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UTILIZATION OF PELLETIZED SLAGS

UTILIZATION OF PELLETIZED SLAGS

by
Ramesh Prakash Gupta, B.E. (Civil)

A Thesis
Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements
for the Degree
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TITLE: Utilization of Pelletized slags

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(Bangalore University)

SUPERVISOR: Dr. John J. Emery

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SCOPE AND CONTENTS:

The utilization of various pelletized slags (Phosphorus, Finnish and Local Iron Blast-Furnace) in a base stabilization process and for autoclaved block manufacture was studied. For the limited number of slags considered, no clear strength development-hydraulic moduli relationship was found. A pelletized phosphorus slag was considered, but due to the adverse influence of minor constituents such as fluorine, satisfactory product strengths were not achieved. Finnish iron blast-furnace pelletized slags were considered for base stabilization, but unlike the local DOFASCO pelletized slags, do not exhibit adequate hydraulicity without activation. For the DOFASCO pelletized slags, it has been determined that field curing and durability of ground pelletized slag stabilized bases will be satisfactory. The feasibility of autoclaving masonry block using ground pelletized

DOFASCO slag as both a cementitious component and aggregate has been demonstrated.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Dr. John J. Emery and Mr. R.P. Cotsworth for their guidance during this research project, and particularly to Dr. Emery for his assistance and patience during the preparation of this thesis.

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Ramesh P. Gupta

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UTILIZATION OF PELLETIZED SLAGS

1. INTRODUCTION

1-1 BACKGROUND

The primary motivation for this study was to foster the utilization of more secondary products from heavy industry, and specifically, the development of new uses for pelletized slags from the iron industry and elemental phosphorus production. Previous work by Kim [40] in the Highway Materials Laboratory at McMaster University had indicated the potential for cementitions uses of pelletized blast-furnace slag in base stabilization and structural brick manufacture. However, critical areas such as field curing temperature influences and the importance of fines levels on freeze-thaw resistance remained to be studied before the base stabilization process would be viable from a field viewpoint. Also, the use of pelletized slag in structural brick manufacture would not utilize nearly as much slag as cementitious applications in masonry block manufacture. Finally, there is much pelletized phosphorus slag available in the United States that is used for bulk applications rather than cementitious purposes. While this slag contains trace contaminents in terms of hydraulicity, it was felt that cementitious usage in base stabilization might be possible. Thus, while this study fits into the general research activities of the Highway Material Laboratory, there was also a need to extend the previous macro level studies to include some consideration of hydraulic moduli and the various other factors influencing the cementitious nature of glassy slags on a micro scale.

There are two general advantages resulting from the utilization of pelletized slag as a cementing material: firstly, the energy saving since the energy-intensive clinkering process of cement manufacture is eliminated (approximately 80% of energy in cement manufacture); and secondly, the resulting reduction in demand for mineral resources while decreasing potential disposal problems. Obviously, cementitious applications for slags should be emphasized since the potential energy savings (typically 4 million Joules/Kg) are more important to any industrial mineral utilization strategy than simple bulk aggregate applications such as those that air-cooled slags are typically used for. For this reason, this study focusses on the cementitious nature of pelletized slags.

1-2 STUDY OUTLINE

As a background to the study, the various manufacturing processes, chemical compositions and physical properties of iron blast furnace slags and phosphorus slags (with emphasis on pelletized slags throughout) are discussed in the following chapter. Since the pelletized process is a rather new development, and still being extended (for instance from ladle technique to direct runner), considerable information is provided on the equipment process and products involved.

Three pelletized slags were examined during this study: phosphorus pelletized slag (and some foamed) from the Stauffer Chemical Company, United States; Finnish pelletized slags from Oy Koverhar Ab, Finland; and pelletized slags from DOFASCO provided by National slag Limited, Hamilton. Throughout this study, National Slag Limited provided technical cooperation.

As a first evaluation step, considerable effort was spent examining hydraulic moduli (strength indicators based on chemical composition) to determine if any clear relationship exists between the many proposed moduli and pelletized slag stabilized base compressive strengths.

Glass contents (degree of vitrification) was also considered at this time. This aspect of the study is given in Chapter 3 and Appendices A and B. The study then focused on the cementitious properties (hydraulicity) of pelletized slag in base stabilization and masonry block manufacture.

All three pelletized slags were considered for base stabilization (Chapter 4), and the phosphorus slag and DOFASCO pellets for block manufacture (Chapter 5). The effect of activators and moisture content on the hydraulicity of pelletized phosphorus slag in base stabilization was considered in detail since slag chemistry (including the minor constituents) does have a significant influence on potential strength development. No information was available in the literature in the hydraulicity of a pelletized phosphorus slag. As this aspect of the study developed other factors such as washing the pelletized phosphorus slag were investigated.

The grindability of all three types of pellets in the EIRICH R7 intensive mixer was considered as part of the base stabilization and block studies. Throughout these studies, the important aspect of moisture content influence on compressive strength was considered for different curing times. Comparisons of base stabilization accelerated curing (100°F) and normal curing (70°F) strength development were made as this is important to field application. The effect of freeze-thaw cycles on base stabilization specimens containing DOFASCO pellets and different proportions of fines (- #200) was also examined. Compaction equipment and related procedures were developed for the laboratory simulation of autoclaved masonry block manufacture using pelletized slag (Chapter 5 and Appendix C). The actual autoclaving step was done at Cooke Concrete Products Limited in Burlington who also provided technical assistance to this aspect of the study. Utilization of phosphorus pelletized slag as aggregate for making non-autoclaved light-weight masonry block was investigated first. Then the influence of various moisture contents and autoclaving times on strength development of masonry block incorporating pelletized slag fines and pelletized slag aggregate from DOFASCO were investigated in detail.

The concluding chapter of the study summarises the prime findings and gives suggestions for future research. The available literature was used to guide the various aspects of the study and is referenced throughout.

2. BLAST FURNACE AND PHOSPHORUS SLAGS

2-1 PRODUCTION OF BLAST FURNACE SLAG

Slags are the non-metallic by-products produced during the reduction and separation of ferrous and non-ferrous metals from ores. A general classification chart for slags is given in Figure 2-1 with emphasis on the production of ferrous slags. The American Society for Testing and Materials defines blast furnace slag as "the non-metallic product consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace" (C125-74).

The blast furnace operation is a continuous process with the carefully controlled raw materials being fed in at the top and molten iron and slag (0.2 to 0.4 tons of slag per ton of iron [43]) being removed at the bottom part of the furnace. The chemical composition of blast furnace slag depends on the nature of the ore, the properties of the fluxing stone, the coke type and consumption and the quality of the pig-iron produced [60]. Fluxing stone is calcined by the heat of the furnace and dissociates into calcium and magnesium oxides (CaO, MgO) and carbon dioxide (CO_2). These oxides of calcium and magnesium react with the silica, alumina and minor impurities in the iron ore to form the slag. The

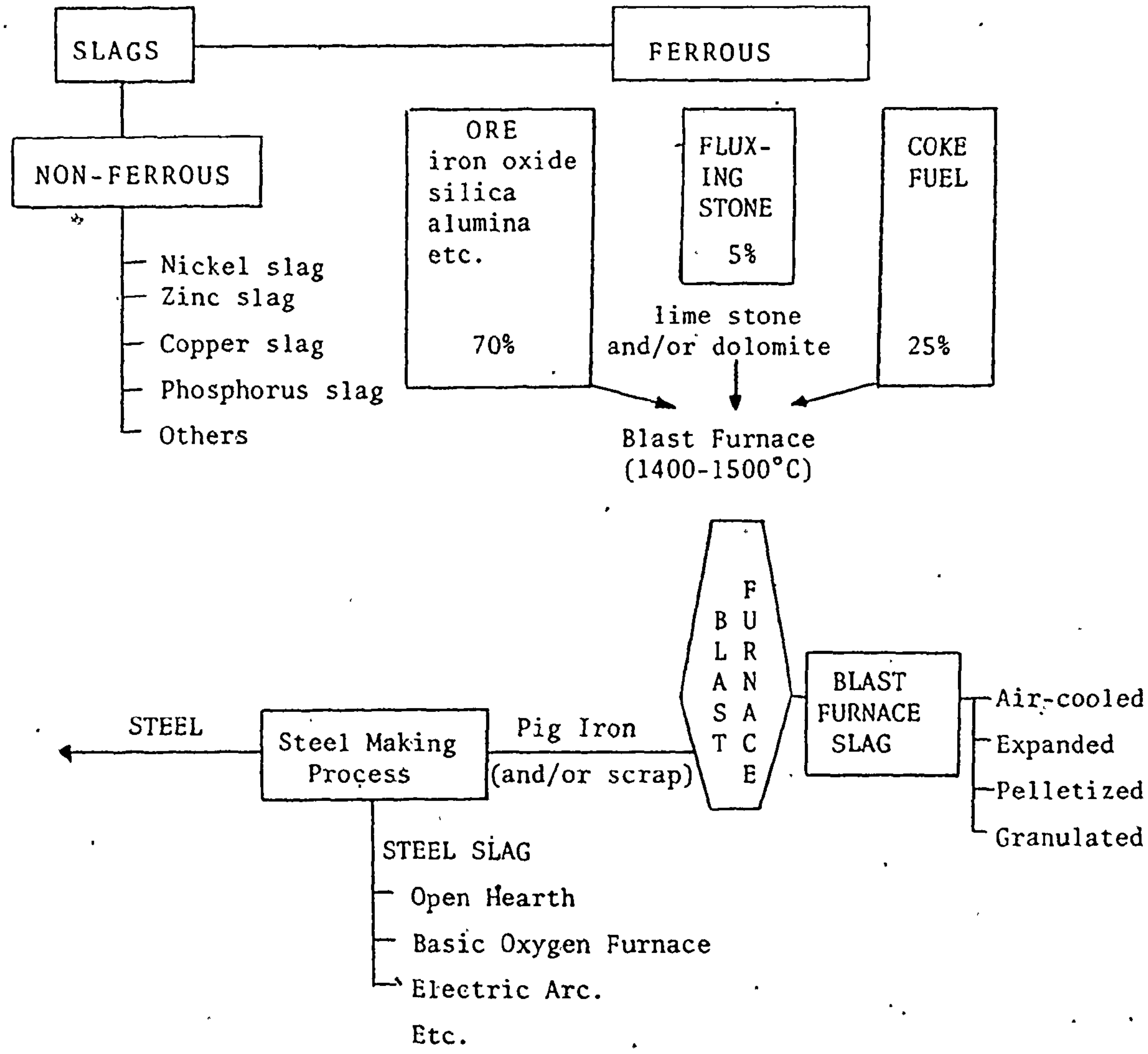


FIGURE 2-1 FERROUS AND NON-FERROUS SLAG PROCESS

other important function of the fluxing lime is to combine with the sulphur that comes from the coke, thereby removing most of the sulphur from the molten iron. Generally, a consistent quality of pig iron is produced and the resulting blast furnace slag also has a reasonably uniform quality. Lack of uniformity in the blast furnace slag can be a significant problem in slag cement manufacturing and other special usages.

Both the chemical and mineralogical composition of blast furnace slag affect its physical properties. Blast furnace slag contains four major oxides - silica, alumina, lime, and magnesia - which constitute about 95% of the total. Minor elements includes sulphur, manganese, and iron, with traces of many other elements and compounds. The chemical analysis of a typical blast furnace slag falls within the range given in Table 2-1..

If the chemical composition of the blast furnace slag remains the same, the density, porosity and mineralogical composition will only be affected by the method of cooling the slag after it leaves the notch at the bottom of the blast furnace. Four distinct types of blast furnace slag can be produced: air-cooled, expanded or foamed, granulated and pelletized, depending upon the method of cooling from the molten state.

TABLE 2-1

TYPICAL CHEMICAL ANALYSIS OF BLAST FURNACE SLAG

CONSTITUENTS		BLAST FURNACE SLAG % [44]	ACTUAL DOFASCO % (b)
Lime	CaO	36 - 43	38.93
Silica	SiO_2	28 - 36	39.00
Alumina	Al_2O_3	12 - 22	8.00
Magnesia	MgO	4 - 11	9.80
Total Sulphur (a)	SO & SO_3	1 - 2	1.80
Total Iron	FeO or Fe_2O_3	0.3 - 1.7	0.75
Manganese Oxide	MnO [36]	0.2 - 1.5	0.67
Potassium Oxide	K_2O	-	0.49

(a) Principally in the form of Calcium Sulphide (CaS).

(b) From D. Hooton, sampled June 27, 1976.

Air-cooled Blast Furnace Slag

Air-cooled blast furnace slag is allowed to solidify under prevailing atmospheric conditions, either in the ladle or a pit and solidification occurs at a temperature of 1400 - 1500°C [43]. Since the slag is allowed to cool slowly, it develops a crystalline structure similar to that of a natural igneous rock. Crystals range from microscopic size to as large as 1/8-inch [44]. After a pit has been filled and the slag cools sufficiently to be handled it is dug out, crushed, and screened to the desired aggregate sizes. While the physical characteristics of air-cooled blast furance slag vary somewhat from furnace to furnace and with time, typical values fall into the fairly narrow range given in Table 2-2.

Foamed or Expanded Slag

Foaming (an European term) of blast furnace slag was first carried out by Carl Schol in Germany in 1911, and substantial quantities are still produced and used as light-weight aggregates [29]. The blast furance slag is discharged rapidly from a ladle into a pit where water is injected into it. The sudden generation of steam inside the molten slag produces a uniformly foamed, grey coloured mass. This foaming process is capable of producing light-weight aggregate from slags with a wide range of compositions.

TABLE 2-2

PHYSICAL PROPERTIES OF AIR-COOLED BLAST FURNACE SLAG

		BLAST FURNACE SLAG		
		(a)	(b)	(c)
sieve analysis	sieve size	% passing		
	1-1/2"	100	-	-
	1"	62	-	-
	3/4"	43	-	-
	1/2"	24	-	-
	3/8"	14	-	-
	#4	0	-	-
Dry weight lb/cu ft	loose	64.80 - 74.00	-	-
	compacted	75.00 - 88.20	76.6	72 - 90
Absorption (24 hr)	%	1.70 - 3.70	2.71 - 4.65	-
Bulk specific gravity		2.15 - 2.41	2.32	2.38 - 2.76
Apparent specific gravity		-	2.45	-
Los Angeles Abrasion (A grading)		29 - 39	41.00	-
Soundness MgSO$_4$ 5 cycle % Loss		-	2.47 - 1.41	-
Polished stone value		-	-	50 - 63

(a) from [5]
(b) from [15]
(c) from [45,44]

According to Lea [43], when blast furnace slags of high CaO content are allowed to cool slowly, they may exhibit the phenomenon known as "falling", i.e., the disintegration of the solidified slag into powder. This is caused by the presence of crystalline β dicalcium silicate in the slag that converts to the γ form with slow cooling [27,68]. The formation of β dicalcium silicate is prevented, if rapid cooling is employed, and there is some controversy in the current literature concerning the possibility of "falling" after any type of blast furnace slag has cooled [26].

In general the sulphur content of foamed slag is less than that of air-cooled blast furnace slag. Since some of the sulphur is released during the foaming process in the form of hydrogen sulphide gas, this can obviously cause environment problems. The chemistry of foamed slags is no different from that of the original molten slag, except for the lower sulphur content.

Granulated Slag

When molten blast furnace slag is suddenly quenched, crystals have no time to form and the slag solidifies as a glassy (vitrified) material. Granulation generally results in a slag with marked hydraulicity and consequent potential utilization in slag cement manufacture.

There are three general methods for granulating slag (granulation is used for many non-ferrous slags also [17, 36]:

(a) Pit process - molten slag is introduced directly into a pit of water.

(b) Jet process - the stream of molten slag is broken up by a high-pressure water jet, and the slag falls into a pit of water to be further quenched.

(c) Dry granulation process - using a mechanical device, the molten slag is granulated into small particles ("slag sand") by impact, then sufficient water for quenching is fed in with the stream of molten slag. Enough heat remains to evaporate most of the residual water and leave a relatively dry product.

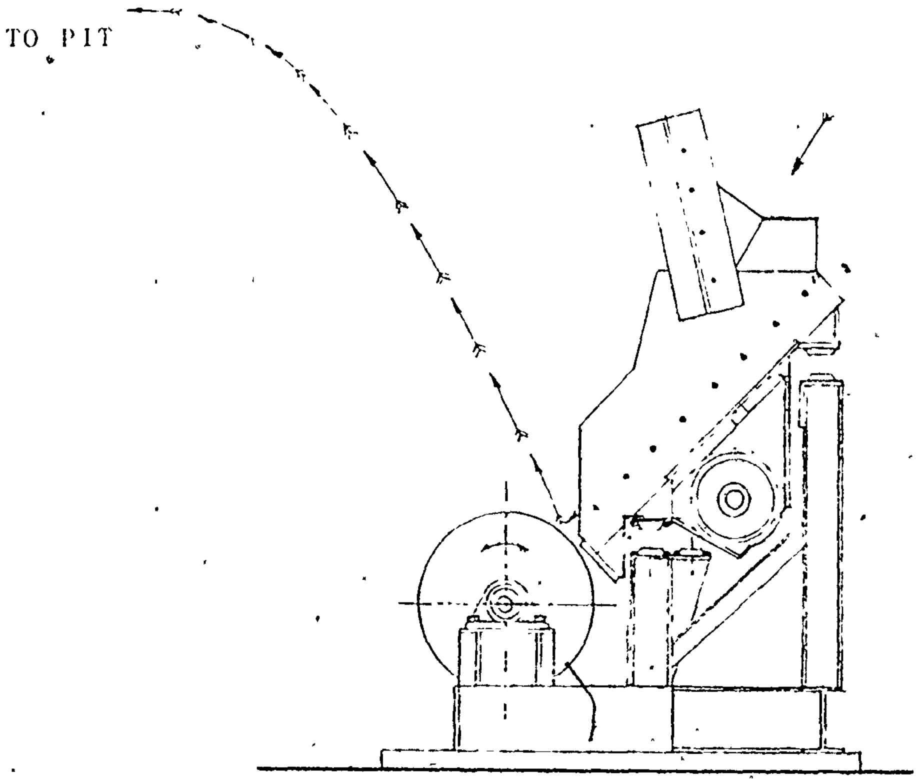
The effect of these processes is found to vary with the temperature of the water; the amount of water used; and the method of water application.

2-2 PRODUCTION OF PELLETIZED SLAG

Pelletized slag is a product categorized between expanded slag and granulated slag because of the physical and mineralogical properties related to its pellet and glassy nature, respectively. The pelletizing process can be viewed as a type of air granulation [42].

The slag pelletizer used in the iron and steel industry was developed by National Slag Limited of Hamilton, as a positive means of bringing the high gas emission levels associated with earlier processes under control [9,35]. Figure 2-2 gives a schematic diagram of the newest type of pelletizers recently installed at DOFASCO's number 4 blast furnace. The molten slag from the blast furnace is fed directly to this pelletizer, which gives significant cost advantages over the other pelletizer at DOFASCO where a ladle is used to transfer the slag.

