	0.065	—	0.291	0.197	0.435	1580	—
Rapidolite	11.3	—	—	—	0.255	0.034	—	0.185	0.231	0.295	1540	—
Attapulgite	19.9	—	0.006	—	—	0.044	—	0.131	0.129	0.690	1530	1380-1500
Serpentine	13.5	—	—	—	—	0.005	—	0.483	0.012	0.500	1800	—

estimated and observed melt ranges are given for non-clay minerals in Table 1 and clay minerals in Table 2. The typical mineral compositions are derived from data tabulated by Deer et al (3).

The most common minerals forming the rocks of the outer crust of the earth are feldspars, quartz, micas, amphiboles, and pyroxenes, the feldspars often comprising more than half of this combination. Because the soils are derived from the earth's rock crust, a large portion of soils will consist of feldspar, quartz, and micas, the amphiboles and pyroxenes being more susceptible to weathering. Clay minerals are largely of diagenetic origin and may be formed in place or be detrital; kaolinite, illite, and montmorillonite are the most common clay minerals.

To determine the melt range for any soil, the mineral constituents of the soil must be identified and the amount of each mineral present must be ascertained. The soil constituents may be expressed as oxides, as in Tables 1 and 2, and their atomic propor-

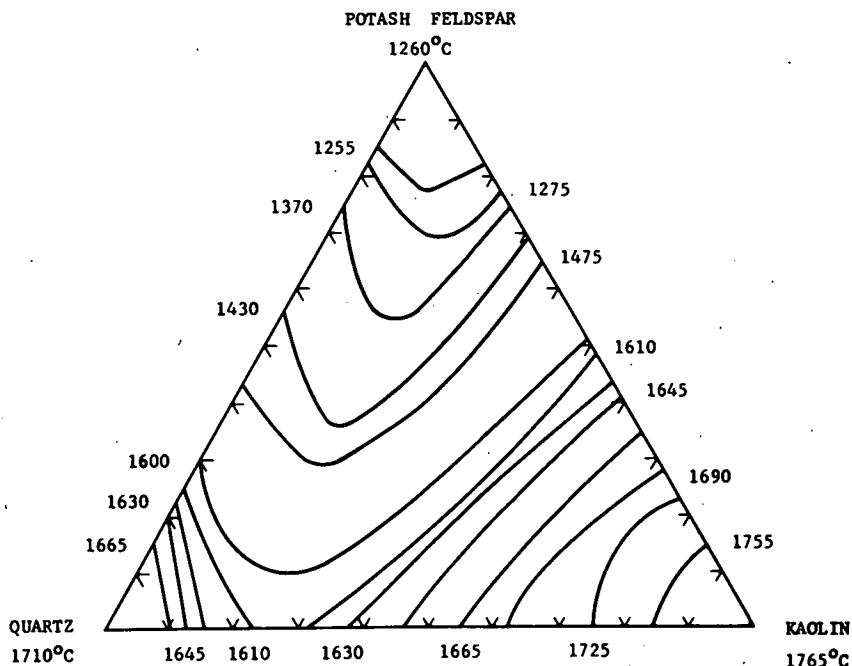


Figure 1. Feldspar-kaolin-quartz ternary phase diagram [after Wilson (6)].