The production of pelletized slag is a fairly simple process once the appropriate equipment is installed and "tuned". From the runner (or ladle) the molten slag is deflected onto the feed plate under water sprays and the resulting pyroplastic materials falls onto the rotating drum, where the fins on the drum break it up and fling the slag into the air for sufficient time that surface tension forms the pellets. The feeder plate and drum are clear in Figure 2-3 and actual production is shown in Figure 2-4. The deflector plate is adjustable, so that the slag can either flow down the full length of the



Section through pelletizer

FIGURE 2-2 SCHEMATIC DIAGRAM OF TYPICAL PELLETIZER [19]

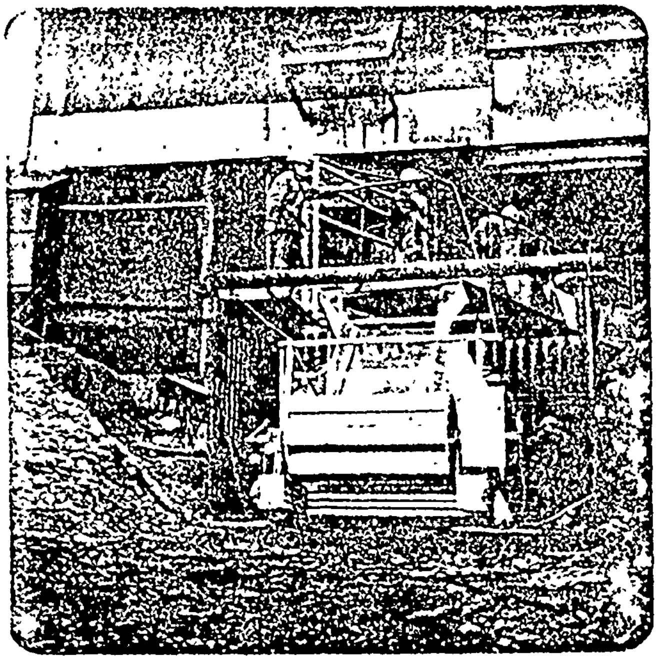


FIGURE 2-3 VIEW OF THE PELLETIZER AT DOFESCO NUMBER 4 FURNACE [19]

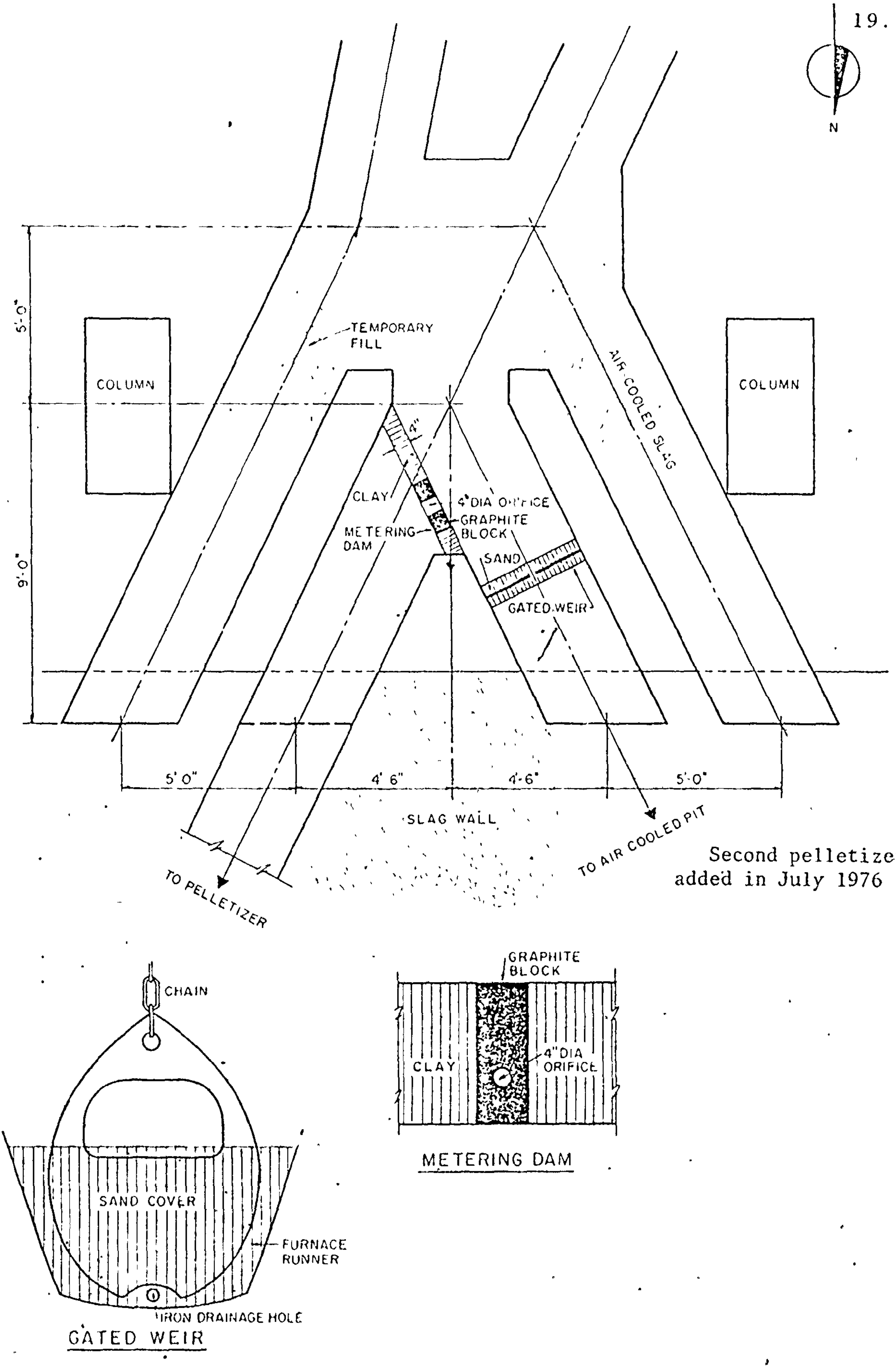
FIGURE 2-4 MAKING OF PELLETS AT DOFESCO NUMBER 4 FURNACE [19]

feed plate and be subjected to water spray for expansion, or under some circumstances, can flow almost directly to the drum. The slag flow can be directed to various runners (Figure 2-5) from the furnace so that air-cooled blast furnace slag is produced in a pit when molten slag production is greater than the pelletizers can handle.

The rotating drum of the pelletizer consists of a rotor which is 36 inches in diameter and 6 feet long. It has eight flingers (fins) on the periphery and water is distributed from holes in its body. The rotating drum is driven at a speed of 280 - 300 rpm and the usage of water varies from 0.5 to 1.0 ton of water per ton of slag [19]. The physical difference between pelletized slag and expanded slag is shown in Figure 2-6. It has been found that increasing the peripheral speed of the drum results in: smaller pellets; more pellets; higher density pellets; higher noise levels; and lower gas emissions. Table 2-3 shows the product control variables in the production of pellets.

This simple method of making pellets virtually eliminates serious air pollution problems [62] by substantially reducing the emission of hydrogen sulphide as shown in Table 2-4.

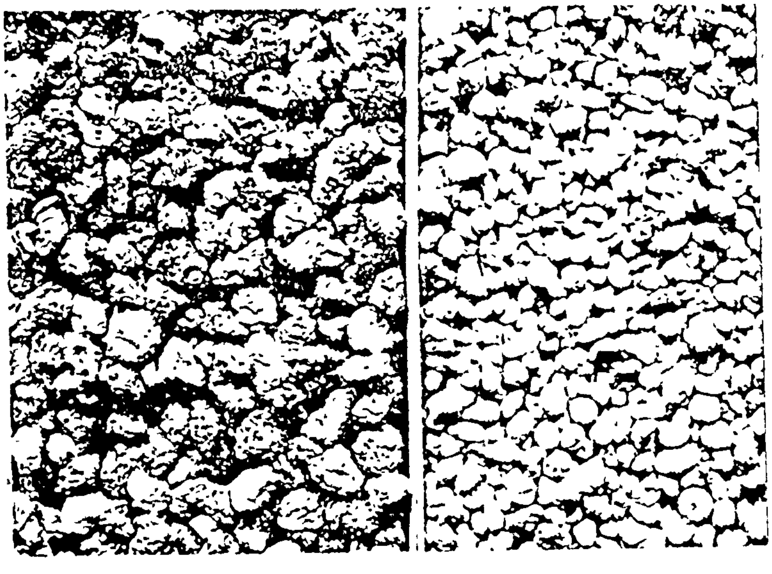
Pelletized slag as a product has several advantages over expanded slag. From the view point of slag handling, the pelletized slag can be loaded out immediately. This quick cooling aspect of pelletization is important in situations in



Second pelletizer
added in July 1976

FIGURE 2-5 ARRANGEMENT OF RUNNERS AT DOFASCO NUMBER 4 FURNACE [19]

(a)



Expanded (b) Pelletized (c)

FIGURE 2-6 (a) PELLETS BEING MADE DURING 1973 TESTS AT DOFASCO
(b) AND (c) DIFFERENCE IN SHAPE BETWEEN PELLETIZED AND EXPANDED BLAST FURNACE SLAGS

TABLE 2-3 [19]

PRODUCT CONTROL VARIABLES IN PELLETIZING

Variable	Effect On			
	Air Pollution (Gas)	Noise Level	Pellet Size	Product Weight
Increase Drum Speed	Reduces*	Increases	Reduces	Increases
Increase Water Quantity	Increases	Probably Reduces	Probably Increases	Reduces*
Increase Slag Volume (tpm)	Increases	Increases	Unknown	Reduces*
Increase Slag Flow Rate (tpm)	Increases	Unknown	Unknown	Increases
Increase Slag Temperature	Increases	Unknown	Increases	Reduces*
Increase Basicity	Increases	Unknown	Not Applicable	Not Applicalbe

* Significant Variables

TABLE 2-4

COMPARISON OF EMISSION RATES [35]

	SLAG IN RUNNER*	STUART TECHNIQUE*	PELLETIZER UNHOODED	PELLETIZER HOODED
Sulphur in slag (%)	2.54	0.83	2.30	N.A.
Air sample at the machine				
Hydrogen sulphide ppm	-	505 - 4350	2 - 50	0 - 30
Sulphur dioxide ppm	-	8.5 - 815	2 - 5	N.A.

* Expanded slag processes

which there is limited space available for slag handling adjacent to the furnace. Pelletized slag has moisture contents averaging 5-1/2%, while water granulated slags typically have moisture contents of about 25% and may range above 100% [23]. The benefits of this low moisture content can be capitalized on in any operation in which the use of a dryer is necessary since the fuel demands for any drying are reduced. Due to the pellets being approximately round in nature, which provides a minimum surface area, the quantity of cement required to obtain a given compressive strength in concrete mixes is reduced by about 20% [25]. From a petrographic viewpoint, the pelletizer can be considered as an "air granulator", since a very high percentage of glass can be produced for those end uses requiring this type of material.

Companies in Finland, Sweden, France, Australia, Britain, Japan and the United States (both blast furnace and phosphorus slag) are using the same technique under licence from National Slag Limited of Hamilton. The transportation of molten slag to the pelletizer may differ between producers, but the basic principles and equipment remain the same.

2-3 PROPERTIES OF PELLETIZED SLAG

Since the production of pelletized slag is relatively new, there is not much information available regarding its properties except for that given here under the utilization of pelletized slag. The chemical analysis of pelletized blast furnace slag falls in the range shown in Table 2-5. This table is compiled from chemical analyses done on pellets received from Finland and Hamilton. Table 2-6 shows some of the physical properties of pelletized blast furnace slag.

TABLE 2-5

TYPICAL CHEMICAL ANALYSES OF PELLETIZED BLAST FURNACE SLAG

CONSTITUENTS		PELLETIZED BLAST FURNACE SLAG (%)	TYPICAL DOFASCO (%)
Lime	CaO	36 - 42	38.10
Silica	SiO_2	34 - 39	35.50
Alumina	Al_2O_3	8 - 11	9.30
Magnesia	MgO	7 - 14	13.50
Manganese	MnO	0.45 - 1.13	0.81
Ferric Oxide	FeO or Fe_2O_3	0.27 - 1.31	1.31
Sulphur	S or SO_3	1.12 - 1.84	-
Phosphorus Pentoxide	P_2O_5	Trace	-
Titanium Oxide	TiO_2	0.40 - 1.13	0.40
Potasium	K	0.37 - 1.38	-

TABLE 2-6

PHYSICAL PROPERTIES OF PELLETIZED BLAST FURNACE SLAG

DESCRIPTION		PELLETIZED BLAST FURNACE SLAG (%) PASSING	
Sieve Analyses	Sieve Size	FINNISH SLAG	DOFASCO SLAG
	1/2"	99 - 100	95 - 100
	3/4"	79 - 95	94 - 97
	# 4	31 - 65	66 - 75
	# 8	6 - 28	28 - 33
	# 16	2.5 - 13	12 - 15
	# 30	1.6 - 7	4 - 6
	# 50	1 - 3	2 - 3
	#100	0.7 - 3	1 - 2
	#200	0.5 - 0.9	0.6 - 0.9
Water Absorption (%) [19]		2.48- 4.76	-
Dry unit weight lb/ft^3 [21]			
Loose		-	52.9 - 53.5 (a)
Loose		-	75.8 (b)
Compacted		-	58.4 - 60.6 (a)
Compacted		-	82.8 (b)

(a) Coarse pellets
(b) Fine pellets

2-4 UTILIZATION OF PELLETIZED SLAG

While the utilization of blast furnace slag has a lengthy history as indicated in Table 2-7, the production and use of pelletized blast furnace slag is a fairly new development (1968). There are many uses for air-cooled, expanded and granulated blast furnace slags (Table 2-8), and current world usage is approximately 140 million tons. For the many potential uses shown in Table 2-8, those that pelletized slag appears most promising in are: light-weight aggregate in structural concrete (fully developed); aggregate in block manufacture (fully developed); slag cement manufacture (first plant of 180,000 tons per annum just started in Hamilton by Standard Industries Limited) [19]; base stabilization (in final development stage); and autoclaved bricks and blocks (in early developmental stages). This study is concerned with the last two usages that are still in the developmental stages.

TABLE 2-7

EARLY UTILIZATION OF BLAST FURNACE SLAG [36,44]

Roman Period	Road building in England. [23]
?	To impart bottle-green colour in glass in England [23]
1589	Cast-slag cannon balls in Germany
1728	Cast-slag building blocks in England; 1761 in Sweden
1761	Slag-lime mortar in Germany
1822	Slag cement in Germany
1830	Slag road in Missouri
1840	Slag wool in Wales; 1875 in Germany, 1873 in the United States
1859	Slag-lime brick in Germany; 1873 in England
1866	Macadam roads in Chicago, Illinois
1873	Portland cement in Germany, 1897 in Pittsburgh, Pa.
1875	Railroad ballast by Illinois Central Railroad; 1885 in Germany, 1890 in England
1879	Mass concrete in England; 1880 in Eastern Pennsylvania
1888	Rolled base under block pavement in Akron, Ohio
1892	Reinforced-concrete construction in Germany; 1897 in Philadelphia, Pa.
1899	Sewage-disposal beds at East Cleveland, Ohio
1904	Composition roofing in Pennsylvania
1906	Slag-concrete products at Jackson, Mich.
1908	Tar-macadam roads in Ohio
1912	Concrete pavement in Ohio
1913	Slag in bituminous concrete, Allegheny County, Pa.

TABLE 2-8

UTILIZATION OF BLAST FURNACE SLAG AND ITS ENGINEERING ADVANTAGES

[27, 33, 34, 36, 44, 45, 48, 56, 64, 65, 68]

UTILIZATION	GENERAL ENGINEERING ADVANTAGES
Air-Cooled Slag	
Aggregate-structural concrete	strength, durability, fire-resistance
-concrete pavement	controlled gradation
-base course for pavement	roughness of surface texture increased surface area, high voids
-asphalt mix aggregate	less frost susceptibility
-base stabilization	insulation
Filter media	lower unit weight (less tonnage)
Glass making	
Slurry seal	
Built-up roofing	
Land reclaimation	
Slag surface treatment	
Mineral wood	
Biological percolating filters	
Oyster propagation	
Ceramic ware	
Backfill -structural	
-pipe [6]	
Railroad ballast	
Masonry cement [53]	
Admixture in concrete [69]	
Expanded Slag	
Light weight structural concrete	lightweight
Structural concrete	nailability
Concrete masonary unit	soundness
	thermal insulation properties
	shrinkage resistant

TABLE 2-8 (cont.)

Granulated Slag Fill material Base material for pavement Manufacture of cement Pipe backfill Land scaping Concrete masonary unit Agriculture Concrete floor fill	Light weight Glass material Lime content Cementing property
Pelletized Slag Manufacture of cement Light weight concrete Base stabilization Autoclaved masonary unit	Light weight Highly glassy material Cementing property

2-5 PELLETIZED PHOSPHORUS SLAG

2-5-1 Production and Properties

Elemental phosphorus can be produced by smelting a mixture of phosphate rock, silica and coke in an electric furnace. Two general types of phosphate ore deposits can be used - igneous or sedimentary. Most phosphate deposits are of sedimentary origin and nearly all of these are calcium phosphates termed "phosphorites" (approximately 12% of supply comes from igneous deposits [57]). The matrix of phosphate rock is composed of clay slimes, silica sand and phosphate pebbles. The pelletized phosphorus slag studied here was produced by Stauffer Chemical Company as a by-product of their electric furnace smelting facility in Tennessee.

Although electrothermic reduction of phosphates has been carried out experimentally early in the nineteenth century, the first electric furnace for the production of elemental phosphorus was not developed until 1889 by Readman [12]. Electric furnace operations are a continuous process with the raw materials (mixture of phosphate rock [typically high in iron], silica and coke) fed in at the top and slag and ferrophosphorus removed separately at the bottom. Figure 2-7 shows the production of slag during this electric furnace process. The specific mechanism by which phosphates are reduced has not been determined conclusively [2, 12], but the reduction of phosphate and the formation of the slag are represented by the following:

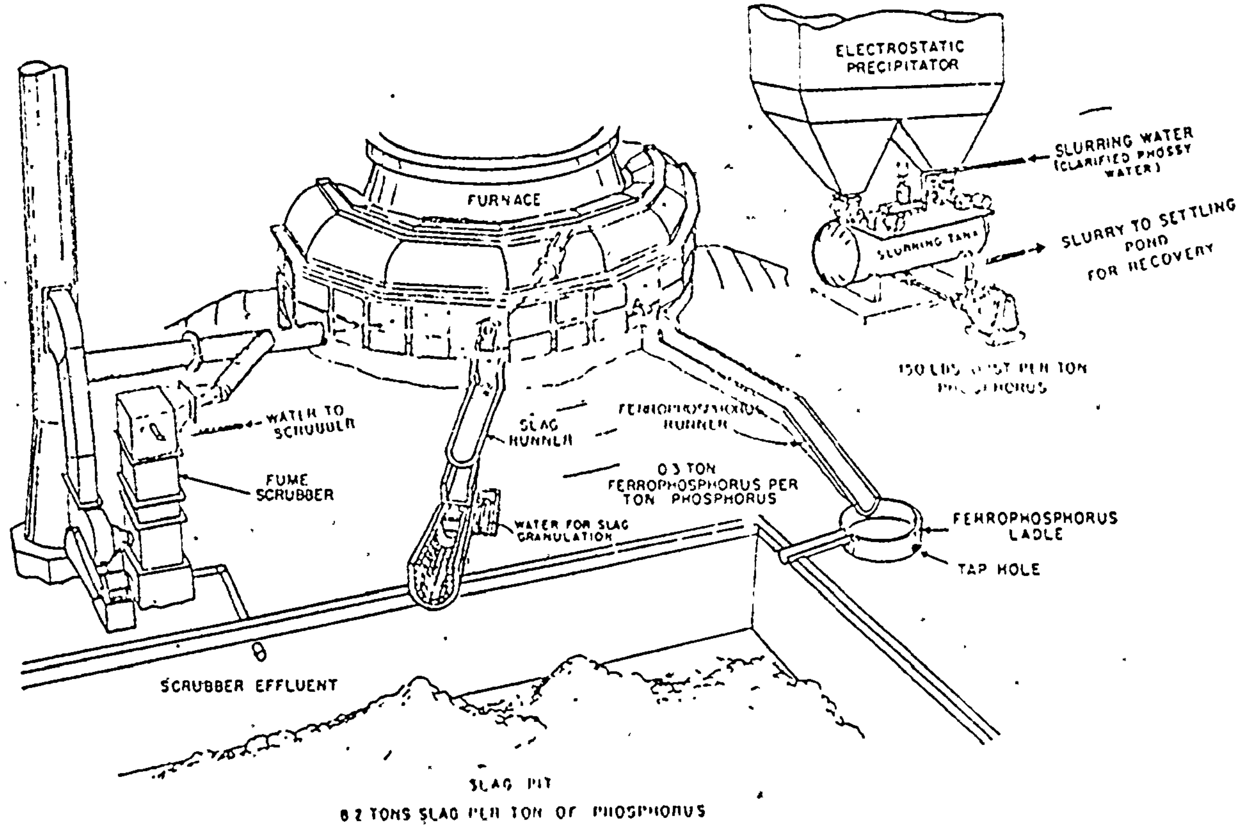


FIGURE 2-7 EQUIPMENT FOR HANDLING SLAG, FERROPHOSPHORUS AND PRECIPITATOR DUST DURING ELEMENTAL PHOSPHORUS PRODUCTION IN ELECTRIC FURNACE [48]

$$Ca_3(PO_4)_2 + 3SiO_2 + 5C \rightarrow 3(CaO.SiO_2) + P_2 + 5CO \quad (2\text{-}1)$$

$$Ca_3(PO_4)_2 + 3Al_2O_3 + 5C \rightarrow 3(CaO.Al_2O_3) + P_2 + 5CO \quad (2\text{-}2)$$

The elemental phosphorus and carbon monoxide produced by this reaction are evolved as gasses, and the calcium silicate is produced as a molten slag. Iron oxide that is present in the charge combines with elemental phosphorus to form ferrophosphorus. Other metal oxides in the charge remain unreduced and collect in the slag as impurities, or they are reduced to elemental form and collect in the ferrophosphorus.

In general, the reduction process involves the behaviour of silica as a strong acid at high temperatures (1,500°C to 1,750°C), and under these conditions it will combine with lime in calcium phosphate. While not completely understood, it has been reported [12] that phosphorus pentoxide (P_2O_5) is liberated at high temperature (above 1,800°C). However, when carbon is introduced into this system, elemental phosphorus is produced and the combined reaction is achieved at lower temperatures (1,250°C to 1,500°C). The constituent in rock phosphate containing phosphorus pentoxide is principally fluorapatite ($Ca_{10}(PO_4)_6F_2$) rather than tricalcium phosphate. In the electric furance process most of the fluorine is removed in the molten slag, probably in the form of calcium fluoride. However, some of the fluorine is still volatilized from the furnace as silicon tetrafluoride (200,000 tons in the United States in 1968) [4].

The actual chemical composition of the phosphorus slag, as well as the phosphorus produced, is mainly controlled by the amount and quantity of phosphate rock and fluxing material, provided other factors remain constant. The size of coke used has an important influence on the slag [2]. If the coke size is too large ($\sim$>3/8" to 7/8") or extremely segregated, it causes high furnace gas temperatures and relatively cold or viscous slag [2,12]. The composition of the phosphate rock affects the fluidity of slag and the ease of tapping. Low-grade phosphate rock containing a large proportion of clay may cause the slag to be viscous due to the presence of a large amount of Al_2O_3. Since the amount of Al_2O_3 present affects the melting temperature of the slag, it also affects the amount of SiO_2 that must be added to obtain slag with a minimum melting temperature. Typically, for the production of phosphorus about 74.8% of phosphate rock, 11.8% of coke and 13.4% of silica rock is required [48].

The raw materials (phosphate rock, fluxing agent, and coke) the grade of phosphorus being made, and differences in operating practice all influence the final chemical composition of phosphorus slag. The operator adjusts the silica to lime ratio to a value which results in the easiest tapping and the best separation of slag and ferrophosphorus. Other constituents in the furnace charge, such as potassium silicate and alumina, may affect the properties of molten slag. The chemical analysis of a typical phosphorus slag is shown in Table 2-9.

The total amount of water required in the production of elemental phosphorus is about 36,000 gallons per ton of phosphorus produced and about 88% of this water is for cooling [3]. The cooling water is not recycled, but much of it is used for slag granulation. In a typical plant, the slag is produced at the rate of about 8 tons per ton of phosphorus recovered.

Phosphorus slag is classified into four main types (contrast with blast furnace slag) - air-cooled, expanded or foamed, granulated and pelletized - depending upon the method of cooling from the molten state. These methods are similar to those discussed previously for blast furnace slag. Granulation is often used where typically the molten slag (2,600°F - 2,700°F) is tapped from the furnace as shown in Figure 2-7. Jets of water at high velocity contact the molten slag and convert it into granules of minus #10 size. The granulated slag and water flow into a pit and part of the water is recycled for further granulation. Most of the slag is then pumped to storage piles where it reacts with fluoride scrubber water as part of the plant's environmental control.

The process of making expanded phosphorus slag is shown in Figure 2-8. Molten slag from the electric furnace flows through a slag inlet trough, where it is treated with water, steam and air. Steam and air are started in at low

TABLE 2-9

TYPICAL ANALYSES OF PHOSPHORUS FURNACE SLAG

CONSTITUENT		PHOSPHORUS SLAG (%)	
		(a)	(b)
Lime	CaO	44.1	50.0
Silica	SiO_2	41.3	39.5
Alumina	Al_2O_3	8.8	6.2
Phosphorus Pentoxide	P_2O_5	1.3	1.0
Floride	F	2.8	2.6
Potassium Oxide	K_2O	1.2	0.7
Sodium Oxide	Na_2O	0.1 - 0.2	0.6
Ferric Oxide	Fe_2O_3	-	0.3
Magnesium Oxide	MgO	0.1 - 0.2	0.3
Sulphur Trioxide	SO_3	-	0.2
Phosphorus	P	-	-
Manganese Oxide	MnO_2	0.1 - 0.2	0.2
Sulphur	S	0.1 - 0.2	-

(a) from [48]

(b) from [12]

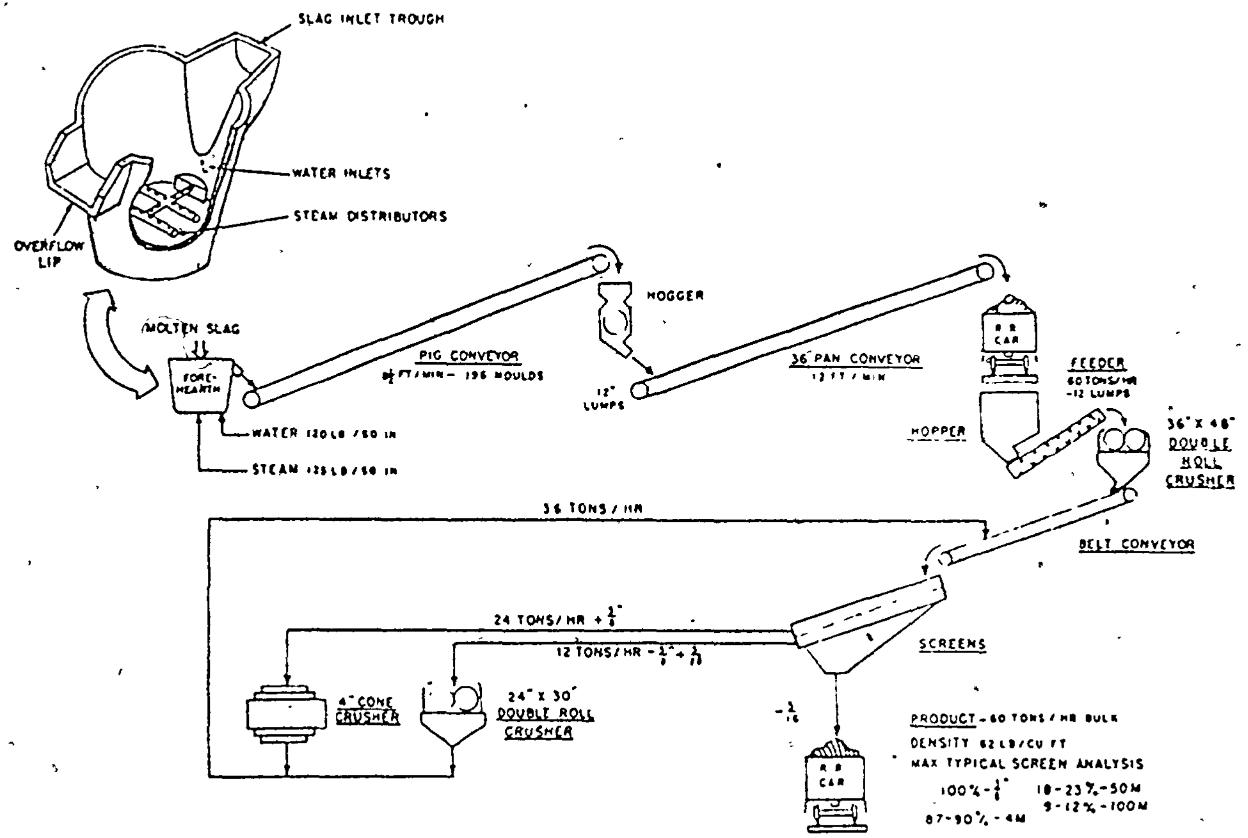


FIGURE 2-8 PROCESS OF MAKING EXPANDED PHOSPHORUS SLAG [48]

rates before the phosphorus furnace is tapped and then regulated to give vigorous agitation during the run. This foaming process produces lightweight aggregate [49,58].

The equipment and method used in the production of pelletized phosphorus slag is similar to that for pelletized blast furnace slag. While the physical characteristics of the phosphorus slag are somewhat variable from furnace to furnace and with time, they fall in the range indicated in Table 2-10. Most phosphate rocks contain between 30 - 200 ppm uranium, 3 - 75 ppm radium and less than 10 ppm thorium, and most of the uranium comes out in the molten slag. However, it has been shown that there is no environmental problem associated with potential radiation from the slag [48].

TABLE 2-10

PHYSICAL PROPERTIES OF PHOSPHORUS SLAG

DESCRIPTION		EXPANDED SLAG			GRANULATED SLAG	AIR-COOLED SLAG	
		(a) %	(b) %	(c) %	(c) %	(d) %	(c) %
Sieve Analysis	Sieve Size						
	+# 4	25	-	-	-	-	-
	+# 8	42	-	-	-	-	-
	-# 50	23	-	-	-	-	-
	-#100	14	-	-	-	-	-
Bulk density lb/ft^3		50	55-62	42	70	93	-
Specific density lb/ft^3		-	-	-	-	-	180
Specific gravity (oven dry)		-	-	-	-	2.7	-
Aggregated crushing value		-	-	-	-	32	-
Aggregate abrasion value		-	-	-	-	17	-
Water absorption (% by mass)		-	-	-	-	1.1	-
Polished stone value		-	-	-	-	44	-

(a) from [30] crushed to -3/8" at T.V.A. Plant
(b) from [48]
(c) from [12]
(d) from [44]

Utilization of Phosphorus Slag

A summary of electric furnace phosphorus slag utilization is shown in Table 2-11. It has been reported that it is difficult to burn cement clinker in the presence of P_2O_5 and it contributes to retardation of the strength development [70]. The phosphorus pentoxide enters into solid solution with dicalcium silicate (C_2S); 1% P_2O_5 thereby lowering the tricalcium silicate (C_3S) content by 9.9% and raising the C_2S content by 10.9%. The effect of this conversion is indicated by a reduced rate of strength development [11, 52]. Since portland cement must contain a substantial proportion of tricalcium silicate, the maximum proportion of P_2O_5 in the cement must not exceed 2.2 to 2.5% [33, 43, 52, 70]. However, this limit may be even lower when phosphorus slag is incorporated, since the proportion of tricalcium silicate is much lower in the slag than in portland cement. Figure 2-9 shows that small amounts of P_2O_5 enhanced the strength [32, 52, 70]. Welch and Gutt [70] showed that with no P_2O_5 the dicalcium silicate was in the γ-form; with 2% it was in β-form; and with 7% and 15% it was in the α' or α-form [see Figure 2-9]. In this case, the α form has no cementing properties and the α' very little, but the β form has high cementing properties provided the lime

TABLE 2-11

UTILIZATION OF ELECTRIC FURNACE PHOSPHORUS SLAG [12, 48, 58]

(✓ Used, X Not Used, ? Not Known)

UTILIZATION	PHOSPHORUS SLAG
Road ballast	✓
Lightweight aggregate	✓
Cement making	X (a)
Slag-lime structural block	X (b)
Base stabilization	?
Ceramics	X (b)
Slag wool	X (a)
Lightweight Concrete block	✓ (b)
Soil liming material	✓
Neutralizer of acid soils	?
Asphalt mix filler	?

(a) Technically feasible but not economical

(b) Would be economical only in special locations

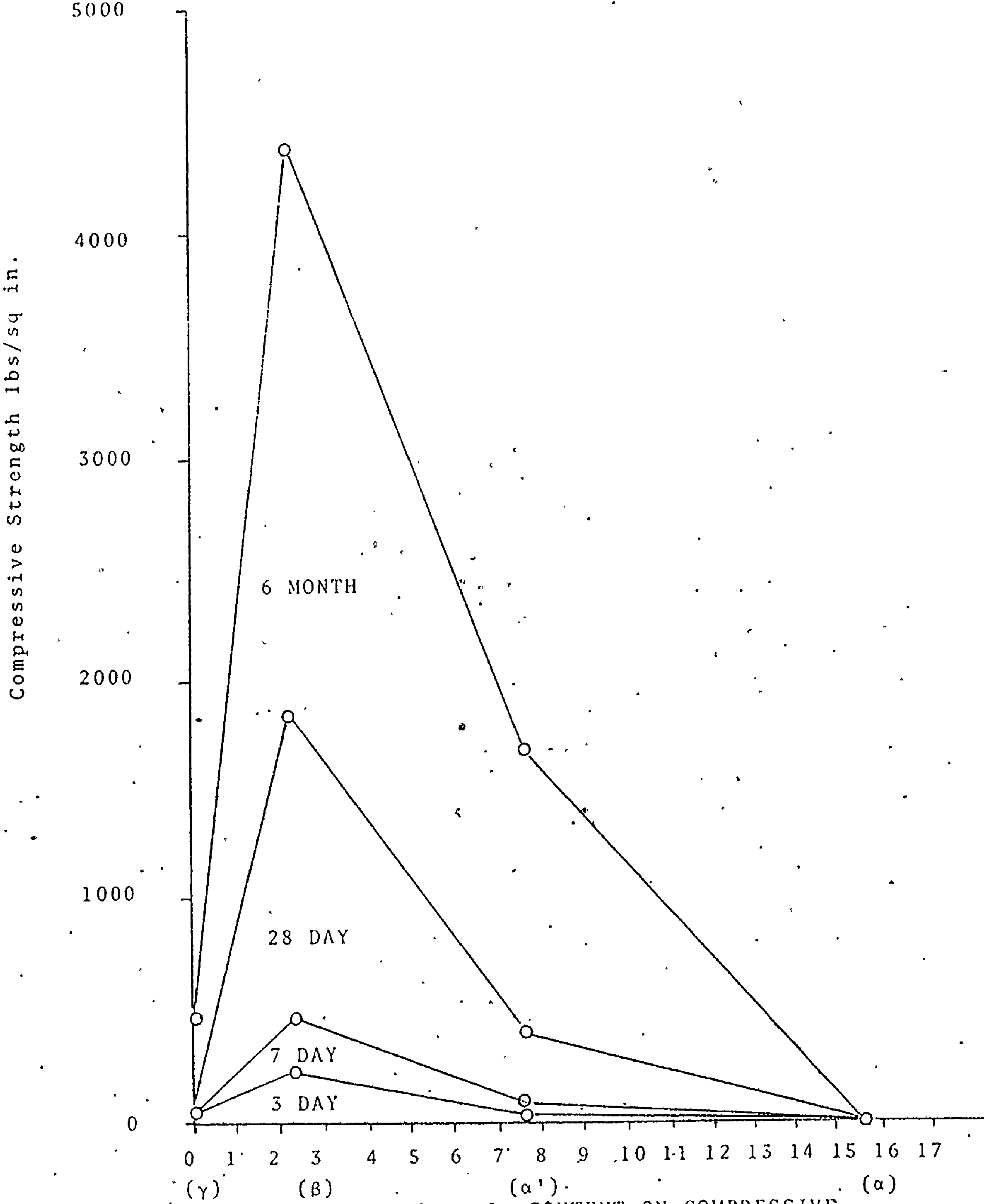


FIGURE 2-9 INFLUENCE OF P_2O_5 CONTENT ON COMPRESSIVE STRENGTH (1/2" 1:3 C_2S - C_3P MORTAR CUBES) [70]

content is reduced so that free lime is not formed. [33, 43].

It is important in the manufacture of phosphorus-gypsum cements to proportion the raw materials to avoid free lime formation. Figure 2-10 shows that the compressive strength also decreases as the fluorine content increases [33]. The phosphorus and fluorine content of the phosphorus slag are thus critical and generally harmful in any cementitious usages.

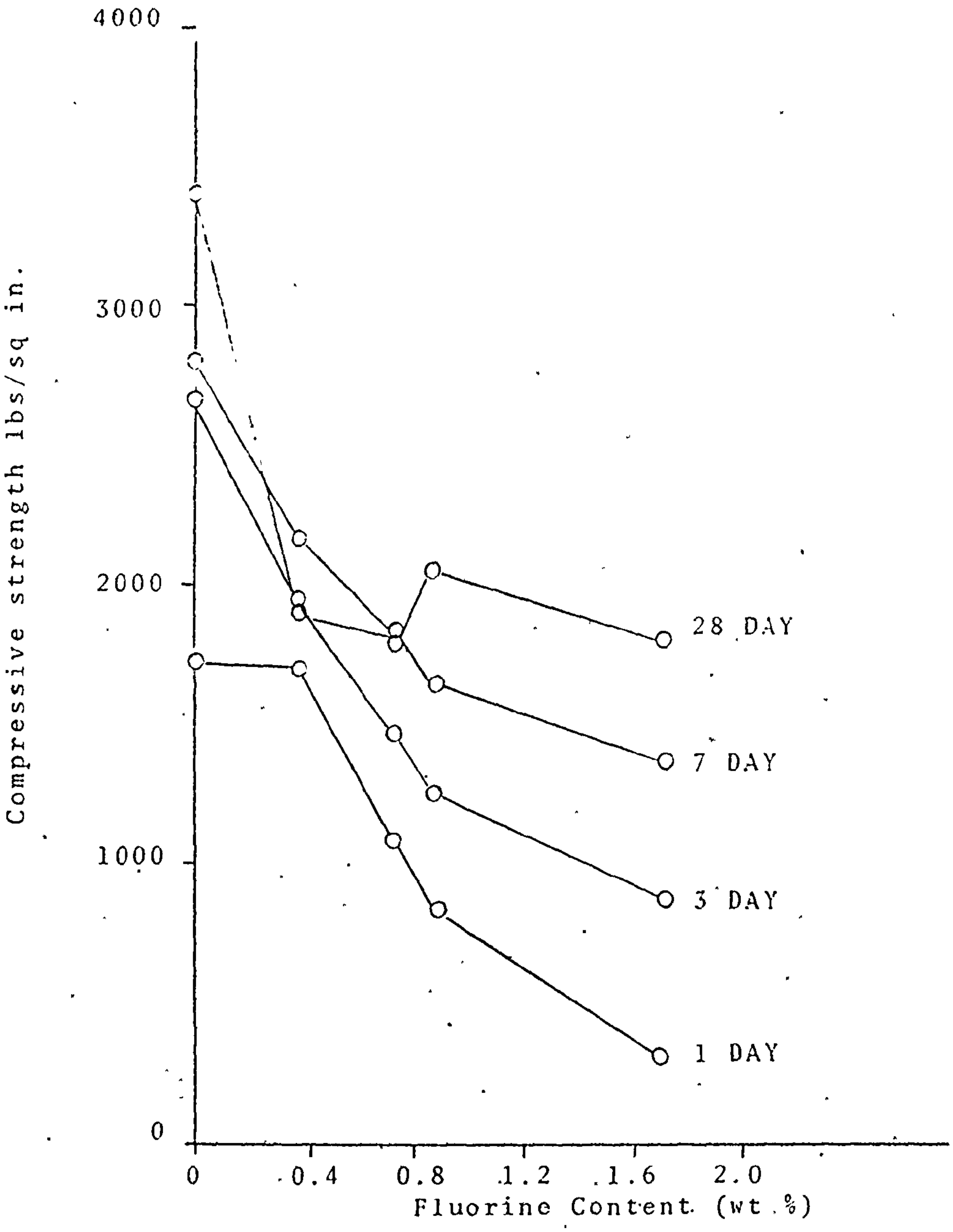


FIGURE 2-10 INFLUENCE OF FLUORINE CONTENT ON COMPRESSIVE STRENGTH (1/2" 1:3 C_3S MORTAR CUBES) [70]

3 CEMENTING PROPERTIES OF GLASSY (VITRIFIED) SLAGS

3-1 MAJOR FACTORS INFLUENCES CEMENTING PROPERTIES

(a) Glass Content

Lortiotin first observed and studied the cementing properties of blast furnace slag in 1784 [17], and in 1862 Emil Langens discovered that granulated slag had good cementing properties when mixed with lime [17, 37]. It is reported that the first production of Portland blast furnace slag cement occured in Germany in 1892 [43]. Most researchers [10, 31, 43, 54], have pointed out that finely ground granulated blast furnace slag does not set on its own, but requires activation. Glassy granulated or pelletized slag, when ground to cement fineness, have latent hydraulic properties which when activated by means of portland cement, lime, calcined gypsum or other sulphates (particularly of calcium, sodium and potassium) results in a cementitious binder.

When molten blast furnace slag is chilled quickly, it solidifies forming an isotropic glassy material, some of which may show under microscope examination brown or black zones whose incipient crystallization has begun. Any transfer from the molten to crystalline state is accompanied by a rearrangement of the ions which then take up definite orientations in the crystals. The rearrangement only takes place slowly and if the slag is chilled quickly, the ions retain their irregular arrangement and crystallization does not occur, i.e., a glassy slag results. Glassy slag (amorphous slag, vitrified slag) is more "energetic" in reactions as a cementitious material than slowly cooled slag because it has not lost its latent (internal) energy through crystallization [13, 36]. The hydraulicity of granulated (or pelletized) blast furnace slag is contributed by many factors. The predominent factors and interrelation between them have been discussed extensively in the literature [10, 17, 36, 37, 41, 43, 46, 47, 54, 60] and form a complex subject [43]. It should be noted that glassy slag is not a pozzolan and its hydraulic reactions are specific with the formation of direct hydrated compounds in the presence of small amounts of activator. Pozzolans such as fly ash and volcanic ash require large quantities of lime for cementing reactions in which insoluble compounds are formed [14, 43, 63]. This study is not concerned with pozzolans or pozzolanic reactions. However, the importance of such materials in construction, particularly fly ash from coal-fired thermal plants, is recognised.

The hydraulicity of glassy slag increases or decreases proportionally with the amount of glass formed during the cooling process. It is important to distinguish between "total glass content" and "glass content", because not all of the glass contributes to the strength development. The German Research Institute [59] developed an ultra-violet technique for separating the different glasses, which is considered to improve the total glass content obtained by conventional microscope technique (these methods are in appendix A) [40, 50]. Different types of grains emit different luminescent colours under ultra-violet light, thereby separating various kinds of glass in the slag. Schroeder [59] concluded from his test results that the slag grains contain various kinds of glass of different hydraulicity. Grains which emitted yellow, grey-brown and blue colour developed lower strength, whereas the pink radiation colours developed the highest strength. Highly crystalline particles emit blue and violet colour [41, 43, 60]. Lea [43] reported that Schwiete and Dolbor obtained a roughly linear relationship between strength and glass content, indicating that increasing the content of crystalline compounds reduces the cementing properties, though some of the crystalline compounds may make some contribution to the development of strength [60]. In addition to the ultra-violet method of determining the glass content and "quality" there are several microscope count methods using cross-polarized light [25, 27]. There does not appear to be a clear indication of the minimum "accepted" glass content (values in the range of 90 to 95% are often quoted) [25]. The "South African" and "McMaster Method" for glass content determination are given in Appendix A.

Table 3-1 shows the grain size effect on glass content for pelletized slag. The pellet grains passing the #16 sieve and retained on the #50 sieve (shaded area on Table 3-1) give the highest glass content during pelletization. This indicates that there is an optimum pellet weight and cooling surface. Research on glass content and distribution in pelletized slag is the subject of a parallel study just initiated by Hooton. Glassy slags alone do not have cementing properties, but if some suitable activator is present, all except the more silicious glassy slags show marked cementitious properties. The amount and kind of activation that gives maximum strength varies with the chemical composition of the slag. The glassy slag combines particularly well with hydrated lime in setting, and gives rise to silicates and aluminates of lime. In general, the more basic the slag, the greater its hydraulic activity [43]. Research indicates that the ratio of CaO/SiO_2 should be in the range of 1.45 to 1.54 for the slag to be sufficiently hydraulic [37, 39, 60].

The hydraulic properties of the glassy slag are due to the presence of alumino-silicate of calcium ($3CaO.Al_2O_3.2SiO_2$). This compound also appears in portland cements, but in this case it is entirely inert, owing to the slow process of cooling. In addition to the physical characteristic (grain shape, specific gravity, etc.) of the slag, vitrification has two important chemical effects:

TABLE 3-1

GRAIN SIZE EFFECT ON GLASS CONTENT [40]

PELLET NUMBER	GLASS CONTENT (%) OF GROUND #200-#300 MATERIAL							
	Total Gradation	+#4	#4-#8	#8-#16	#16-#30	#30-#50	#50-#100	-#100
18	94	76	86	88	93	▨ 95	91	83
19	81	65	75	80	▨ 81	79	80	68
22	80	65	73	83	▨ 90	84	82	71
25	78	58	66	75	84	▨ 90	78	61
26	77	70	71	82	▨ 91	90	80	65
35	89	84	89	89	▨ 95	▨ 95	86	72
8	74	69	54	75	88	▨ 90	75	60

one being to make the slag highly hydraulic if it has a suitable chemical composition; and the other being to remove some sulphur [10, 13, 17, 36, 43, 47, 61]. In the presence of $Ca(OH)_2$, sulphur produces polysulphides which can give a green colouration to slag concrete [47]. A restriction on total sulphur is generally made.