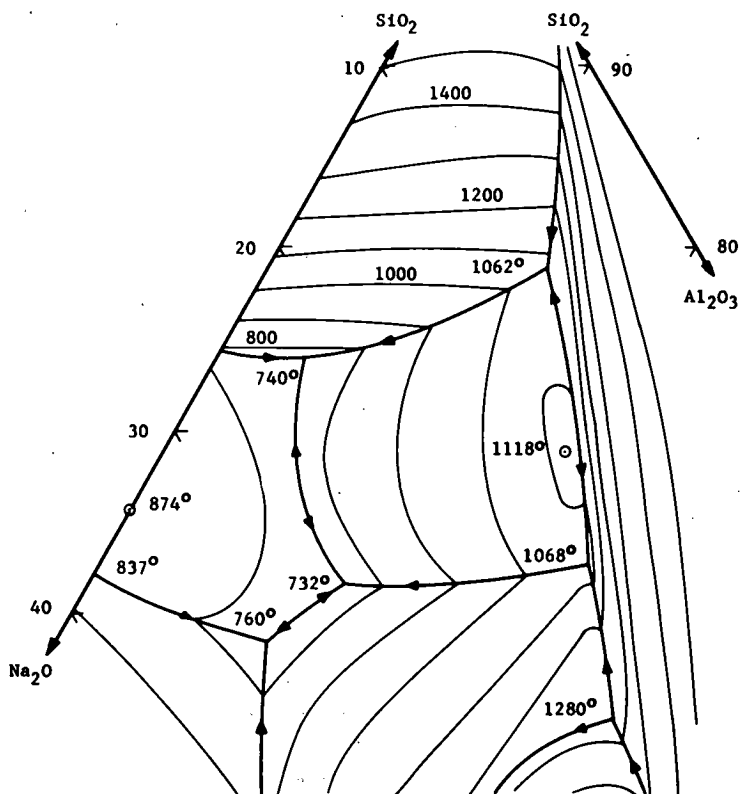


Figure 2. A portion of the system  $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ ; composite [after Levin et al (5)].

tions may then be computed. After the soil mineral composition is determined, a summation of the more predominant oxides must be made.

The upper melt range of the soil may be determined from oxide ternary phase diagrams. In general there will be only three or four predominant oxides in the soil. When more than three oxides are present, an interpolation must be made between phase diagram temperature values. This interpolation may be considered as linear in nature for purposes of estimating the soil melt range because a slight depression in melt point is ordinarily produced by the addition of another oxide. The amount of melt temperature depression is given by Raoult's law.

The most common phase system encountered in the study of refractories is the silica-alumina binary phase system, including the most common clay minerals. Refractory bricks made from these clays are in this binary phase system. A direct comparison may be made between estimated and observed melt temperatures for different silica-alumina ratios (4).

The most common rock minerals—the feldspar suite—contain a discontinuous solid-state series of mineral compositions consisting of lime, soda, and potash feldspars. Minor amounts of some other oxides may be present in the feldspars but are not common. The feldspar ternary phase diagram is given by Levin et al (5, p. 313) and shows that the potassium and sodium feldspars, as well as the potassium and sodium oxides, have similar melt ranges except for the formation of leucite from potash feldspar when more than about 75 percent of potash feldspar is present.

The fusion ranges for the potash feldspar-kaolin-quartz (flint) ternary phase system were determined before 1907, as shown by Wilson (6, p. 252). Soda feldspar gives melt ranges similar to the potash feldspars, so that the phase diagram (Fig. 1) may be used to estimate the melt ranges of mixtures when albite or perthite are used instead of the microcline.

Phase diagrams are given by Levin et al (5) and Muan and Osborn (7) for all of the more common soil mineral oxides that may be encountered. A portion of the  $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$  ternary phase diagram is shown in Figure 2. Phase diagrams give full-melt temperatures for pure mineral systems in each case. Because there are always minor constituents and trace elements in soils, melt ranges for soils will nearly always be lower than those indicated by ternary phase diagrams. As an example, the fusion temperatures given in Figure 1 are generally about 100 C below those given by the comparable  $\text{Al}_2\text{O}_3-\text{K}_2\text{O}-\text{SiO}_2$  ternary phase diagram. Some metal oxides, such as  $\text{Na}_2\text{O}$ , greatly depress the melt point of oxide mixtures, even when present in small quantities.

Additional ternary phase diagrams most relevant to soil minerals are the seven diagrams that include  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  as end points together with either  $\text{CaO}$ ,  $\text{FeO}$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ , or  $\text{TiO}_2$  as a third end point, as well as composite systems  $\text{CaO}-\text{MgO}-\text{SiO}_2$  and  $\text{MgO}-\text{FeO}-\text{SiO}_2$ . The quaternary phase diagrams (7) of  $\text{CaO}-\text{MgO}-\text{SiO}_2$  for differing amounts of  $\text{Al}_2\text{O}_3$  are also very helpful.

The ternary phase diagram, Figure 1, includes many of the common pedalfers soils of the humid temperate and subtropical zones of the world, potash-soda feldspars being considered together. The upper melt range of the potash feldspar-kaolin-quartz mixtures may be computed in the following manner, considering a mixture of 25 percent K-feldspar, 50 percent kaolin, and 25 percent quartz:

25% K-feldspar

Formula (ideal)	$\text{K}_2\text{O}$	$\text{Al}_2\text{O}_3$	$6\text{SiO}_2$	
Atomic weight	94	102	360	= 556
Atomic proportion [A.P.]	0.163	0.184	0.647	
A.P. X 25%	4.2%	4.6%	16.2%	

50% Kaolin

Formula (ideal)	$\text{Al}_2\text{O}_3$	$2\text{SiO}_2$	
Atomic weight	102	120	= 222
Atomic proportion	0.459	0.541	
A.P. X 50%	22.9%	27.1%	

25% Quartz

Formula	$\text{SiO}_2$	
Atomic weight	60	= 60
Atomic proportion	1.000	
A.P. X 25%	25.0%	

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Oxide ratio	$\Sigma$	4.2%	27.5%	68.3%	= 100.0%
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The observed and estimated full-melt temperature (Figs. 1 and 2) may be compared for different proportions of feldspar, kaolin, and quartz comprising artificial soil mixtures. Generally, the estimated melt temperatures appear to be about 100 C higher than the observed melt temperatures. The minerals used to produce the data for Figure 1 were not chemically pure, and therefore a lower melt range is to be expected.

In fusion tests the high viscosity of the melted feldspar, the low rate of solution of the quartz, and the slow diffusion of the partially mixed and partially melted batch materials hinder the attainment of equilibrium and of homogeneity, so that the constituents not only differ from the equilibrium phases but the composition varies throughout the mixture.

The following is an example of the determination of the melt range of a calcareous sandy soil from the Rio Grande basin. The mineral composition was estimated from X-ray diffraction and chemical analyses, and, using the oxide constituent proportions given in Tables 1 and 2, the total oxide content was computed and adjusted for loss of water and carbon dioxide. The computed dry-melt oxide content, in percent, included:  $\text{SiO}_2$ , 73.4;  $\text{Al}_2\text{O}_3$ , 11.7;  $\text{CaO}$ , 9.8;  $\text{Na}_2\text{O}$ , 2.3;  $\text{K}_2\text{O}$ , 2.0;  $\text{MgO}$ , 0.5; and  $\text{Fe}_2\text{O}_3$ , 0.3.

TABLE 3  
FUSION RANGE OF SOIL AGGREGATE MATERIAL

Soil No.	Material	Approximate Melt Range (deg C)	
		Estimated	Observed
(a) Natural soils			
1	Black Hills bentonite	—	1340
2	Calcareous soil, Tijeras, N. M.	1950-2050	—
3	Coastal clayey soil, Texas	1600-1620	—
4	Estancia Playa soil, N. M.	1350-1400	1220-1260
5	Granitic detrital soil, N. M.	1200-1320	1310-1335
6	Hawaiian lateritic soil	1900-1950	—
7	Hayes, Kansas, soil	1250-1495	1235-1285
8	Magnesian soil, N. M.	1350-1435	1260-1310
9	Podzol soil, Wisc.	1350-1450	—
10	Rio Salado dune sand, N. M.	1300-1400	1330-1340
(b) Aggregates			
	Basalt (and gabbro)	—	1140*
	Clays (North America)	—	1580-1800
	Clays (aluminous)	—	1800-1880
	Clays (carboniferous)	—	1605-1675
	Granite (and rhyolite)	—	800-1100
	Kaolins (southern)	—	1645-1765
	Silica sand	—	1700-1750
(c) Artificial soils			
	Calcareous soil	1300-1325	1235-1300
	Clayey soil	1300-1390	1310-1340
	Organic calcareous soil	1275-1300	1220

\*Basalt may have a melt range from 1100 to 1400 C.

tion of the slag layer still contained much unmelted quartz, the feldspars having nearly all melted.

Lists of observed melt temperature data have been compiled for soil minerals by Norton (8) and Clark (9), but little melt temperature data are available on soil mineral-aggregate material. Some readily available data are listed in Table 3, including melt-temperature data for both rock and soil mineral aggregates. The soil samples used for melt range determinations were prepared by Post (4), and the fusion tests were conducted by R. W. Foster at the New Mexico Bureau of Mines and Mineral Resources for Sandia Corporation.

The artificial soils included the following minerals: calcareous soil containing 25 percent calcite, 15 percent kaolinite, 30 percent perthite, and 30 percent quartz; clayey soil containing 10 percent calcite, 30 percent kaolinite, 30 percent perthite, and 30 percent quartz; and organic calcareous soil containing 22.5 percent calcite, 13.5 percent kaolinite, 27.0 percent perthite, 27.0 percent quartz, and 10.0 percent carbon. The fusion range of granite and basalt were taken from data by Tuttle and Bowen (10), and the remainder of the aggregates, listed in Table 3, from Norton (8).