Since the glass content of slag is so critical to its hydraulicity, the nature of glass will be briefly considered here. Most substances, if heated above their melting points and cooled in the absence of nucleating substances, can be under-cooled; that is they will remain liquid at temperatures below the stable melting point. An undercooled liquid becomes more viscous as its temperature is lowered, and changes into a rigid, isotropic solid. The two main theories for considering the behaviour of glassy slag are: the random network theory by which glass constituents can be divided into two classes, network formers and network modifiers [43, 54]; and the crystallite theory in which the glass structure contains small regions of crystalline order containing most of the metal cations, linked together by an amorphous region formed by the residual anions [43, 54]. Figure 3-1(a) is a two-dimensional representation of a glass according to the network theory, and Figure 3-1(b) represents the structure of silica glass according to the crystalline theory. Schröder [60], further concluded from his tests results that the slag grains contain various kinds of glass of different hydraulic characteristics. More work

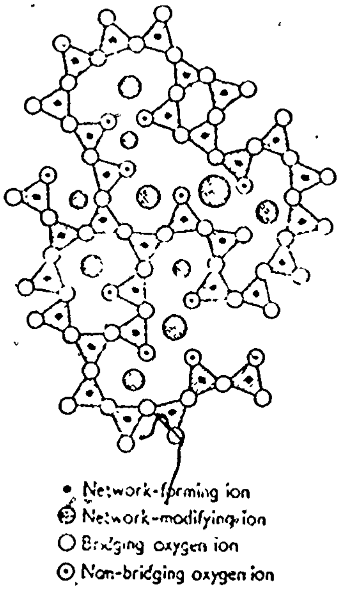


FIGURE 3-1 (a) SCHEMATIC TWO-DIMENSIONAL REPRESENTATION OF GLASS ACCORDING TO NETWORK THEORY [54]

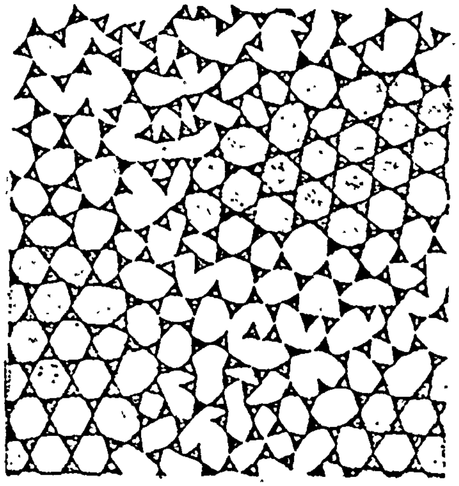


FIGURE 3-1 (b) TWO-DIMENSIONAL REPRESENTATION OF SILICA CRYSTALLITE THEORY [54]
SHADED REGIONS CRYSTALLINE

is needed on determining glass content before hydraulic properties can be adequately predicted on the basis of theories of network and crystalline behaviours [33].

(b) Grindability

Stutterheim [66] indicated that it is generally much harder to grind granulated blast furnace slag than portland cement clinker, as a result of which, the slag component of an integrally ground cement tends to be coarser than the clinker component. While reduced grindability may be the case for granulated glassy slag, Kim [40] has shown that pelletized glassy slags have superior grindability. This is probably related to the formation of a more porous friable structure during pelletization.

Since the hydraulic reactivity of the slag is lower than that of the clinker, intergrinding represents an inefficient utilization of slag hydraulicity, because the strength developed at early ages is inhibited. Kramer [41] pointed out that in order to improve the quality of slag cement and reduce variability, each component can be ground separately to yield an optimum combination of properties.

(c) Fineness

The fineness of ground slag influences the strength developed and the rate of development as shown in Table 3-2. The effect of fineness is not directly related to the property of slags themselves, but does depend on the chemical composition and vitrification process to the

TABLE 3-2

EFFECTS OF SLAG (a) FINENESS ON
STRENGTH OF CONCRETE [43]

FINENESS (b)	COMPRESSIVE STRENGTH (psi) (c)				
	1 Day	3 Days	7 Days	28 Days	90 Days
3095	104	360	855	2460	3950
3930	127	417	1220	3160	4690
4850	152	522	1535	3600	5270
6140	173	707	1810	3925	5670
100% Portland Cement	915	2415	3510	4950	6370

(a) Hydraulic modulus = 1.0

(b) By air permeability cm^2/gr

(c) 30:70 portland cement: slag in 1:2:4 (vol) gravel concrete, w/c = 0.55, water stored extent that these effect the grindability of the slags. High fineness of grinding provides more surface for reaction, therefore, the less active the slag, the finer it should be ground [39]. It is well known that if other factors are equal, the chemical activity of a substance is directly proportional to specific surface. Theoretically, there is no limitation on the fineness of grinding for cementing materials, but there are economic and technical limits. Also, there are some practical considerations that must be taken into account, such as the type of grinding and if the grain size of the ground slag is too small, some hydration may occur during storage.

(d) Storage

Aging effects on the potential cementing properties of ground glassy slag have not received much attention, however, this does not mean that there is no age problem. Stutterheim [66] has indicated that ground slag fines, in the absence of any additive, have remarkably good storage properties, comparable to portland cement. He indicated that there are cases where ground granulated slag has not deteriorated after storage in paper bags for three years. Lea [43] studied slag's sensitivity to deterioration in storage and its low strength in comparison with modern portland cements. He found that deterioration in storage was one of the reasons for the abandonment of slag-cement production in many countries. The effect of storage on the glass content of moist ground pelletezed slag is shown in Figure 3-2. This information indicates that the ground moist pelletized slag should be used soon after production to ensure that potential cementitious behaviour is not lost.

(e) Chemistry

The chemical composition of slags and other cementing material is readily shown on composition tetrahedron diagrams (Figure 3-3) and ternary diagrams (Figure 3-4). In the ternary diagram, a relative location is expressed by the SiO_2 - CaO - Al_2O_3 system, while in the tetrahedron diagram, it is expressed by the SiO_2 - Al_2O_3 - CaO - Fe_2O_3 system, these oxides being the major constituents. Pelletized blast furnace slags, phosphorus slag, flyash and portland cement are shown in the ternary diagram (Figure 3-4). This information is of importance when using composition as an indicator of hydraulicity.

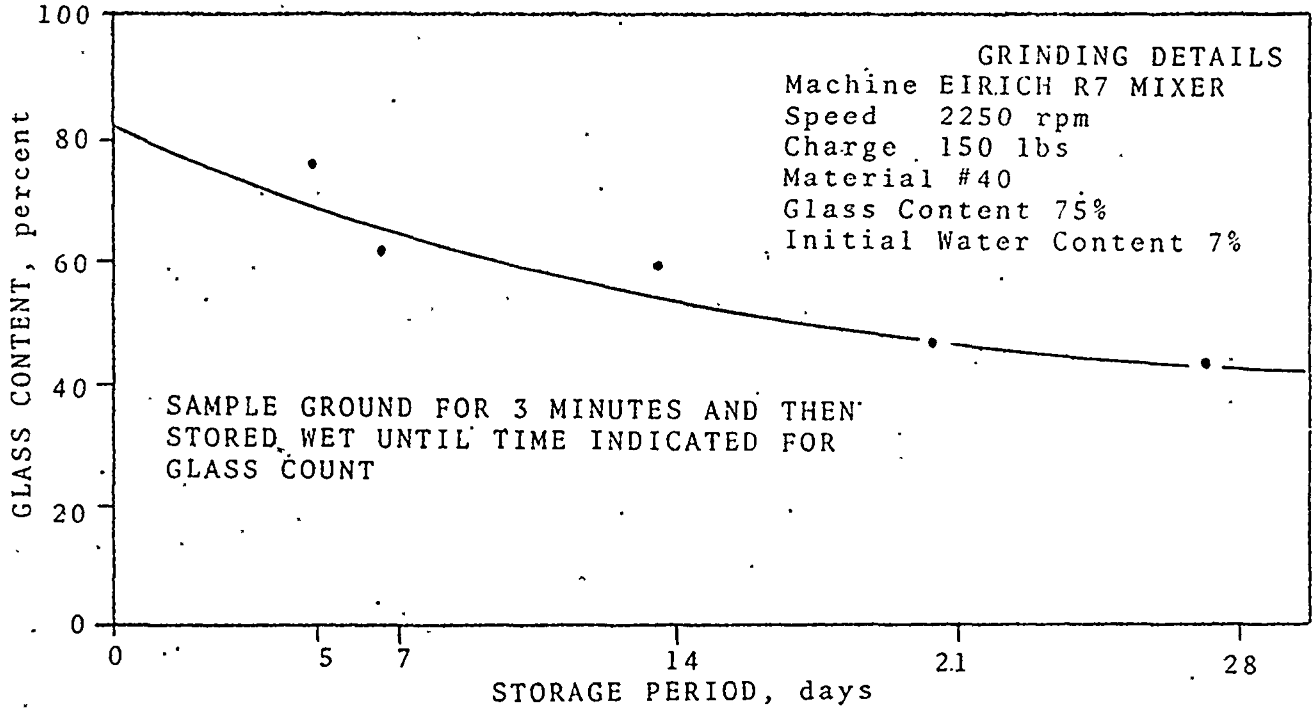
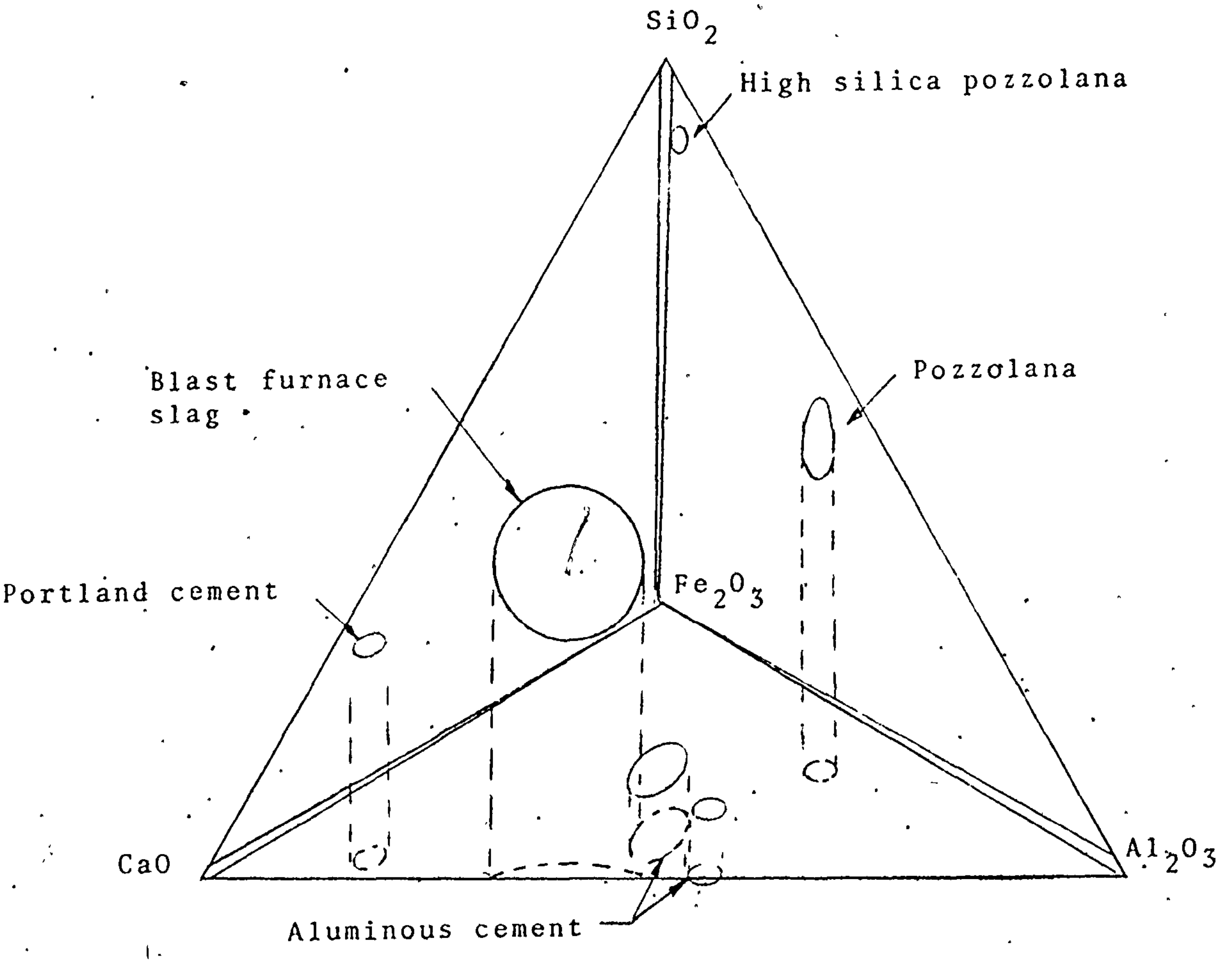


FIGURE 3-2 EFFECT OF STORAGE ON THE GLASS CONTENT OF MOIST GROUND PELLETIZED SLAG [24]



TETRAHEDRON DIAGRAM

FIGURE 3-3 COMPOSITIONS OF CEMENTS, SLAG AND POZZOLANAS IN THE $CaO-Al_2O_3-SiO_2-Fe_2O_3$ SYSTEM. [47]

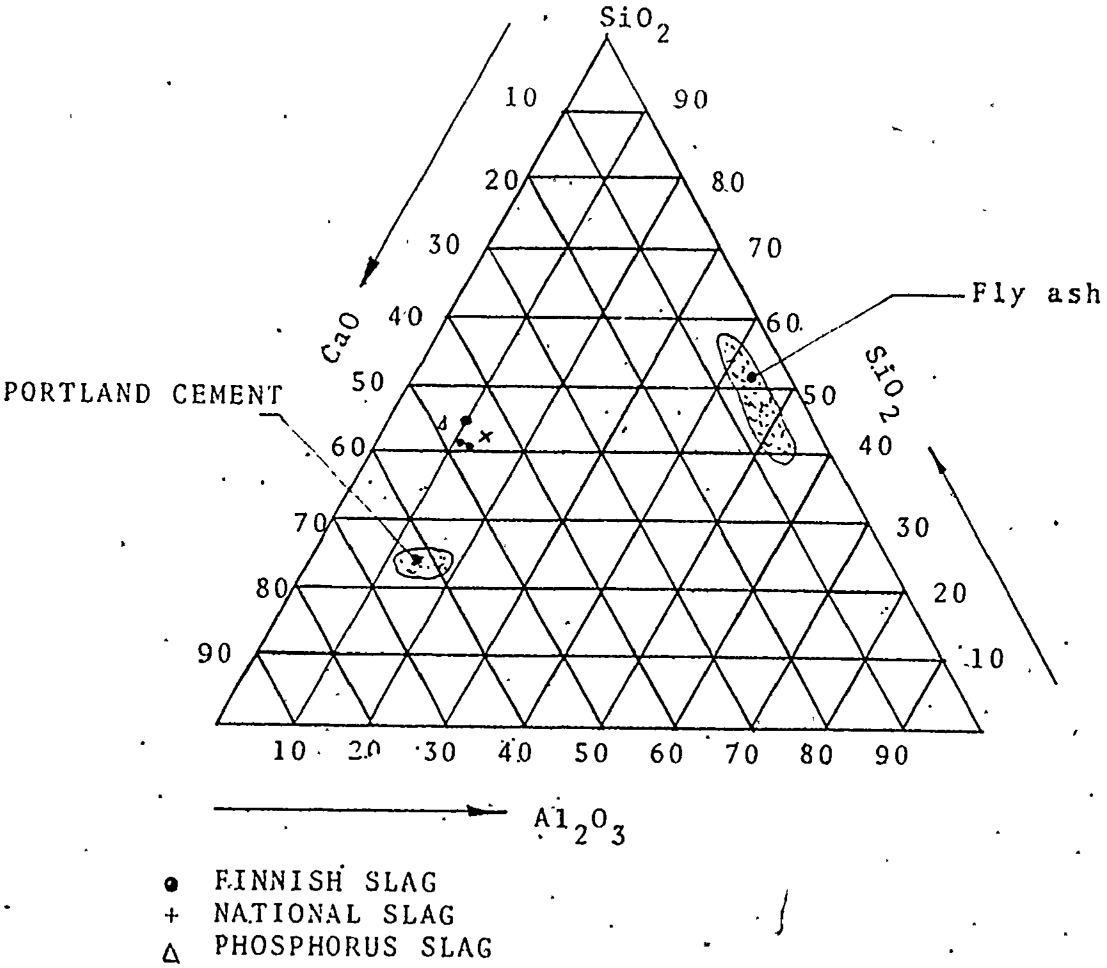


FIGURE 3-4 TERNARY DIAGRAM

3-2 CRITERIA FOR EVALUATION OF HYDRAULIC PROPERTIES

Many researchers have tried to establish some index relationship betwwen strength development and chemical composition of glassy slags, with or without activators. Of the many hyraulic moduli that have been developed, only those that show some promise from the literature are described here. A rather complete description of the many others is given in Appendix B. All of these moduli predictions are based on the assumption that the glass content effects are constant and "homogeneous". Most of the moduli consider three or four main oxides, usually CaO, SiO_2, Al_2O_3 and MgO, since these comprise about 95% of the total. A combined moduli for predicting the strength of slag-cement at 90 days was given by Parker and Nurse [27, 31, 33, 37, 39, 43, 55] that relates strength to the total glass content and basicity:

$$M = \frac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3} \qquad (3\text{-}1)$$

and $\%\ \text{strength}\ (S)_{90} = 0.38G(M-0.72) + 75$ (3-2)

where $(S)_{90}$ = the 90 day strength of a 1:2:4 concrete of water cement ratio 0.60 and assuming a mixture of 65% ordinary portland cement and 35% slag cement;

M = Basicity ratio or modulus for potential activity of slag; and

G = percent glass content determined by microscope analysis.

The product GM was adopted as a guide to the activity of a slag. The higher the value of GM, the more hydraulic the slag provided that M has a value between 0.72 and 1.50. At lower values of M, the slag has no hydraulic activity and above 1.5 the slag cannot be granulated without devitrification occuring [43]. Parker and Nurse [55] concluded that the moduli (3-1) gave the best estimate of hydraulicity of slag when used in the 65:35 mixture of ordinary portland cement and slag cement, when combined with the percentage of glass in the slag. The moduli (3-1) implies that MgO is as effective as CaO in producing hydraulic properties in a slag; but the slags tested only had MgO contents up to 7.5%. Experimental work done by Stutterheim [60, 67] shows that cements made with granulated slags having from 13% to 21% of MgO do not yield unsound concrete even after many years of moist storage. Studies on granulated blast furnace slags of high magnesia content have indicated that with contents of 15% to 20%, the MgO contributes little to the hydraulic activity [43].

Lea [43] has indicated that by simple multiplication of the glass content (as determined by the ultraviolet analysis) with the CaO/SiO_2 ratio, a linear relationship exists with the strength values:

$$\text{Strength} = G^1 M^1 \qquad (3\text{-}3)\ [27, 41, 60]$$

Where G^1 = glass content as determined by ultra-violet test

M^1 = Basicity ratio (= CaO/SiO_2)

In Germany, moduli (3-3) is often used as a quick method for assessing the hydraulicity of granulated slag, though it is only useful for slags produced by one particular furnace. These three moduli (3-1) to (3-3), indicate that neither composition modulus (M or M^1), nor glass content (G or G^1) alone are sufficient to characterize the hydraulic properties of a slag and that some product of the two is required [43]. It is often considered that the basicity, rather than the amount of individual oxides is a satisfactory measure of the hydraulicity of the slag. As a routine part of the control procedures in iron production, a number of empirical formulae, based on chemical analysis, have been developed. The simplest moduli for hydraulicity evaluation are:

$$CaO/SiO_2 \qquad (3\text{-}4)$$

and

$$SiO_2/Al_2O_3 \qquad (3\text{-}5)$$

The hydraulic value increases with an increase in both these ratios (3-4) and (3-5) [22, 36, 37, 43, 44, 51] up to a limiting point when increasing CaO content makes vitrification difficult [43]. However, it has been indicated

[36, 43, 60] that crystallization proceeds rather slowly in slag high in silica and more rapidly in those high in magnesia and lime. It has been suggested that for supersulphate cement the basicity ratio in moduli (3-4) should be between 1.45 to 1.54 [38, 39, 50, 60] and ratio in moduli (3-5) should be between 1.8 to 1.9 [7, 39, 54]. In France and Germany, the lime to silica ratio is specified to be less than 1.4 [15], and there should not be yellow fluorescence when examined under ultra-violet light.

Cheron and Lardinois [16] established a linear relationship between the mechanical strengths and the chemical composition of artificial granulated slags:

$$I_n = \frac{CaO + 1.4\,MgO + 0.56\,Al_2O_3}{SiO_2} \qquad (3\text{-}6)\ [1, 16, 23]$$

This ratio was derived from tests conducted on 56 different slags having different compositions. The index varied from 1.4 to 2.2. For values of I_n lower than 1.4 a better correlation was obtained when the Al_2O_3 coefficient of 0.56 in moduli (3-6) was replaced by 0.70.

An "Index of Quality" moduli is extensively used in France:

$$i = 20 + CaO + Al_2O_3 + 0.5\,MgO - 2SiO_2 \qquad (3\text{-}7)\ [27, 37, 38, 39, 43]$$

In applying this index of quality, and inserting percentage weight into it, the hydraulic properties of slag are classified as follows:

Medium if $i < 12$

Good if $i = 12 - 16$

Very good if $i > 16$

According to Lea [43], Blondiau has put the minimum desirable value at 19 for slags of low (3.5%) MgO content. Some researchers have found that the effect of Al_2O_3 is considered to be on the unfavourable side.

3-3 EVALUATION OF MODULI

The pelletized slags from Finland and National Slag Limited were evaluated by each of the above moduli (19 in all) and those given in Appenidx B. Chemical analyses used are shown in Table 3-3 and Table 3-4 gives all the moduli with their suggested hydraulic activity limits.

A computer program was prepared to determine all the moduli and to print graphs of stabilized base compressive strength (Chapter 4) versus each individual moduli to determine if any clear relationship exists. Although phosphorus slag does not fall into the category of pelletized blast furnace slag, all the moduli were also used to determine its hydraulic activity.

None of the moduli exhibited any relationship with the stabilized base compressive strengths. However, moduli (3-6), (B-3 to B-5), (B-7) and (B-8) indicate that as the value of index increases, there is an increase in stabilized base compressive strength. Moduli B-9 indicates that as the value of index decreases, the stabilized base compressive strength increases. A typical plot between moduli and stabilized base 28 day compressive strength is given in Figure 3-5. Therefore, it is concluded that, to determine if some

TABLE 3-3

COMPOSITION AND COMPRESSIVE STRENGTH OF PELLETIZED SLAG

COMPOSITION		BLAST FURNACE SLAG				PHOSPHORUS
		Finnish Slag (d)			Dofasco	Stauffer
		118-I	118-II	118-III	#117 (a)	#120 (a)
CaO		40.80	41.50	40.80	38.10	47.10
SiO_2		35.80	36.20	37.60	35.50	41.20
Al_2O_3		8.90	9.40	8.20	9.30	5.50
MgO		8.50	8.30	7.80	13.50	0.94
FeO		0.30	0.30	0.30	0.80	0.40
Fe (Total)		-	-	-	0.51	0.46
MnO		0.84	0.74	0.93	0.81	NIL
TiO_2		1.07	0.98	1.13	0.40	0.30
Free lime		-	-	-	0.73	0.28
S		1.10	1.18	1.12	-	0.13
P_2O_5		0.01	0.01	0.01	-	2.55 (b)
V_2O_5		0.04	0.04	0.04	-	-
K		1.34	1.38	1.29	-	-
Glass Content %(c)		75	65	49	78.4	73
Compressive Strength psi	Age in Days					
Proportions:	7	350	300	290	860	255
Granular A 70%	14	915	520	345	1400	270
Ground Slag 30%	28	1785	1155	615	1950	290
(Net fines ≃ 5%)						

(a) Conducted by DOFASCO
(b) Geology Laboratory, McMaster University
(c) McMaster Method (See Appendix A)
(d) Provided by Oy Koverhar Ab of Finland.

TABLE 3-4

INDEX CALCULATION FOR SLAG

NO.	MODULI	INDEX					EVALUATION				
		FINNISH SLAG			(a) 117	(a) 120	FINNISH SLAG			117	120
		118-I	118-II	118-III			118-I	118-II	118-III		
3-1	$M = \frac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3}$	1.25	1.25	1.19	1.33	1.12	-	-	-	-	-
3-2	$(S)_{90} = 0.38\ G\ (M - 0.72) + 75$	90.11	88.10	83.75	93.17	86.10	J	J	J	J	J
-	$M^1 = \frac{CaO}{SiO_2}$	1.14	1.15	1.09	1.09	1.15	-	-	-	-	-
3-3	G^1M^1	85.50	74.80	53.40	85.50	83.90	-	-	-	-	-
3-4	$\frac{CaO}{SiO_2}$	1.14	1.15	1.09	1.09	1.15	b	b	b	b	b
3-5	$\frac{SiO_2}{Al_2O_3}$	4.02	3.85	4.59	3.82	7.49	c	c	c	c	c
3-6	$\frac{CaO + 1.4\ MgO + 0.56\ Al_2O_3}{SiO_2}$	1.61	1.61	1.50	1.77	1.26	✓	✓	✓	✓	c
3-7	$i = 20 + CaO + Al_2O_3 + 0.15\ MgO - 2SiO_2$	2.35	2.65	-2.30	3.88	-9.05	c	c	c	c	c

TABLE 3-4 (Continued)

NO.	MODULI	INDEX					EVALUATION				
		FINNISH SLAG			(a)	(a)	FINNISH SLAG				
		118-I	118-II	118-III	117	120	118-I	118-II	118-III	117	120
B-3	$\dfrac{\frac{CaO}{56} + \frac{MgO}{40} + \frac{Al_2O_3}{102}}{\frac{SiO_2}{60}} \geqq 1.0$	1.72	1.72	1.60	1.90	1.34	✓	✓	✓	✓	✓
B-4	$\dfrac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3} \geqq 1.0$	1.25	1.25	1.19	1.33	1.12	✓	✓	✓	✓	✓
B-5	$\dfrac{CaO + MgO + Al_2O_3}{SiO_2} \geqq 1.0$ (DIN 1164)	1.63	1.64	1.51	1.74	1.31	✓	✓	✓	✓	✓
B-6	$\dfrac{CaO \cancel{+ CaS + 1/2} MgO + Al_2O_3}{SiO_2 + MnO} \geqq 1.5$	(h) 1.47	(h) 1.49	(h) 1.37	(h) 1.51	(h) 1.29	c	c	c	✓	c
B-7	$\dfrac{CaO + MgO + Al_2O_3}{SiO_2 + MnO} > 1.0$	1.59	1.60	1.47	1.70	1.31	✓	✓	✓	✓	✓
B-8	$\dfrac{CaO + MgO}{SiO_2 + Al_2O_3} < 1$	1.10	1.09	1.06	1.17	1.03	c	c	c	c	c
B-9	$\dfrac{2.8\ SiO_2 + 1.1\ Al_2O_3 + 0.7\ Fe_2O_3}{CaO + 1.4\ MgO}$	2.09	2.10	2.21	1.91	2.50	e	e	e	d	e

TABLE 3-4 (Continued)

NO.	MODULI	INDEX					EVALUATION				
		FINNISH SLAG			(a) 117	(a) 120	FINNISH SLAG			117	120
		118-I	118-II	118-III			118-I	118-II	118-III		
B-10	$\frac{SiO_2 + Al_2O_3}{CaO}$	1.10	1.10	1.12	1.15	0.99	f	f	f	f	f
B-11	$\frac{CaO + 0.5\ MgO + Al_2O_3}{SiO_2 + MnO}$	1.47	1.49	1.37	1.51	1.29	c	c	c	c	c
B-12	Hydraulic Index $\left(\frac{70}{30}\right) = \left(\frac{a-c}{b-c}\right) \times 100$	J	J	J	J	J	-	-	-	-	-
B-13	$\frac{100\ CaO}{2.8\ SiO_2 + 1.1\ Al_2O_3 + 0.7\ Fe_2O_3}$	37.08	37.15	35.70	35.30	38.92	-	-	-	-	-
B-14	$\frac{CaO}{2.4\ SiO_2 + 1.2\ Al_2O_3 + 0.65\ Fe_2O_3} \leqq 1$	1.03	1.03	1.00	1.03	1.17	g	g	✓	g	c

(a) Free lime content is added to CaO content.
(b) Does not meet the requirement for the production of Super Sulphate Cement.
(c) Inferior.
(d) Relatively low limed natural cement.
(e) Feeble in hydraulic properties.
(f) Natural Cement.
(g) Border line case.
(h) CaS is not counted in this index calculation.
(✓) Meets the required limits.
(J) Not known.

$$M = \frac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3} \quad (B-4)$$

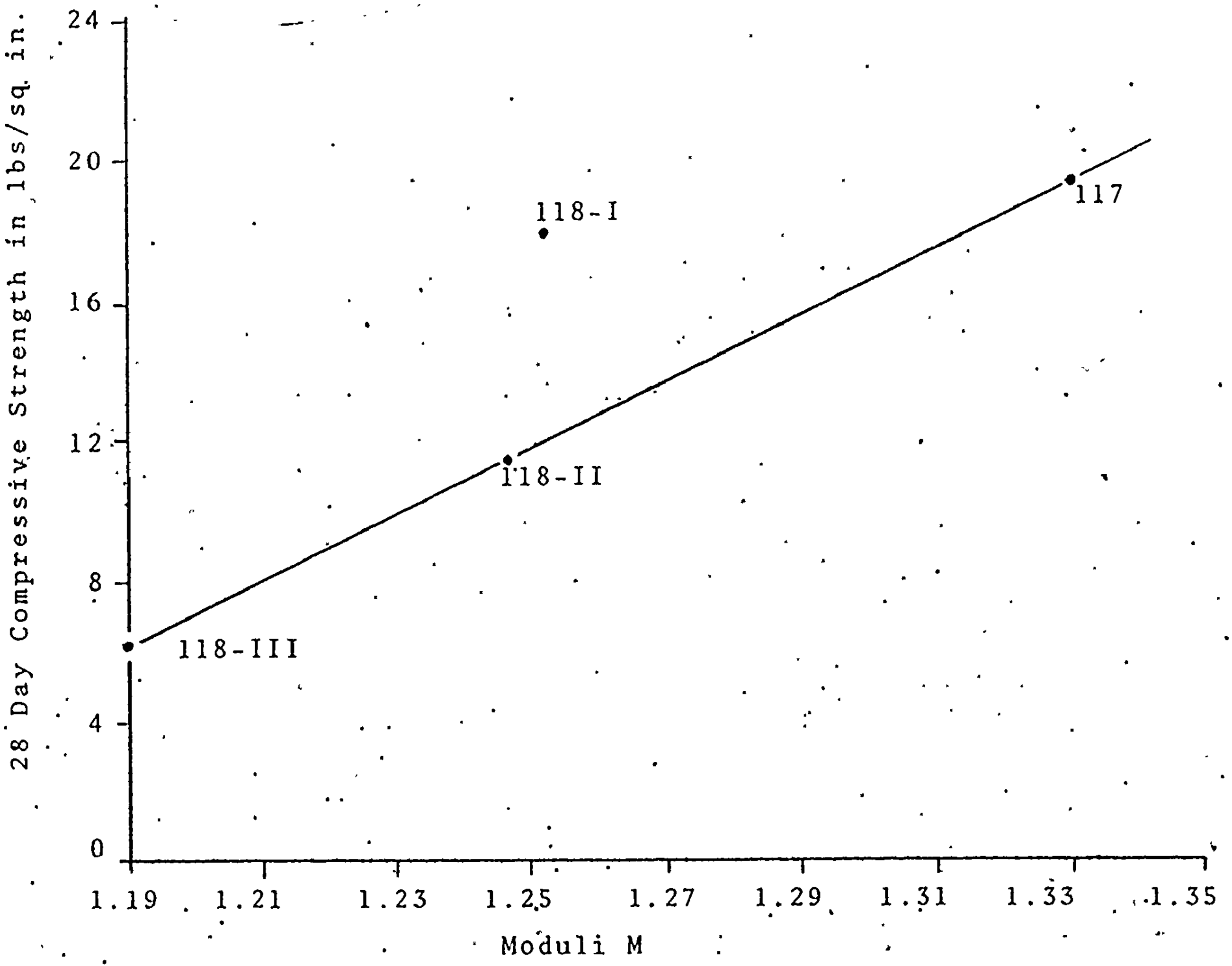


FIGURE 3-5 RELATIONSHIP BETWEEN STABILIZED BASE COMPRESSIVE STRENGTH AND MODULI M

relationship eixsts between stabilized base compressive strength and moduli, several pelletized glassy slags with different chemical compisitons should be used.

4. BASE STABILIZATION

The basic function of highway pavement structures is to provide a comfortable riding surface for the safe operation of vehicles over a defined range of speeds during the anticipated service life of the pavement. The basic structure of a pavement consists of a surface course which is in direct contact with the wheel loads and an underlying base(s) between the surface course and subgrade. The materials which make up the various layers in the pavement structure must meet performance requirements related to the function of that particular layer. The two conventional materials used for pavement surfaces are portland cement concrete (rigid pavement) and asphaltic concrete. Base courses can be compacted layers which use natural or graded aggregates or chemically stabilized layers in which the aggregates are treated with a binder, such as hydrated lime, portland cement, asphalt cement, etc. Mechanical stabilization is obtained by compaction. Chemical stabilization, which includes both improving the cohesion and changing the engineering properties of base materials, is of prime interest here. In particular, the use of pelletized blast furnace slag is examined for this purpose.

4-1-1 MATERIALS USED IN BASE STABILIZATION STUDIES

4-1-1-1. Granular A air-cooled blast furnace slag

(Crushed run, air-cooled blast furnace slag)

This air-cooled blast furnace slag is processed and marketed by National Slag Limited and originates from both STELCO and DOFASCO. Granular A blast furnace slag has a bulk specific gravity of 2.37 and typical gradation is shown in Table 4-1. The gradation has some variation from time to time during production so that a controlled gradation was used throughout the base stabilization studies as follows:

27% retained on the 3/8" sieve; 23% passing the 3/8" sieve and retained on the #4 sieve; and 50% passing the #4 sieve.

A typical chemical composition for this blast furnace slag is shown on Table 2-1.

4-1-1-2 Pelletized Slag

Based on field evidence of self-cementing properties observed at the older DOFASCO pelletizer, it appeared possible that a base stabilization process could be developed using ground pellets. This was initiated in the work of Kim (1973 - 1975) and has been reported by Emery, Kim and Cotsworth [24]. However, there were many aspects requiring further study and explanation that were completed in this study.

TABLE 4-1

GRADATION OF GRANULAR A AIR-COOLED BLAST FURNACE SLAG

SIEVE SIZE	% PASSING	ADJUSTED % RETAINED
3/4"	99.0	27%
3/8"	82.7	
#4	58.1	23%
#8	38.5	50%
#16	25.4	
#30	16.8	
#50	10.3	
#100	6.3	
#200	1.3	

All of the pellets used for compressive strength test specimens were ground in an EIRICH R7 intensive mixer to get 16% to 17% passing the #200 sieve. The pellets used in the test program were received from the United States (phosphorus pellets), Finland; and National Slag Limited. The gradations of these pellets are given in Table 4-2 and chemical compositions in Table 3-3.

4-1-1-3 Lime

Commerical grade, high calcium, hydrated lime was used as supplied by Domtar Chemical of Toronto from their Beachville plant (Beachville Chemical Hydrate). Its chemical analysis and physical properties are shown in Table 4-3.

4-1-1-4 Sodium Carbonate (Na_2CO_3)

Reagent grade sodium carbonate (Na_2CO_3) was used. It was added in powder form when preparing compressive strength specimens.

TABLE 4-2

GRADATION OF PELLETIZED SLAG

SIEVE SIZE	% PASSING				
	Finnish Slag			National Slag 117	Phosphorus Slag 120
	118-I	118-II	118-III		
3/4"	99.5	99.8	97.6	99.2	100
3/8"	93.7	95.1	79.6	95.9	98.8
#4	64.4	64.1	31.7	77.8	91.6
#8	28.2	25.3	5.8	36.0	73.6
#16	12.9	11.0	2.5	13.8	41.0
#30	7.0	6.2	1.6	5.3	14.8
#50	3.1	3.1	1.0	2.2	5.1
#100	3.0	1.7	0.7	1.4	2.5
#200	0.6	0.9	0.5	0.8	1.2

TABLE 4-3

CHEMICAL ANALYSES AND PHYSICAL PROPERTIES OF HYDRATED LIME

(Data supplied by DOMTAR)

CHEMICAL ANALYSIS		
Compounds		Percent
Silicon Dioxide and Insolubles	SiO_2	0.50
Ferric Oxide	Fe_2O_3	0.10
Alumina	Al_2O_3	0.30
Sulphur	S	0.06
Magnesium Oxide	MgO	0.60
Calcium Oxide	CaO	73.80
Available Lime Index as Calcium Oxide	CaO	71.50
Available Lime Index as Calcium Hydroxide	$Ca(OH)_2$	94.50
Carbon Dioxide	CO_2	0.90
Moisture	H_2O	1.00
Unhydrated Oxides	...	0.40

TABLE 4-3 (Continued)

PHYSICAL PROPERTIES			
Density	loose	24	pcf
	packed	36	pcf
Blaine fineness		13,000	cm^2/gr.
Sieve Analyses	% Passing		
	sieve size		
	#50	100	
	#100	99.9	
	#200	96.0	
	#325	93.0	

4-1-2 PHOSPHORUS PELLETIZED SLAG

4-1-2-1 Test Program

This study was largely restricted to a laboratory investigation of the potential use of ground phosphorus slag for stabilization of base courses. The test program consisted of the five steps summarized in Table 4-4.

4-1-2-2 Test Procedures

After drying at room temperature, the granular A gradation was controlled as indicated in Table 4-1, and the pellets were ground in the Eirich R7 intensive mixture to obtain 16% to 17% fines. Throughout this study, the term "fines" will be used for the minus #200 ground pelletized slag (-75μm). Table 4-5 and Figure 4-1 show the grinding characteristics of the phosphorus pellets. Base stabilization testing was in accordance with the standard methods specified by ASTM or AASHO, where suitable methods have been developed. A list of the test methods adopted for the study is given in Table 4-6.

TABLE 4-4

EXPERIMENTAL PROGRAM FOR STUDYING BASE STABILIZATION USING PHOSPHORUS PELLETIZED SLAG

STEP	PURPOSE
1	Grindability in the EIRICH R7 intensive mixer
2	Compressive strengths without activators
3	Optimum lime content for strength development
4	Effect of washing pellets on compressive strength development
5	Effect of sodium carbonate addition on compressive strength development

TABLE 4-5

GRINDING TIME vs % OF FINES PASSING #200 SIEVE

Machine - EIRICH R7 intensive mixer

Speed - 2,250 rpm (drum running clockwise)

Charge - 150 lbs

Material - Phosphorus pelletized slag (#120) dry

Sieve Size	% Passing (a)				
Time (minutes)→	0	1	2	3	4
3/4"	100				
3/8"	98.8	100	100	100	100
#4	91.6	98.0	99.0	99.1	99.8
#8	73.6	88.3	92.3	94.2	97.6
#16	41.0	70.1	76.6	80.6	85.7
#30	14.8	44.1	52.6	58.3	65.6
#50	5.1	24.0	31.1	36.6	43.1
#100	2.5	14.5	19.7	23.8	28.8
% fines (#200)	1.2	7.6	11.0	13.3	16.7

(a) Average of two tests in each case

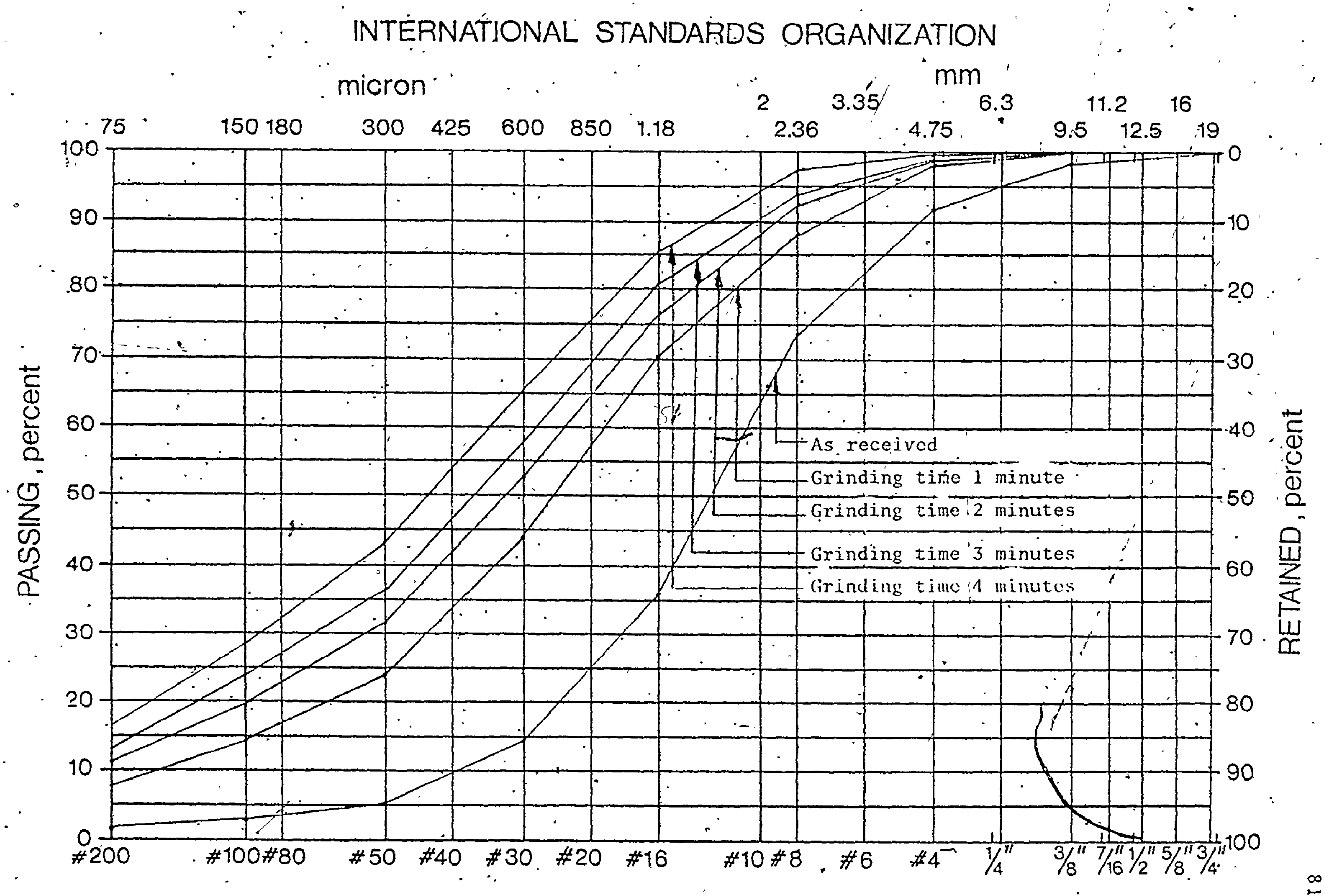


FIGURE 4-1 GRINDABILITY IN EIRICH R7 INTENSIVE MIXER AND GRINDING CHARACTERISTICS OF PHOSPHORUS SLAG, #120

TABLE 4-6

TEST METHODS

No.	Test	Material Tested	Method Used
1	Optimum Moisture Content	Aggregate	ASTM D1557, AASHO T180
2	Specific Gravity of Fines	Fines, Cement	ASTM C188, AASHO T133
3	Fineness of Fines	Fines, Cement	ASTM C204, AASHO T153
4	Glass Content	Fines, Pellets	Microscope Test (Appendix A)
5	Compressive Strength Test	Stabilized Base	ASTM C593 (except 5 lifts used instead of 3)
6	pH Test	Pellets	Fisher Universal pH indicator
7	Specific Gravity of Coarse Aggregate	Aggregate	ASTM C127, AASHO T85
8	Specific Gravity of Fine Aggregate	Aggregate	ASTM C128, AASHO T84
9	Sieve Analysis of Fine or Coarse Aggregate	Aggregate	ASTM D136, AASHO T27
10	Sampling of stone, slag, gravel, sand for highway use	Aggregate	ASTM D75, AASHO T2
11	Freez-Thaw Resistance	Stabilized base	ASTM D560 (method B)

(Current ASTM or AASHO Procedure used where available)

Preparation of Compressive Strength Specimens

Four-inch diameter modified Proctor specimens were prepared according to ASTM D1557-70 (10 lb hammer, 5 layers, 18 in. drop, 25 blows per layer). It was found best to control the water content on the basis of a "no slump" condition (a firm mix that can be cast in the hand), since the mix is too coarse for the normal Proctor procedure where a well defined optimum water content is usually observed. The optimum water content for strength development was found to be 8.2% at a dry density of 125 lb/ft^3 for the mix proportions used: 70% Granular A and 30% ground pelletized slag (approximately 5% net fines). After compaction the specimens were removed from the special split mold, sealed in double plastic bags, and cured at 100°F in an oven for the specified time. Sealed curing generally insures that adequate moisture is available for any reactions during the time periods studied (7, 14, 28 days). After curing, the specimens were capped with hydrostone and failed in compression. Three specimens were made and the results averaged for each test mix unless otherwise indicated.