## WORLD SOIL TYPES

### Common Soil Constituents

The predominant soils that comprise the surface of the earth have been classified in terms of soil assemblages (11) and weathering stage (12). These classifications are very general and not always consistent. Although moisture content, grain-size distribution, and density are important parameters in the investigation of the fusion and heat conductance of soils, the mineralogical composition of soils is by far the most important factor in determination of soil fusion temperatures and reaction products.

A determination of soil samples that are characteristic of the majority of the land area of the world was made by correlating soil classification, weathering stage, and predominant mineralogy of the soil types and observing their common constituent characteristics (4). The soil type is primarily dependent on source material, topography,

With the given  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  ratio of 11.7-73.4, the other oxides give approximately the following melt ranges (deg C): CaO, 1470;  $\text{K}_2\text{O}$ , 1050;  $\text{Na}_2\text{O}$ , 950; MgO, 1595; and  $\text{Fe}_3\text{O}_4$ , 1550. Using a linear interpolation based on the ratio of the other oxides present, the upper melt limit of the soil was found to be about 1340 C, the perthitic feldspar melting incongruently at about 1200 C.

The surface soil at Trinity Site in the Jornada del Muerto is similar in composition to the soil of the Rio Grande basin and displays a comparable melt range. The soil at Trinity Site was melted to a maximum depth of about one inch for about a 1500-ft radius from the nuclear detonation, the temperature of the soil surface probably approaching one million degrees centigrade for a fraction of a second and sustaining a melt temperature for several seconds. The X-ray diffraction analysis of the slag (trinitite) indicates that while the surface was completely melted the lower por-

and climate, while the weathering stage is primarily dependent on topography and climate. The soil type and the weathering stage of the soil are, of course, time-dependent.

The world distribution of soil and rock includes 12 kinds of soil assemblages, which were selected by Goldberg et al (11) as representative of the most common soils, where soil is considered to be the natural unconsolidated material overlying consolidated rock.

The weathering stage of the soil types was derived from the soil weathering classification proposed by Jackson et al (12) and was used to aid in determining the predominant mineralogy possible for each soil type.

The first five of the twelve soil types and lithosol have common constituent characteristics that comprise 46.7 percent of the total land area of the world. The next three soil types comprise another 9.0 percent of the land area and differ little in mineral content from the first five. It appears from these data that the mineralogical composition of a soil is largely dependent on source materials and, generally, only dependent on weathering where the climate is windy, hot, or humid, or some combination of the three conditions prevail.

The list of ten representative soils in Table 3 are comprised of common soil minerals that include ten of the most common oxides of the crust of the earth in various combinations. The majority of soil minerals are silicates, many of which contain significant amounts of alumina. Of the remaining mineral oxides, sodium and potassium tend to give low soil-melt ranges, as in granitic soils, and calcium and magnesium tend to give higher soil-melt ranges, as in limestones. Iron, aluminum, and titanium oxides tend to give intermediate-to-high melt ranges, as do the clay minerals.

### Soil Mineral Analysis

The mineralogical analyses of the ten soil samples were accomplished by X-ray diffraction, using the spectrometric power technique, and by chemical test procedures. The soils were reduced in size to material passing a No. 140 sieve, and the mineral aggregates to material passing a No. 200 sieve.

The carbonate, gypsum, halite, and goethite mineral contents were determined by chemical test procedures and the other mineral contents were determined by X-ray diffraction. The estimated composition of the ten soil samples is given in Table 4. The soil samples were chosen to be representative of typical soil oxide assemblages found throughout the world soil types rather than typical soils.

The X-ray powder diffraction data that were used for the analyses of the soil samples were obtained mainly from the ASTM powder diffraction file. Many other sources were used, including data published by the British Mineralogical Society (13), the *American Mineralogist*, the *Mineralogical Magazine*, and *Geochimica et Cosmochimica Acta*.