4-1-2-3 Test Results and Discussion

Step 1: Grindability in the Eirich R7 intensive mixer.

Early work by Kim using the granular A and non-ground pellets without additional fines had not produced the desired minimum compressive strength of 500 psi after seven days sealed curing at 100°F (or 1000 psi if freeze-thaw resistance not checked) [20]. For this reason, a procedure was developed and adopted here for pre-grinding pellets in the Eirich R7 intensive mixer to obtain 16% to 17% fines which results in approximately 5% net fines in the final 70% granular A and 30% ground pellets mix [40]. The grinding efficiency for the intensive mixer is highest for the first minute as indicated in Figure 4-1. The desired fines level was acheived in approximately 4 minutes. It has been found that the grinding efficiency of the Eirich intensive mixer drops off very rapidly after about 15 minutes [24].

Step 2: Compressive strength test without an activator.

Specimens were prepared for 7, 14, and 28 day compressive strength tests with the results shown in Table 4-7. The 260 psi compressive strength developed after 7 days is far below the 500 psi minimum acceptable level. Compared

TABLE 4-7

COMPRESSIVE STRENGTHS OF SPECIMENS MADE USING PHOSPHORUS SLAG PELLETS

MIX	Age in Days	COMPRESSIVE STRENGTH (psi)		
		Without Activator	With Na_2CO_3 Activator	Washed Pellets without Activator
Proportions:	7	260	220(a) 185(b)	230
Granular A" 70% Ground pellets 30% (Net Fines≈5%)	14	270	-	-
Water Content 8.2%	28	290	-	-

(a) 5% Sodium Carbonate

(b) 10% Sodium Carbonate

with the 7 day compressive strength, there were increases of approximately 4% and 11.5% for 14 and 28 day respectively. This indicates that the bulk of any cementing reaction occured rapidly, but the level achieved with this phosphorus slag is very low in comparison to that of pelletized blast furnace slag (860 psi) discussed in Section 4-1-4. Phosphorus compounds were shown by Nurse [54] to adversely effect the setting and hardening of cementitious materials except at low levels. The optimum phosphorus content was found to be 0.20 to 0.25% for beneficial effects on strength, but more than 0.5% was found to be deleterious. The phosphorus slag used contains 2.55% phosphorus pentoxide based on wet chemistry as shown in Table 3-3. It was concluded that this high phosphorus content was responsible for the very poor cementing properties observed. Further, it was believed that the slag contains some fluorine, which may have further adverse effects on strength development. It was obvious from the low compressive strengths that some treatment would be required to develop a satisfactory stabilized base, if at all possible.

Step 3: Optimum lime content for strength development.

Since it is known that lime often acts as an activator (Section 3) with consequent increased compressive strength, the influence of lime addition was investigated. The optimum lime content was determined by using compressive strength specimens consisting of 70% Granular A, 25% ground pellets (with fines removed) and 5% ground pellet fines. (The fines were separated from the ground pellets for accuracy of blending.) The lime was added at levels of 3, 5, 10, 20, 25 and 30% of the ground pellet fines content (i.e., 0.15, 0.25, 0.5, 1.0, 1.25 and 1.5% of the total mix). These levels, as a percentage of fines, were selected since there is some indication in the literature that about 5 to 10% lime addition based on the fines are optimum for slag cement activation [40]. Granular A was mixed in the following proportion where the material was split on several additional sieves to ensure proper batching (Table 4-1):

- 3/4" to + 3/8"	27%
- 3/8" to + #4	23%
- #4 to + #16	20%
- #16 to + #50	15%
- #50 to + #200	12%
- #200 to Pan	3%

The mix proportions are shown in Table 4-8 with the respective compressive strengths. These results are also summarized in Figure 4-2. It should be noted that there is a small additional amount of free lime in the Granular A and also in the pellets.

The following observations can be made from this series of mixes:

TABLE 4-8

OPTIMUM LIME CONTENT USING GROUND PHOSPHORUS SLAG PELLETS

	Fines	GROUND FINES AND LIME PROPORTIONS						Strength
		(a)	Lime $Ca(OH)_2$		(b)	Net Lime CaO		
Mix No.	% fines	Weight (gm)	X% of fines	Weight (gm)	Weight of CaO	%of fines	%of mix	(c) psi
70-71	5	275	0	-	-	-	-	200
72-73	5	275	3	8.0	5.75	2.10	0.105	420
74-75	5	275	5	14.0	10.05	3.65	0.183	320
76-77	5	275	10	27.5	19.75	7.18	0.359	455
78-79	5	275	20	55.0	39.50	14.36	0.718	490
80-81	5	275	25	68.8	49.41	17.97	0.899	385
82-83	5	275	30	82.5	59.25	21.54	1.077	340

(a) Blaine fineness of fines 2108 cm^2/gm

(b) Weight of CaO obtained from weight of $Ca(OH_2)$ x 0.945 x 0.76, the purity of hydrated lime is 94.5%. Only the CaO is considered to be an activator.

(c) Average of two specimens prepared by modified Proctor compaction, with 8.2% water content and 7 days sealed curing at 100°F. Specimen mix proportion, 70% Granular A, 25% pellets (with fines removed), and 5% ground pellet fines, Lime X% of 5%.

PROPORTIONS:

Granular A	70%
Pellets (+#200 Sieve)	25%
Pellet fines	5%
Lime	X% of 5%

SPECIMEN: Modified Proctor Method

CURING: at 100°F in double plastic bag for 7 days

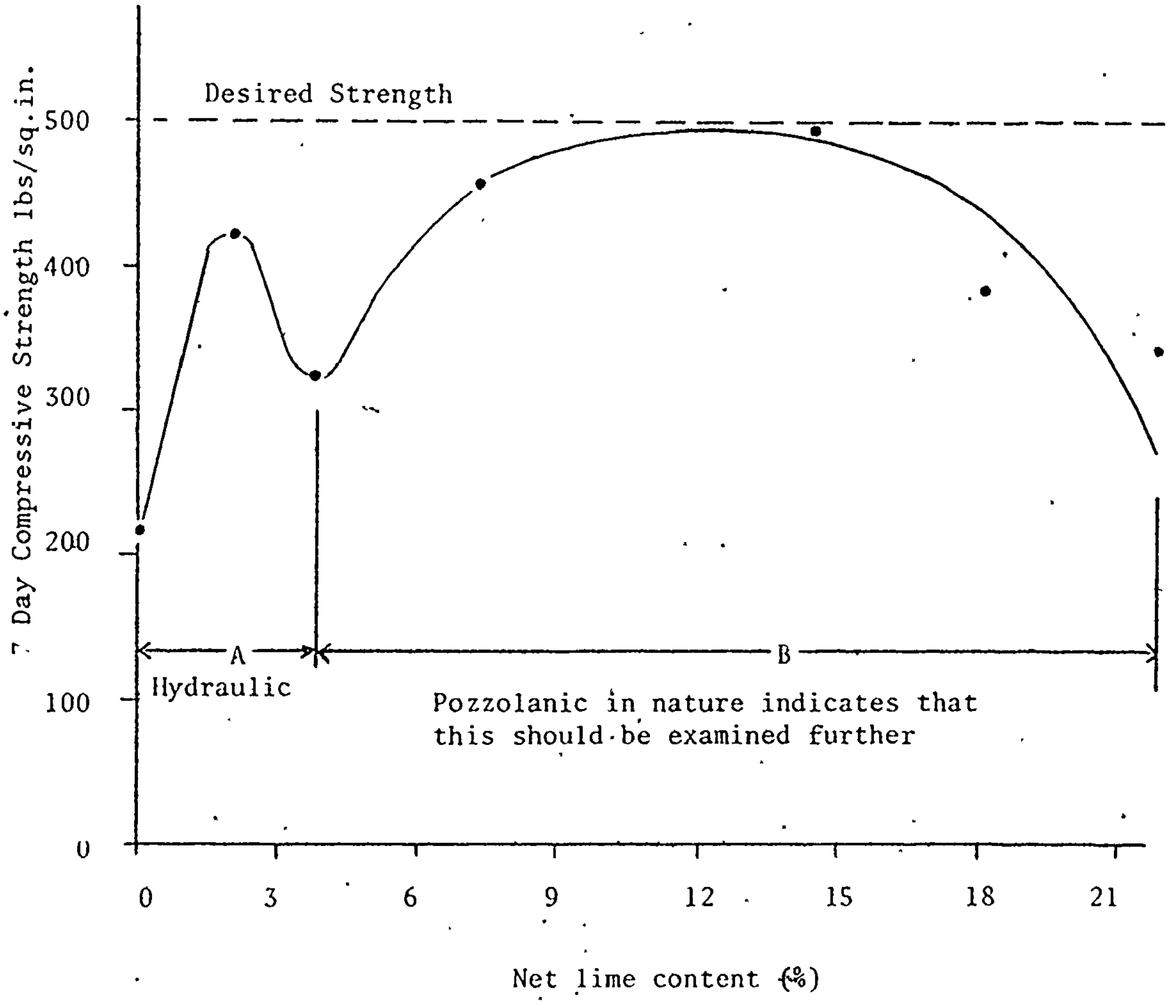


FIGURE 4-2 NET LIME CONTENT VS COMPRESSIVE STRENGTH

1. Mix No. 70-71, which contains no lime, gave the lowest compressive strength of 200 psi, and the highest compressive strength achieved was 490 psi for test no. 78-79 at a net CaO content of 14.36% of the fines or 0.72% of the mix. The maximum strength will probably be at 12.6% net CaO content but still marginally below the desired 500 psi. (The small difference in strength between mix no. 70-71 and the corresponding mix in Table 4-7 is probably due to better gradation control in the Granular A, particularly the - #4 materials.)

The addition of lime, which generates Ca^{++} ions in solution, increased the compressive strengths significantly, but the ground fines from phosphorus pellets have such poor self-cementing properties that even this doubling of compressive strengths resulted in less than 500 psi.

2. The phosphorus slag's composition shown in Table 3-3 is out of the typical range shown in Table 2-5 for blast furnace slags that generally have cementitious properties if glassy. Every major component plays an important role in determining cementing activity. The CaO and SiO_2 are higher, and Al_2O_3 and MgO are lower in the phosphorus slag than the normal range for blast furnace slags. This is also evident in the poor hydraulic moduli values for this phosphorus slag (Table 3-4). Schroder [60] found that if the CaO/SiO_2 ratio in vitreous slags was between 1.1-1.3, there was improvement in strength by increasing

the MgO content up to 10%. The CaO/SiO_2 ratio of phosphorus slag is 1.15 but the MgO content is only 0.94%. Schröder indicated that according to Oelschlager slags low in MgO content showed poor hydraulic properties. This is undoubtedly another reason for phosphorus slag having poor cementing properties in addition to the phosphorus pentoxide and fluorine content.

3. The two peaks observed in Figure 4-2 have been shown rather than a single smooth curve. These peaks are similar to those observed by Midgley, Chopra [51] and Kim [40]. A possible explanation of the first peak would be hydraulic reaction at low lime addition. The second peak could be due to reactions of a more pozzolanic nature. This is an area that requires substantial future research. If this hypothesis is correct, very small lime additions would be adequate for activation and free lime available from Granular A and from pellets would be of great importance.

Step 4: Effect of washing pellets on compressive strength.

Phosphorus and fluorine are deleterious as described in Step 1 and in the previous chapter. For this reason, it was considered desirable to wash the pellets so that any free P_2O_5 and fluorine would be dissolved and washed away. The pellets were washed three times in fresh water and then dried at room temperature before grinding in the standard way to the gradations given in Table 4-9 and Figure 4-3. It took somewhat longer to get the desired fines level (16 to 17%) since some fines had obviously been washed out. The 7 day compressive strength of 230 psi in Table 4-7 is similar to that obtained for unwashed pellets. Any reduction in strength, apparent in Table 4-7, is probably due to the loss of free lime and very fine slag during washing.

Step 5: Effect of sodium carbonate on compressive strength development.

Activators such as sodium carbonate (Na_2CO_3) has been suggested for use with slag cements and in slag base stabilization [40]. This was studied for the proportions shown in Table 4-7 with the resulting compressive strength indicated. The addition of 5 and 10% Na_2CO_3 of the fines content (5%) in the powder form gave 7 day compressive strength of 220 and 185 psi respectively. These strengths are somewhat lower than the specimens prepared without the activator, which indicates that Na_2CO_3 has little influence, or even a negative influence, on the strength development of phosphorus pelletized slag.

In summary, only lime activation improved the low ground pelletized phosphorus slag base stabilization (12.5% of fines appears optimum) compressive strengths in simulated field applications. The strength level still fell somewhat below the desired 500 psi. While other mixes and/or activa-

TABLE 4-9

GRINDING TIME vs % FINES PASING #200 SIEVE

Machine - EIRICH R7 intensive mixer

Speed - 2250 rpm (drum running clockwise)

Charge - 150 lbs

Material - Washed and dried phosphorus pellets (#120)

SIEVE SIZE	% PASSING (a)					
Time (minutes) →	0	1	2	3	4	5
1/2"	100	100				
3/8"	98.4	99.9	100	100	100	100
#4	89.1	96.3	98.7	99.0	99.4	99.7
#8	68.6	82.4	89.8	90.9	93.8	95.9
#16	37.9	61.1	71.7	72.4	77.9	82.2
#30	12.8	35.2	47.4	48.9	55.5	60.9
#50	4.1	19.0	29.0	31.0	36.0	51.2
#100	1.7	11.1	18.4	20.7	24.7	27.7
% Fines (#200)	0.7	6.0	10.5	12.3	13.8	16.5

(a) Average of two tests in each case.

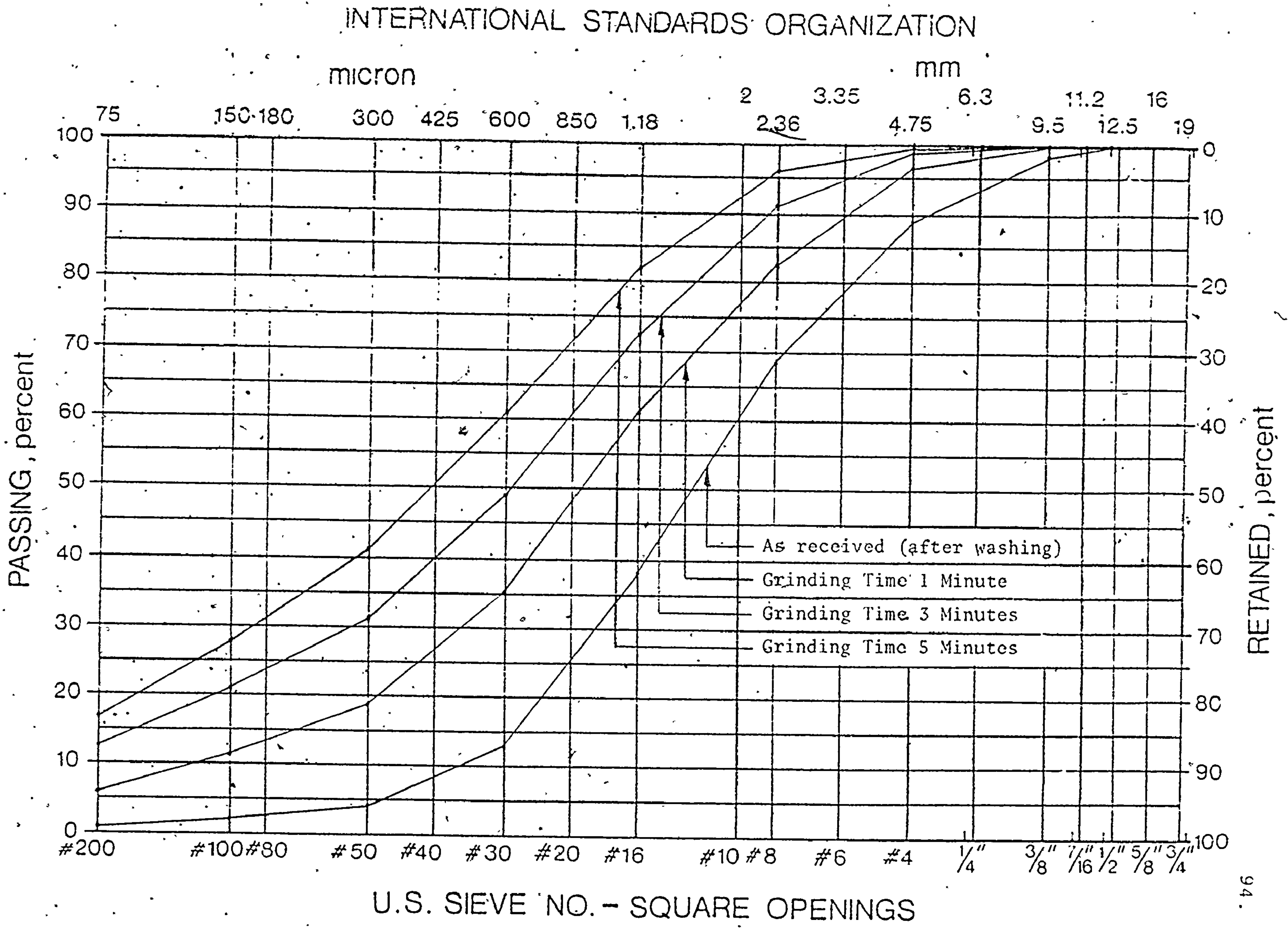


FIGURE 4-3 GRINDABILITY IN EIRICH R7 INTENSIVE MIXER AND GRINDING CHARACTERISTICS OF PHOSPHORUS SLAG, #120 (AFTER WASHING)

tion could be tried, it is not considered likely that a ground pelletized phosphorus slag base stabilization process is very feasible. The freeze-thaw resistance would probably be a further problem.

4-1-3 PELLETIZED BLAST FURNACE SLAG FROM FINLAND

4-1-3-1 Base Stabilization Test Schedule

The study was largely restricted to a laboratory investigation of base stabilization using ground pelletized blast furnace slag from Oy Koverhar Ab of Finland. The three samples of pellets received (118-I, 118-II, and 118-III) were each used in the ground form along with Granular A in a similar way to the base stabilization tests on phosphorus pelletized slag described in the previous section. The test program consisted of the three steps summarized in Table 4-10. The glass content of the material passing the #200 sieve and retained on the #325 sieve was determined by the McMaster procedure as given in Appendix A. These glass contents are given in Table 4-11. The chemical composition of the three Finnish pelletized slag are similar to each other as indicated previously in Table 3-3. The calculated values of the moduli for the Finnish slags are given in Table 3-4.

4-1-3-2 Test Procedures

The materials were prepared in the same way as discussed in Section 4-1-2 for phosphorus pelletized slag.

TABLE 4-10

EXPERIMENTAL PROGRAM FOR THE BASE STABILIZATION STUDY USING FINNISH PELLETIZED SLAG

STEP	PURPOSE
1	Grindability in EIRICH R7 intensive mixer
2	Effect of moisture content and curing time on stabilized base compressive strength, 118-I
3	Stabilized base compressive strengths at optimum moisture content

TABLE 4-11

COMPRESSIVE STRENGTH AT
OPTIMUM MOISTURE CNTENT

MIX	AGE IN DAYS	FINNISH PELLETIZED SLAG		
		118-I	118-II	118-III
		COMPRESSIVE STRENGTH in lbs/sq in. (b)		
PROPORTIONS:				
Granular A 70%	7	350	300	290
Ground pellets 30%				
(Net Fines 5%)	14	915	520	345
Water Content 8.4%	28	1785	1155	615
Glass Content % (a)		75	65	49
Specific gravity of Fines		2.931	2.936	2.960
Blaine Fineness cm^2/gm		1716	1983	1885

(a) McMaster Method (Appendix A)

(b) Average of two specimens, prepared by modified Proctor compaction, sealed curing at 100°F in double plastic bags

4-1-3-3 Test Results and Discussion

Step 1. Grindability in EIRICH R7 intensive mixer

Table 4-12 and Figure 4-4 show the grindability of the Finnish pellets in the EIRICH R7 intensive mixer. It is clear from Table 4-11 and Table 4-12 that the production of fines increases with the decreasing glass content (opposite to anticipated trend). However, the initial gradations were not identical, so that comments on grindability of other sizes is not really possible.

Step 2. Effect of moisture content and curing time on stabilized base compressive strengths, Finnish slag 118-I

Modified Proctor specimens were prepared as previously outlined for phosphorous pelletized slag in Section 4-1-2. Table 4-13 shows the stabilized base compressive strengths for different moisture contents and curing times, and this information is further summarized in Figure 4-5. It can be seen that the compressive strength at 28 days is more sensitive to moisture content than the earlier strengths. It should be noted that the 7 day aim compressive strength at 500 psi was not achieved.

Step 3. Stabilized base compressive strengths at optimum moisture content

From step 2, it was found that the optimum water content for Finnish slag 118-I is 8.4% to achieve maximum

TABLE 4-12

GRINDING TIME VS % FINES

MACHINE - EIRICH R7 intensive mixer

SPEED - 2250 rpm (drum running clockwise)

CHARGE - 150 lbs

MATERIAL - Finnish pelletized slag, 118-I, 118-II, 118-III
Average of two tests in each case

Time (minutes) ⟶	As received			1			3-1/4		2-3/4
Material	118-I	118-II	118-III	118-I	118-II	118-III	118-I	118-II	118-III
Sieve Size	% Passing								
1"	100.0	100.0	99.6	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	99.5	99.8	97.6						
5/8"	98.9	99.4	94.2						
1/2"	97.1	98.3	89.2						
3/8"	93.7	95.1	79.6	100.0	100.0	100.0	100.0	100.0	100.0
# 4	64.4	64.1	31.7	93.6	92.8	87.3	99.2	96.4	94.2
# 8	28.2	25.3	5.8	71.5	69.0	72.7	89.8	84.0	74.1
# 16	12.9	11.0	2.5	49.6	47.6	56.2	73.4	65.2	58.1
# 30	7.0	6.2	1.6	34.1	34.5	44.7	57.1	50.8	46.5
# 50	3.1	3.1	1.0	20.2	24.0	34.3	40.8	37.9	35.7
#100	3.0	1.7	0.7	13.0	15.8	25.5	28.5	27.1	26.2
% Fines (- #200)	0.6	0.9	0.5	4.9	7.5	15.7	16.6	16.6	17.0

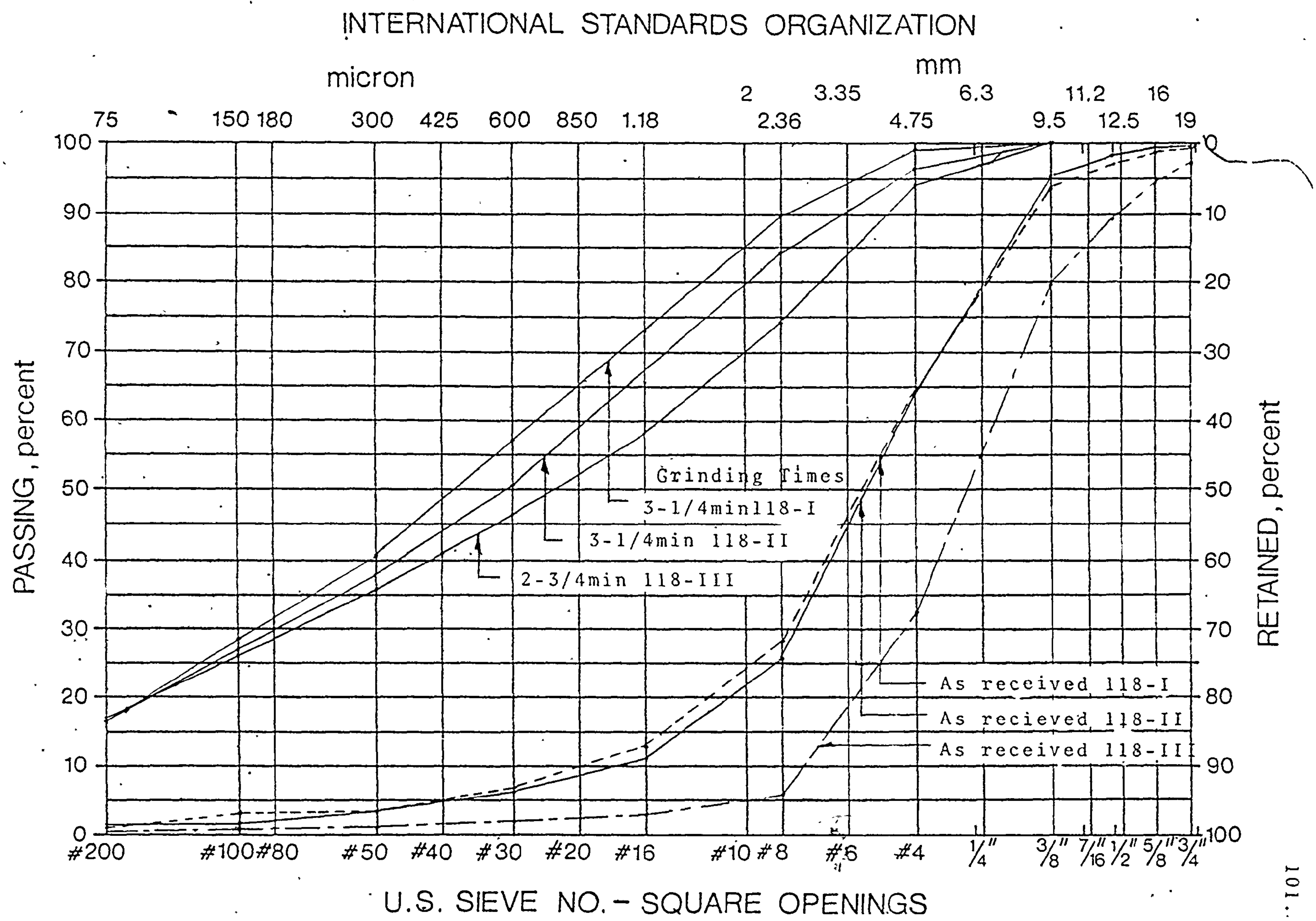


FIGURE 4-4 COMPARISON OF FINAL GRADATION FOR SAME FINES LEVEL IN GROUND FINNISH PELLETS

TABLE 4-13

EFFECT OF MOISTURE CONTENT ON COMPRESSIVE STRENGTH

118-I

MIX DESIGN	WATER CONTENT % (Actual)	AGE IN DAYS	COMPRESSIVE STRENGTH psi (b)
PROPORTIONS: Granular A 70% Ground pellets (118-I) 30% (Net fines 5%) Glass content 70%	5.50	7	310
		14	710
		28	1015
	7.14	7	410
		14	695
		28	1490
	8.40	7	350
		14	915
		28	1785
	9.00	7(a)	320
		14	695
		28	1225
Specific gravity of material passing #200 sieve			2.931
Blaine fineness of fines Cm^2/gm			1716

(a) Average of two specimens

(b) Average of three specimens, sealed curing at 100°F in double plastic bags

PROPORTIONS:	
Granular A	70%
118-I Ground pellets	30%
(Net fines 5%)	
Glass Content	70%

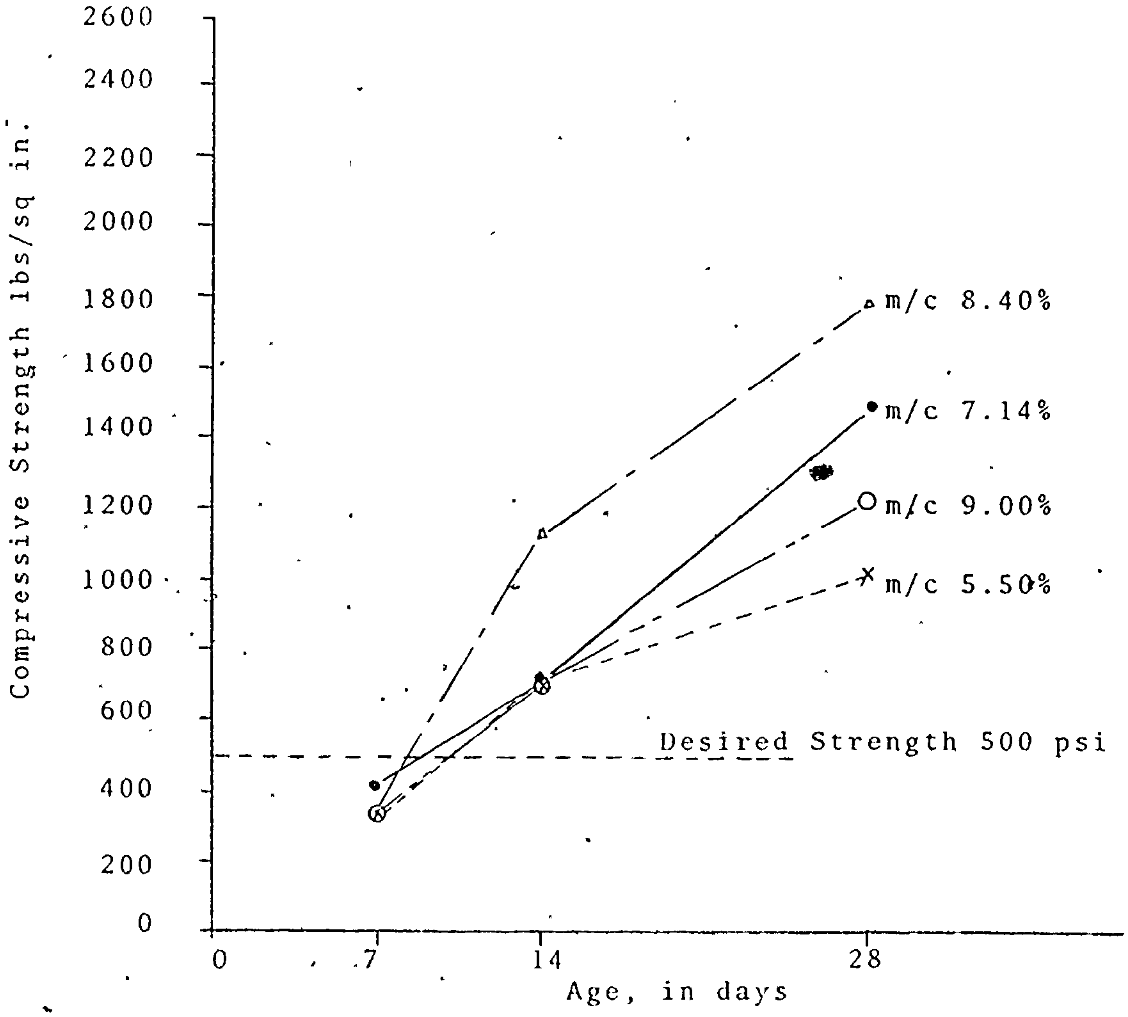
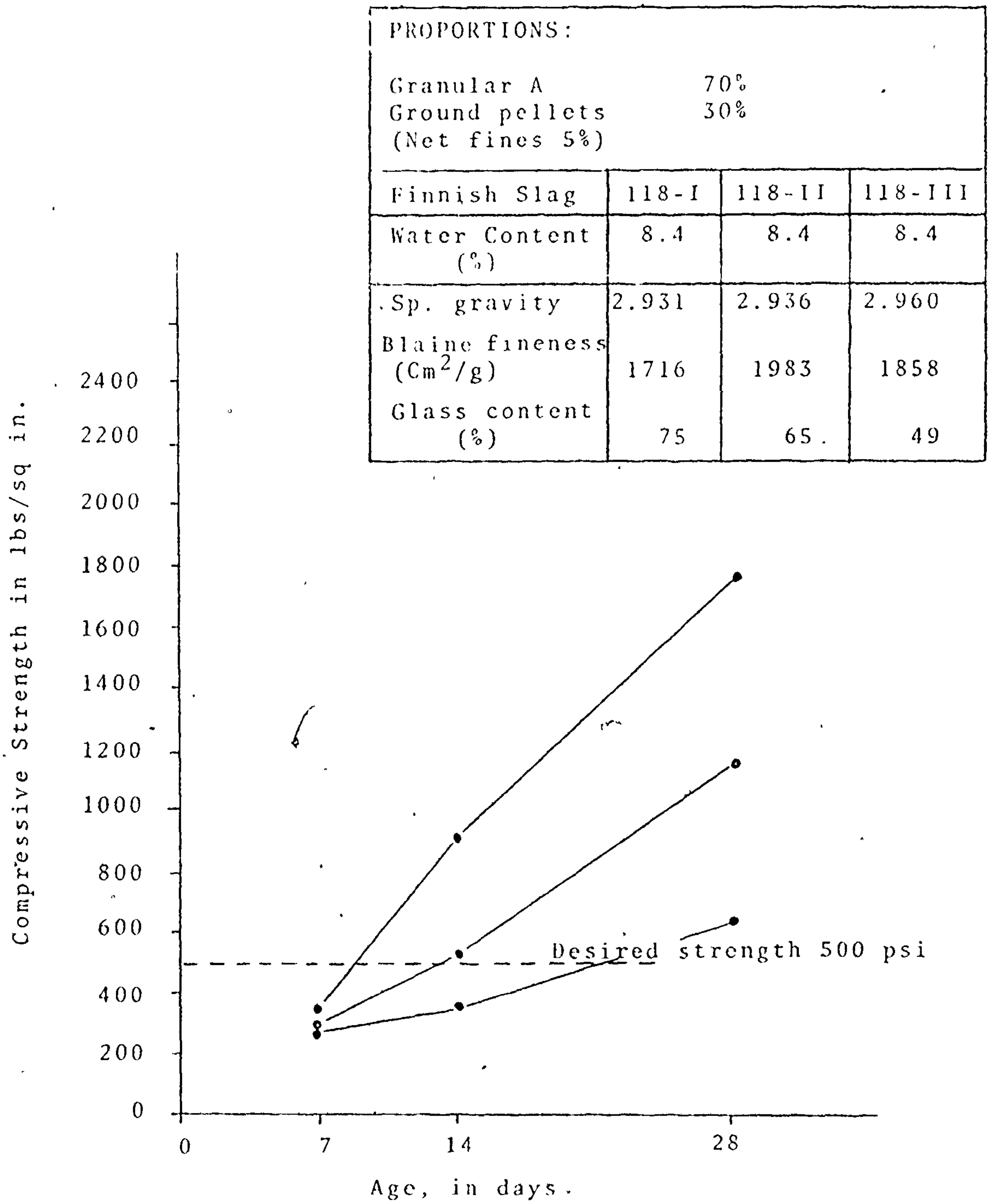


FIGURE 4-5 EFFECT OF MOISTURE CONTENT ON STABILIZED BASE COMPRESSIVE STRENGTH, 118-I

compressive strengths for a wide range of curing times. Therefore, specimens were prepared for the other two samples (118-II and 118-III) using this optimum 8.4% water content.

In Table 4-11 and Figure 4-6, for the three Finnish pelletized slags tested for compressive strength at optimum moisture content, 118-I had the highest compressive strengths. However, none of these slags developed the aim compressive strength of 500 psi at 7 days, and this is probably attributable to the relatively low glass contents. There was no significant trend in 7 day compressive strengths except 118-I was approximately 17% higher than the other two slags (i.e. 118-II and 118-III) and 118-I has the highest glass content.

No further tests such as freeze-thaw resistance were performed on these pellets since they were considered to be marginal for base stabilization use without special activators. It should be noted that the use of activators particularly hydrated lime, is common if enough free lime is not already present in the slags. This results in some cost disadvantages and it was hoped that the Finnish pelletized blast furnace slags would be adequate without such additions. Obviously, based on this study, the manufacturer should consider a range of possible activators if base stabilization uses are still contemplated.



PROPORTIONS:

Granular A 70%
Ground pellets 30%
(Net fines 5%)

Finnish Slag	118-I	118-II	118-III
Water Content (%)	8.4	8.4	8.4
Sp. gravity	2.931	2.936	2.960
Blaine fineness (Cm^2/g)	1716	1983	1858
Glass content (%)	75	65.	49

FIGURE 4-6 AGE VS COMPRESSIVE STRENGTH

4-1-4 PELLETIZED BLAST FURNACE SLAG FROM NATIONAL SLAG LTD., HAMILTON

4-1-4-1 Base Stabilization Test Program

This study was largely restricted to a laboratory investigation of the potential use of ground pelletized slag for stabilization of base courses. The test program consisted of the five steps summarized in Table 4-14. The slag was pelletized at DOFASCO's No. 4 (Figure 2-3) blast furnace in Hamilton. The pellets were used in the ground form along with Granular A in a similar way to the base stablization test described in previous sections. The glass contents shown in Table 4-17 were done in accordance with the McMaster procedure in Appendix A. The chemical composition of pelletized slag #117 from DOFASCO is shown in Table 3-3. The calculated values of the moduli for this slag based on the chemistry shown in Table 3-3 is given in Table 3-4.

4-1-4-2 Test Procedures

The materials were prepared in the same way as discussed previously in Section 4-1-2 for the phosphorus pelletized slag, unless indicated otherwise.

TABLE 4-14

EXPERIMENTAL PROGRAM FOR STUDYING BASE STABILIZATION USING PELLETIZED SLAG FROM NATIONAL SLAG

STEP	PURPOSE
1	Grindability in the EIRICH R7 intensive mixer
2	Determination of optimum moisture content
3	Effect of moisture content on compressive strength
4	Comparison of accelerated curing vs normal curing
5	Influence of fines level on freeze - thaw resistance

4-1-4-3 Test Results and Discussion

Step 1. Grindability in EIRICH R7 intensive mixer.

The grindability of the pellets in the EIRICH R7 intensive mixer is given in Table 4-15 and in Figure 4-7. It can be seen from Figure 4-7 that the grinding efficiency for the intensive mixer is highest for the first minute. The desired fines level of 16 to 17% was readily achieved in approximately 3-1/4 minutes.

Step 2. Determination of optimum moisture content

Modified proctor specimens were prepared according to ASTM procedure C593-69 as described previously. The 7 day compressive strengths and dry densities before curing at different moisture contents are given in Table 4-16, and this information is further summarized in Figure 4-8. The modified Proctor optimum water content was found to be 8.5% at a dry density of 129.5 pcf for the following mix proportions (i.e. fines were added separately):

Granular A (as before):		
- 1/2" + 3/8"	27%	
- 3/8" + # 4	23%	70%
- # 4 + Pan	50%	
Ground pellets (+ #200 sieve)	25%	
Pellet fines (- #200 sieve)	5%	

TABLE 4-15

GRINDING TIME VS % FINES

MACHINE - EIRICH R7 intensive mixer

SPEED - 2250 rpm (Drum running clockwise)

CHARGE - 150 lbs

MATERIAL - Pelletized Slag from DOFASCO, #117
Average of two test in each case

Grinding Time in minutes→	As received	1	2	3-1/4
Sieve Size	% Passing			
3/4"	99.2	100.0	100.0	100.0
3/8"	95.9	100.0	100.0	100.0
# 4	71.8	96.3	98.7	99.3
# 8	36.0	76.7	86.9	91.3
# 16	13.8	52.1	65.4	73.4
# 30	5.3	31.1	47.3	55.6
# 50	2.2	23.2	32.6	39.4
#100	1.4	15.4	22.0	26.4
% Fines (- #200 Sieve)	0.8	9.5	13.5	16.6

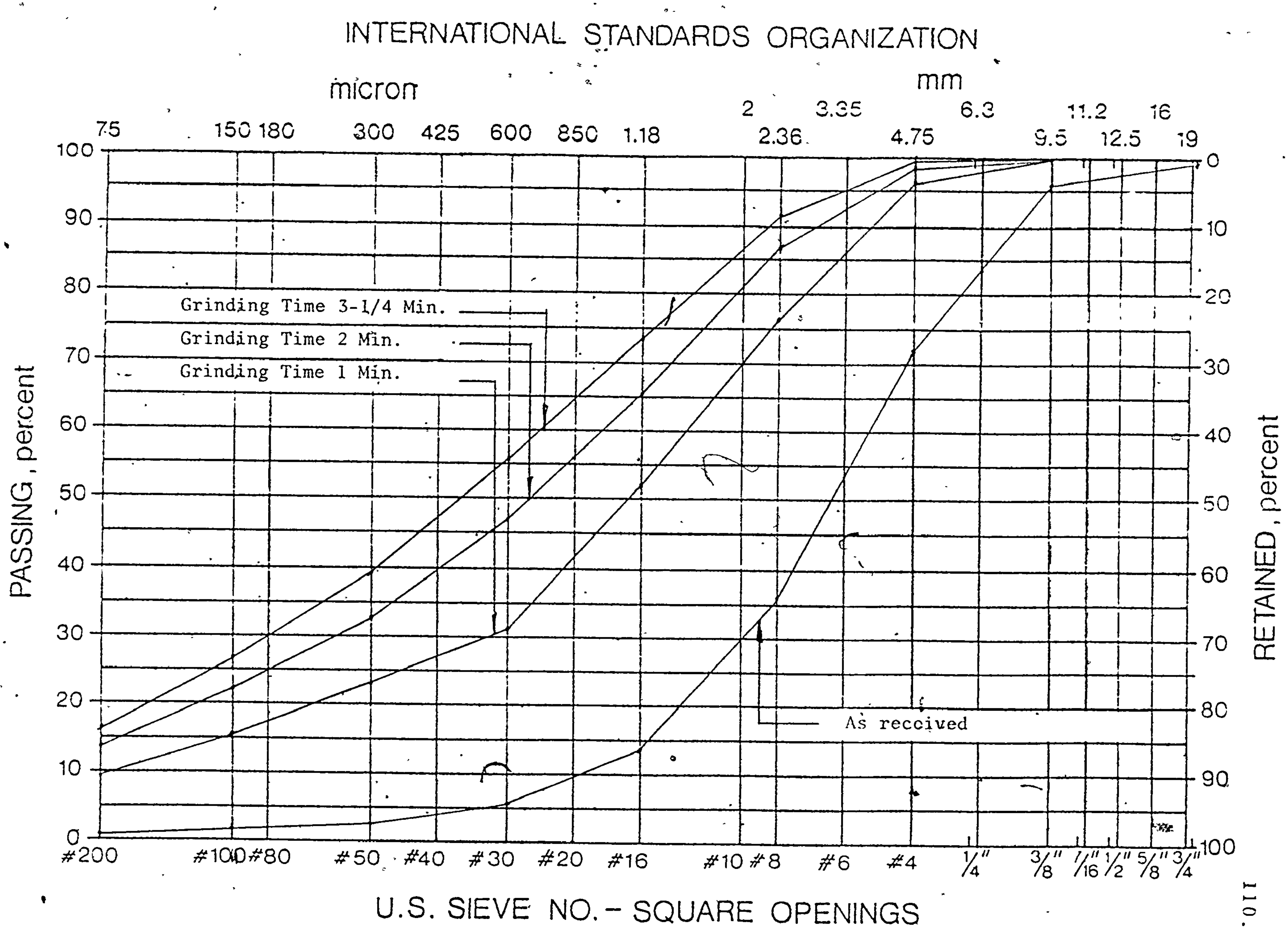


FIGURE 4-7 GRINDABILITY IN EIRICH R7-INTENSIVE MIXER AND GRINDING CHARACTERISTICS OF NATIONAL SLAG, #117

TABLE 4-16

EFFECT OF MOISTURE CONTENT ON COMPRESSIVE STRENGTH

MIX	MOISTURE CONTENT %		7 DAY COMP. STRENGTH in psi (a)(b)	DRY DENSITY lbs/cu/ft
	Assumed	Actual		
PROPORTIONS: Granular A 70% Ground pellets 25% Fines 5%	8.0	8.0	640	126.0
	8.5	8.5	860	129.5
	9.0	8.9	800	128.6
	9.5	9.5	680	126.0

(a) Average of two specimens, prepared by modified Proctor compaction, sealed curing at 100°F in double plastic bags.