TABLE 4  
COMPOSITION OF REPRESENTATIVE WORLD SOILS

Mineral	Soil Constituents (percent) for Soil No. (see Table 3):									
	1	2	3	4	5	6	7	8	9	10
Quartz	5	8	45	8	45	—	50	—	60	50
Oligoclase	5	1	—	5	20	—	10	25	10	20
Microcline	—	—	—	—	10	—	10	—	15	25
Hornblende	—	—	—	—	—	—	—	—	5	2
Muscovite	—	—	—	—	—	—	—	—	—	—
Biotite	5	—	—	—	—	—	—	—	—	1
Kaolinite	—	—	25	—	—	—	5	—	—	—
Montmorillonite	80	8	25	5	7	—	5	—	—	—
Illite	—	2	—	—	3	—	5	—	—	—
Chlorite	—	—	—	—	3	—	—	30	5	—
Calcite	—	75	—	13	6	—	—	5	—	—
Dolomite	—	3	—	25	—	—	—	—	—	—
Gypsum	—	—	—	31	—	—	—	—	—	—
Goethite	—	1	—	—	—	55	—	—	—	—
Gibbsite	—	—	—	—	—	30	—	—	—	—
Others	5	2	5	13	6	15	15	40	5	2

Note: Sample 4 contains about 8 percent halite, sample 6 about 10 percent  $Fe_3O_4$ , sample 7 about 5 percent mixed-layer clays, and sample 8 about 35 percent talc.

### THERMAL SOIL STABILIZATION

#### History

A discussion of the thermal stabilization of soils may include the production of pottery, ceramics, and bricks; however, the term is also applicable to the increase in stability and bearing capacity of soils by application of heat. Thermal stabilization of soils may also be effected by freezing (14).

The degree and type of thermal stabilization depend on the amount of heat energy used. The free water



may be driven out of the soil by temperatures up to 350 C (reversible) or temperatures up to 550 C (irreversible); the dried soil may be fired to a temperature of 600 C (bricking), or the dried soil may be heated above incipient fusion temperatures.

Thermal stabilization of soils was first used successfully for road construction in Australia nearly 30 years ago (14), and since then the method has also been used for other purposes, such as the stabilization of slopes and foundations (15). Equipment is now available for producing the amount of heat energy necessary for foundation stabilization (14) and surface stabilization (15).

### Procedure

For effective thermal stabilization of soils it is only necessary to brick the soil or to reach incipient fusion temperatures. Most soils melt incongruently over a temperature range so that it is only necessary to reach the initial melt range to effectively cement the soil mass. The bricking of the soil is caused by loss of structural water by the soil minerals with the formation of new minerals.

Fluxing agents are commonly used to lower the melt range of mineral aggregates so that stable products can be more readily formed. Whereas limestone is commonly used as a fluxing agent for steelmaking, it is not suitable as a soil fluxing agent because of its moderately high melting range when included with soil oxides. Calcite, when added to a typical acidic granitic soil in amounts up to 45 percent, will actually increase the soil full-melt temperature slightly (4). Another common fluxing agent in metallurgical work is soda ash (sodium carbonate). Soda ash is readily available at low cost and causes low melt ranges when mixed with soils.

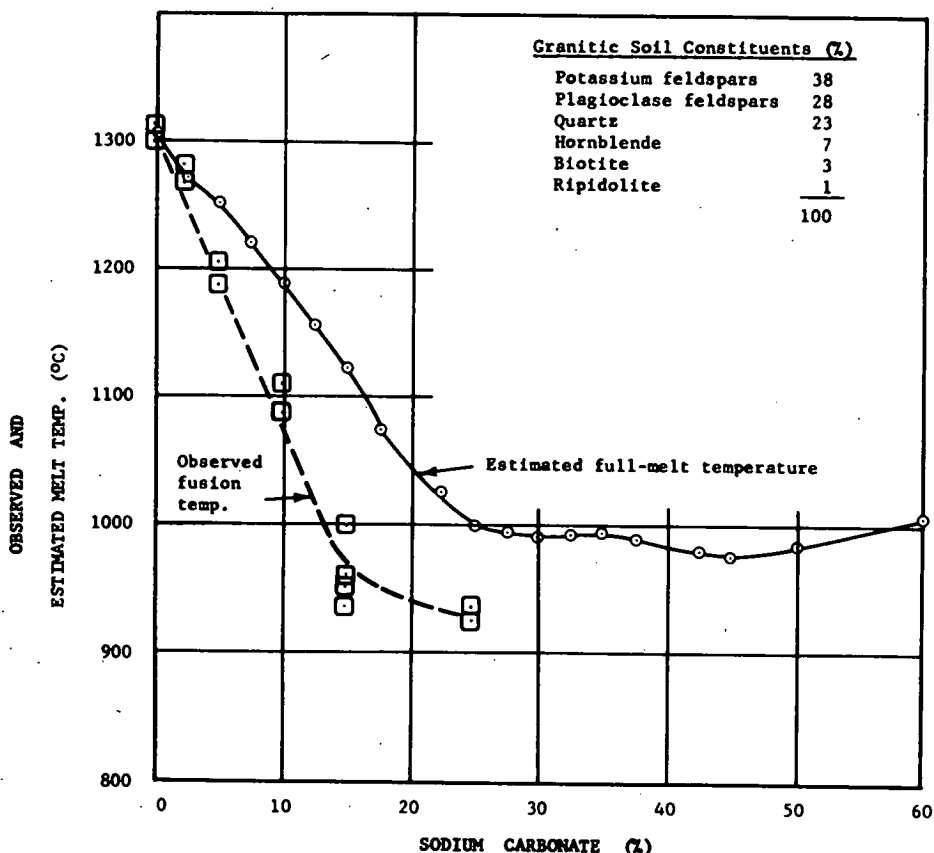


Figure 3. Effect of  $\text{Na}_2\text{CO}_3$  additive on the melt temperature of a granitic soil.

### Fusion Tests

A soil sample was obtained that is typical of the granitic detrital soils of the Sierra Uplift of California. The mineralogical composition of the soil was determined by X-ray diffraction and the dry-melt oxide constituents were computed using the data from Tables 1 and 2.

The soil mineral constituents are given in Figure 3 with the feldspar series in two parts. The potassium feldspars include 22 percent orthoclase, 10 percent microcline, and 6 percent anorthoclase (tentatively), and the plagioclase feldspars include 15 percent andesine, and 13 percent oligoclase. The percentage values represent the average of results from five soil mineral analyses.

The predominant dry-melt oxides in the soil (in percent) were: CaO, 2.7; K<sub>2</sub>O, 4.1; Na<sub>2</sub>O, 3.9; FeO + Fe<sub>2</sub>O<sub>3</sub>, 1.9; MgO, 1.6; Al<sub>2</sub>O<sub>3</sub>, 15.7; and SiO<sub>2</sub>, 70.1. The effect of differing amounts of soda ash additive on the full-melt temperature of the soil was estimated using the ternary phase diagrams and the results were plotted (Fig. 3). The amount of additive is given in terms of percent of air-dry soil weight.

Pyrometric test cones were prepared from mixtures of the granitic soil and the sodium carbonate additive in accordance with a standard method (ASTM Designation C 24-56). The amount of additive expressed as a percent of the air-dry soil weight varied for different specimens from 0 to 25 percent. The test cones were mounted on plaques of refractory clay, and heating was conducted in an electric furnace. Instead of using standard pyrometric (PCE) cones to indicate approximate temperature equivalents corresponding to softening of the test cones, thermo-couples were installed in the furnace and connected to instrumentation for recording temperatures. This arrangement provided for a wider range of measurable temperatures and, it is believed, to more accurate determinations of furnace temperatures. The fusion (end-point) temperature or softening of a test cone was indicated by visual observation of the top bending over and the tip touching the plaque in accordance with the ASTM method. The experimental results are plotted in Figure 3 and indicated as observed fusion temperatures.

As expected, the observed fusion temperatures for the soil-additive mixtures are lower than the estimated melt temperatures because of impurities in the soil. More importantly, both the predicted and the observed values indicate clearly that the melt temperature of the granitic soil can be lowered when soda ash is mixed with the soil.

### SUMMARY

Most soils apparently exhibit a melt range that varies between 1250 and 1750 C, the fat clay soils tending to melt at about 1700 C and the feldspar-rich soils tending to melt at about 1300 C. Soils with a high alumina or lime content tend to have a very high melt range, corundum melting at about 2000 C and calcite at about 2500 C. Soils consisting of detrital granite tend to have a very low melt range of about 1100 C because of the large proportion of potash and soda feldspars normally present in granite. After a soil has completely melted, the melt consists of a homogeneous mixture of oxides derived from the original constituent minerals if the soil is heated in an open-air environment. Theoretical and laboratory investigations indicate that the addition of soda ash lowers the melt temperature range of a typical soil from the Sierra Uplift to within a usable range for practical application.

The effect of other common fluxing agents on the melt range of soils should be investigated for ordinary types of soils. Because of the slowness of heat transmission in soils, the use of additives that include oxidants with fluxing agents should be considered in future research in this area.

Field tests for thermal stabilization of soils should be conducted using existing mobile down-draft heaters modified to treat prepared soil media. The effects of type and amount of fluxing agents on the bearing capacity of a stabilized soil should be investigated.

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