(b) Green colour was found inside specimen.

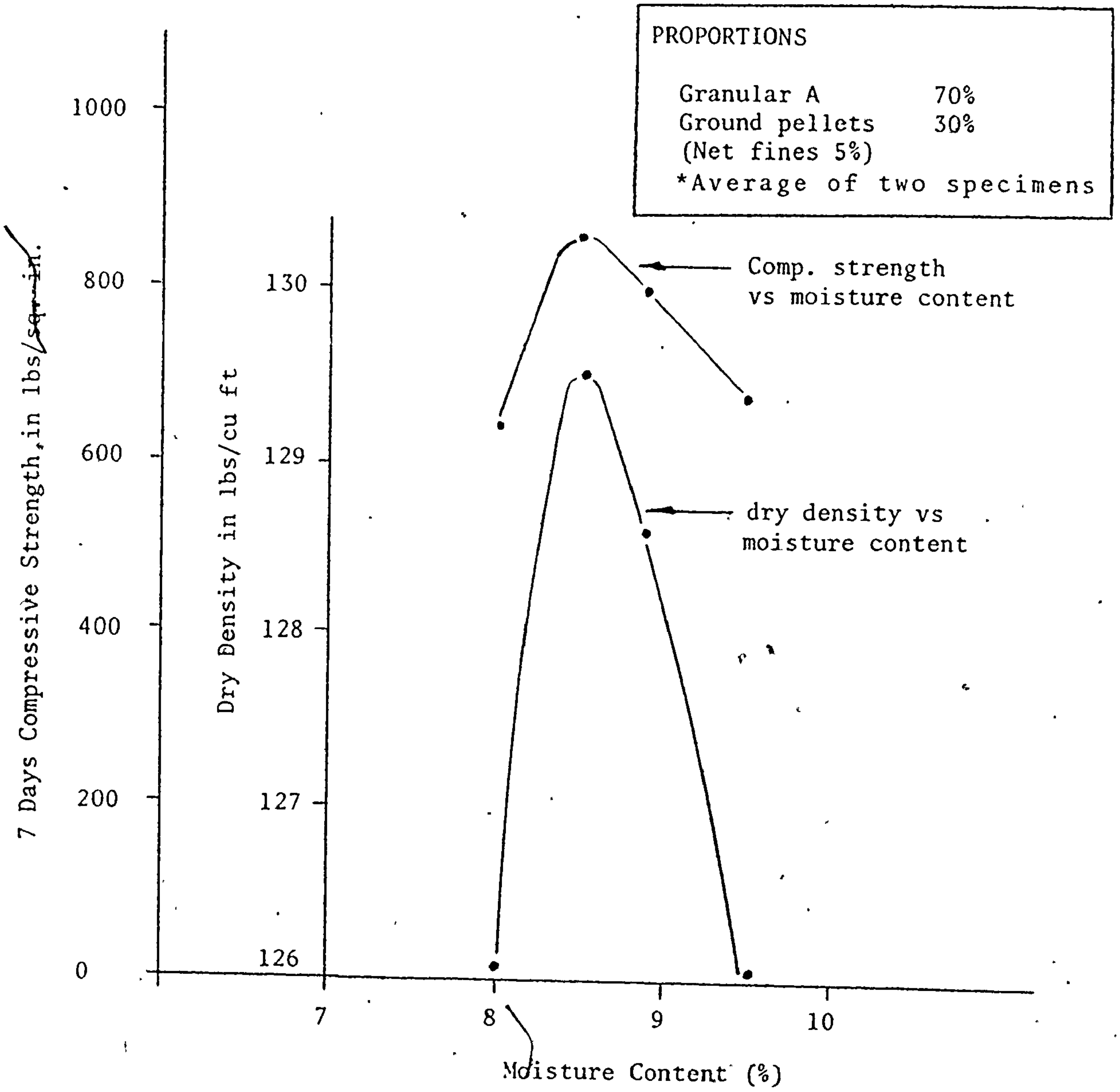


FIGURE 4-8 DETERMINATION OF OPTIMUM MOISTURE CONTENT

After failing the specimens, a green colour and sulphur like smell was detected which provided evidence on the maturity of the reaction or hydration. It was found that the specimens which had lower strengths exhibited less colour and smell than the strong specimens. This indicates that the pellets contain sulphide in some form of CaS and in the well cured condition polysulphides are formed with the emission of hydrogen sulphide (H_2S)[47].

In conclusion, it was possible to determine the optimum moisture content for the adopted mix proportion and as shown in the previous section. This moisture content gave the peak compressive strength. This method of determining the optimum moisture content (i.e. for peak dry density) appeared superior to the empirical no slump test that required operator's experience and a "feel" for the mix being studied.

Step 3. Effect of moisture content on compressive strength

From Table 4-16, it can be seen that the compressive strength is more sensitive to moisture content at lower moisture contents than at higher moisture contents. The maximum compressive strength achieved was 860 psi at 8.5% moisture content which also corresponded to the optimum moisture content. This indicates that it is important to determine the optimum moisture content for a particular slag sample in order to achieve the highest compressive strength.

By increasing moisture content by 0.5% from 8.0 to 8.5% (i.e. the optimum), the 7 day compressive strength increased by 34.5% (from 640 psi to 860 psi). However, the compressive strength decreased by 7.5%, when moisture content was increased further from 8.5 to 9.0%. This marked sensitivity to compaction moisture content would be of particular concern during field construction.

Step 4. Comparison of accelerated curing versus normal curing

This step was mainly included to determine the influence of normal temperature (70 ± 2)°F as compared to the standard laboratory accelerated curing. Further, the level of fines required to give the desired compressive strength of 500 psi after 7 days curing at normal temperature studied, since more fines may be required at lower temperature. A significant criticism of previous studies was the accelerated curing temperature adopted. Since field curing would be at much lower temperature than 100°F (say around 70°F during the construction period) the normal curing procedure adopted appears more realistic for design purposes.

The fines were separated from the total ground pellets and were added at the time of specimen preparation. Compressive strength specimens were made using 5, 10 and 15% fines for the normal curing condition and 5% fines for the accelerated curing condition. The strengths of 7, 14 and 28 day specimens prepared for different fines levels are shown in Table 4-17, and this information is further summarized in Figure 4-9.

These results indicate the following:

1. As anticipated, there is a significant difference in compressive strengths at different curing ages (5% fines level) for accelerated curing. This indicates that the hydration reaction is certainly accelerated at 100°F and would be much slower under normal curing conditions as found in the field. However, even with this slower strength gain, the 5% fines level and normal curing gave adequate strength after about 12 days. It would appear that 17 days normal curing is equivalent to about 7 days accelerated curing. Since curing time during base stabilization is not generally a construction constraint, the longer curing times that would apparently be required are quite satisfactory.

2. It was found for the 7 day compressive strength that in order to achieve strength of approximately 850 psi, 5% fines are required for accelerated curing and 15% fines are required for normal curing. However, the same general relationship is not true for 14 day and 28 day curing as the strengths tend to move closer together. This indicates

TABLE 4-17

COMPARISON OF ACCELERATED CURING VS NORMAL CURING

MIX	AGE IN DAYS	COMPRESSIVE STRENGTH in psi (a)			
		Fines (X%)			
		Accelerated curing (100°F) (b)	Normal curing (70°F) (c)		
PROPORTIONS:		5%	5%	10%	15%
Granular A 70%	7	860	330	605	855
Ground pellets (+#200) (30-X) %	14	1395	1640	1495	1950
X%	28	1950	1235	2330	3205
Dry Density lbs/cu ft		129.5	129.5	131	132
pH value	9.8				
Glass content % (d)	78.4				

(a) Average of two specimens prepared by modified Proctor compaction, with 8.5% moisture content

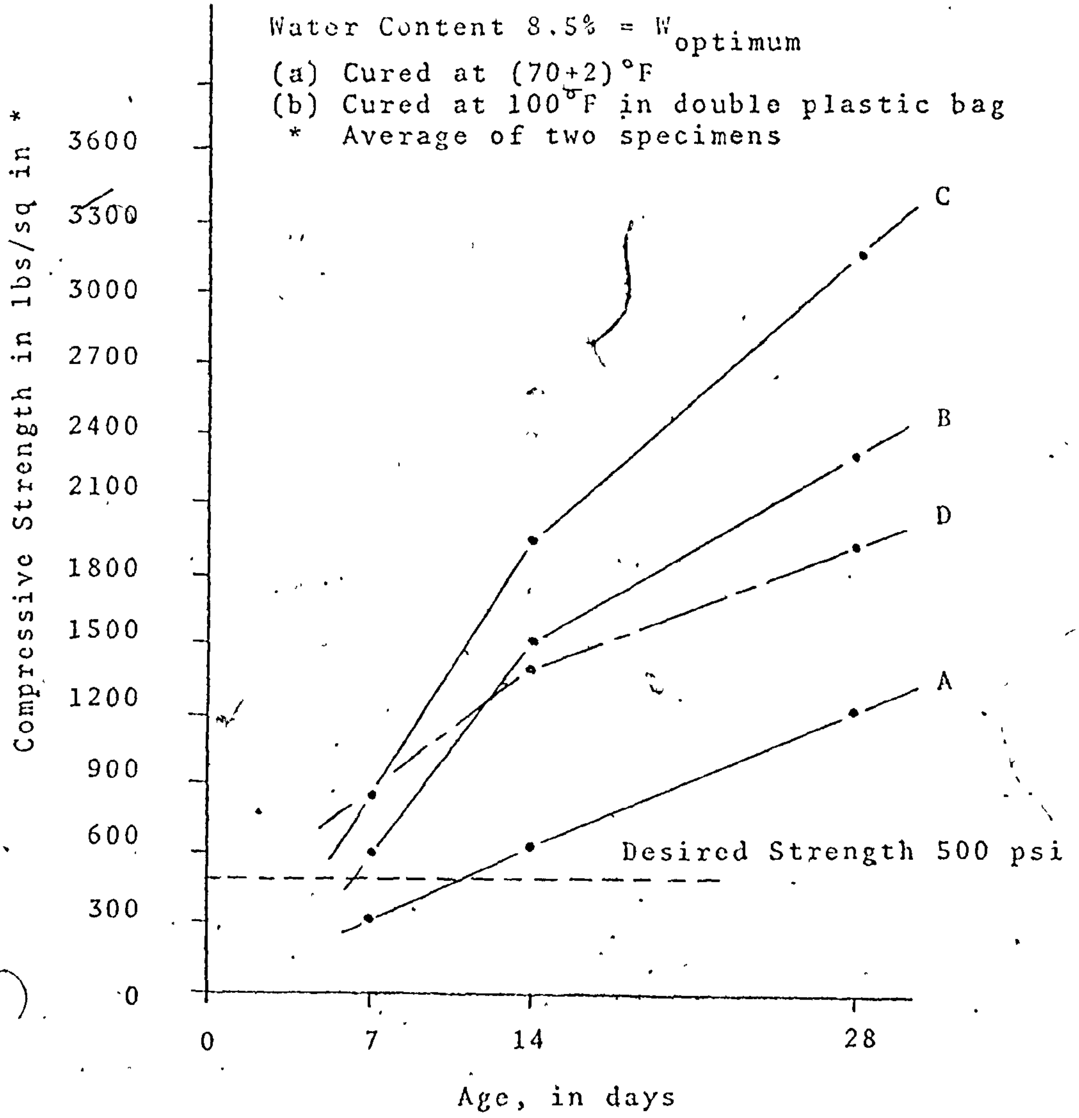
(b) Sealed curing in double plastic bags at 100°F

(c) Cured in moist room at 70°F

(d) McMaster Method (Appendix A)

PELLETIZED SLAG #117

	PROPORTION			Method of curing
	Granular A	Material retained #200Sieve	Material passing #200Sieve	
A	70%	25%	5%	Normal (a)
B	70%	20%	10%	Normal
C	70%	15%	15%	Normal
D	70%	25%	5%	Accelerated(b)


Water Content 8.5% = $W_{optimum}$

(a) Cured at (70+2)°F

(b) Cured at 100°F in double plastic bag

* Average of two specimens

FIGURE 4-9 COMPARISON OF ACCELERATED CURING VS NORMAL CURING OF COMPRESSIVE STRENGTH that the hydration reaction proceeds somewhat slower after 7 days for accelerated curing.

3. The mix which would have a strength closest to the minimum acceptable of 500 psi at 7 days would be one containing approximately 9% fines for normal curing condition; a fairly reasonable fines level when compared to other base stabilization methods. For accelerated curing conditions, the equivalent fines level would be about 3%. However, as pointed out previously curing age is not a critical criteria for periods up to a few weeks in the field. For this reason, fines levels should be established based on normal curing periods of say two to three weeks. That is, the most economic design will involve a more realistic field curing period and a reduced fines content.

4. In general, the increase in compressive strength was greatest for the first 14 days and slowed at longer times. The increases in strengths from 7 to 14 days and 14 to 28 days were 94% and 93%, 147% and 56%, 128% and 64% for 5, 10, and 15% fines respectively for normal curing conditions. This indicates that most of the hydration reaction takes place in 14 days, and the reaction tends to slow down at longer times in a similar way but slower rate, to accelerated curing, except for 5%

fines where little slowing in strength gain was observed. This may indicate that the amount of moisture available at higher fines levels was not adequate to complete hydration.

It is considered that the information summarized in Figure 4-9 and discussed above is critical to having the pelletized base stabilization process adopted for field use. It has been shown that by simply lengthening the curing period to say two or three weeks, that adequate strengths are achieved, even for fines levels based on accelerated curing for much shorter periods. Thus, the simulation of the field process has been made more realistic.

Step 5 Influence of fines level on freeze-thaw resistance

Specimens were prepared using the procedures described previously for 5, 10 and 15% fines as shown in Table 4-18. For all specimens, the optimum 8.5% moisture content from Step 2 was used. The test results after 12 cycles of freeze-thaw on pelletized slag base stabilization with different proportion of fines are shown in Table 4-18. The specimens were not prepared using the standard Proctor method usually adopted for freeze-thaw studies (i.e. low compactive effort) since the modified Proctor (i.e. high compactive effort) is far more representative of base stabilization compaction in the field. Except for the higher compactive effort, these tests were in accordance with ASTM

TABLE 4-18

TEST RESULTS AFTER 12 CYCLES OF FREEZE-THAW ON SPECIMENS WITH DIFFERENT FINES LEVELS

MIX	% Fines X	Moisture Content		Soil Cement loss %	Max. Volume Change %	Dry Density lbs/cu.ft (b)
		Assumed %	Actual %(a)			
PROPORTIONS	5	8.5	8.5	15.53(b)	-4.11(b)	128.5
Granular A 70% Ground pellets (+#200 Sieve) (30-X)%	10	8.5	8.5	7.78(c)	+1.69(d)	131.7
Fines X%	15	8.5	8.4	4.83(b)	+1.86(d)	132.3

(a) Average of two samples

(b) Average of two specimens

(c) Average of three specimens

(d) Only one specimen

procedure (ASTM D560, method B) and PCA recommendations. For freezing the specimens, an inexpensive commerical deep freezer (-30^{0}C) was used, and for thawing the specimens were kept in a 100% humidity room with the temperature maintained at (70 ± 2)°F.

The results can be summarized as follows:

1. The specimen with 5% fines failed to meet the 14% allowable "soil cement" loss (abraded material). However, the soil cement loss decreases as the amount of fines increases so that about 6% fines will be sufficient to meet the allowable 14% loss.
2. All specimens tested (5, 10 and 15% fines) meet the % volume change required of less than +2%.
3. It is clear from the freeze-thaw testing, that while a slightly higher fines level may be required to meet this specification, the pelletized base stabilization process can be readily designed to meet both strength and freeze-thaw requirements. A minimum strength of 1000 psi without freeze-thaw testing has been suggested as an alternative design. From Figure 4-9 and Table 4-17, this appears a most reasonable alternate design approach.

5 SIMULATION OF MASONRY BLOCK MANUFACTURE USING PELLETIZED SLAG

5-1-1 Phosphorus pelletized slag

5-1-1-1 Test Program

It was shown in section 4-1-2 that the pelletized phosphorus slag gave poor base stabilization results (Table 4-7). Even when lime was added as an activator, the minimum desired compressive strength of 500 psi was not achieved (Table 4-8). It was thought that this pelletized phosphorus slag, along with a small quantity of Portland cement, and with air-cooled phosphorus slag (#121) to make up the bulk might be suitable for making masonry blocks.

5-1-1-2 Test Procedures

The pelletized slag (#120) and air-cooled slag (#121) both were received from Stauffer Chemical company, U.S.A. The air-cooled phosphorus slag when received was in irregular large pieces, light brown in colour and of low unit weight. After drying at room temperature, the air-cooled phosphorus slag was crushed to give the gradation as indicated in Table 5-1 and the material was separated and stored in bags according to sieve sizes. Similarly, the ground pelletized phosphorus slag was separated and stored according to the same sieve sizes. The compressive

TABLE 5-1

ADJUSTED GRADATIONS OF PHOSPHORUS SLAG AND AIR-COOLED SLAG FOR MASONRY BLOCK MIX

SIEVE SIZE	% RETAINED	
	Pelletized Slag #120	Air Cooled Slag #121
3/16"	0	0
1/4"	2	2
#4	8	8
#8	24	24
#16	24	24
#30	17	17
#50	8	8
#100	9	9
Pan	8	8

strength specimens were prepared using 50% pelletized slag (#120) and 50% air-cooled slag (#121). The total mix design was one part of portland cement by weight to 5 parts of the combined pelletized slag and air-cooled slag. These proportions were selected to give a fairly light-weight block. The compaction apparatus developed, and the method for preparing compressive strength specimens are described in Appendix C.

5-1-1-3 Test results and discussion

Specimens were prepared at 8, 9, and 10% moisture content by weight of the total mix. (The optimum moisture content was found to be 9% for the block mix.) The specimens were cured at 180°F in sealed double plastic bags for one day. After one day of curing, the specimens were tested for compressive strength with the results given in Table 5-2. To check on the influence of specimens drying, excess moisture was made available in a pan during curing of one set of the specimens. The compressive strength increased by approximately 7.1% when these specimens were cured with excess moisture being available. This indicates that the other specimens probably dryed out and there was not enough moisture available for completion of the hydration process. For specimens cured at room temperature, the compressive strength was greatly reduced (137%) from those with accelerated curing.

TABIE 5-2

ONE DAY COMPRESSIVE STRENGTHS

MIX	MOISTURE CONTENT %	COMPRESSIVE STRENGTH psi
PROPORTIONS		
Pelletized slag #120 50%	8	665 (a)
Air-cooled slag #121 50%	9	985 (a)
	9	1055 (b)
DESIGN MIX (1:5)		
1 part portland cemnt to	10	970 (a)
5 of combined #120 and	10	370 (c)
#121	9	415 (c)

(a) Sealed curing at 180°F in oven, average of three specimens

(b) Sealed curing at 180°F with excess water available, average of three specimens.

(c) Sealed curing at room temperature (70±2)°F, average of two specimens

It is recommended that adequate moisture always be provided in the laboratory during high temperature curing of ground pelletized slag products. Since the product strengths were well below 2000 psi, the general aim strength for such block mixes, no further studies were completed on the pelletized phosphorus slag. Based on the low base stabilization and block mix strengths, it is believed that the use of the pelletized phosphorus slag from Stauffer Chemical Limited in cementitious applications will not be successful. For this reason, future research on these pellets should focus on bulk aggregate applications.

5-1-2 PELLETIZED BLAST FURNACE SLAG FROM DOFASCO (NATIONAL SLAG LIMITED, HAMILTON)

5-1-2-1 Test Program

This part of the study was restricted to a laboratory investigation of the potential use of unground pelletized slag for making masonry blocks. It was considered desirable to investigate the use of DOFASCO pelletized slag in masonry units since the block industry has been using considerable quantities of these pellets for this purpose, and a standard method of simulating the block process could be developed on this basis in the laboratory. The aim of this part of the study was to develop the background and techniques to study the use of ground pellets as cementitious material in masonry blocks, thus providing another application for pellets.

5-1-2-2 Test Procedures

It can be seen from Table 5-3 that the #144 pellets are much coarser than the #145 pellets. Therefore, to get the desired block mix gradation 20% coarse pellets and 80% fine pellets were used by weight. The compressive strength specimens were prepared using one part of portland cement by volume to 8 parts of combined pellets (20% #144 plus 80% #145). The apparatus developed and the method of preparing compressive strength specimens are given in Appendix C. In section 5-1-1, it was indicated that the compressive strength increased by 7.1%, when the specimens were cured with excess moisture present in a pan at the bottom of the sealed plastic bags. Therefore, all of the specimens in this series and the next series were cured with excess moisture available, sealed in double plastic bags at 180°F.

TABLE 5-3

AS RECEIVED GRADATIONS OF PELLETIZED SLAGS FROM NATIONAL SLAG

SIEVE SIZE	COMMERCIAL GRADATION AS RECIEVED	
	#144 coarse	#145 fine
	% passing	
3/8"	100	
#4	49.5	100
#8	4.6	80.6
#16	2.7	44.2
#30	2.3	21.9
#50	1.9	10.0
#100	1.5	4.5
% Fines (- #200 Sieve)	0.8	1.7

5-1-2-3 Test Results and Discussion

The test results for compressive strength specimens prepared at different moisture contents are indicated in Table 5-4 and summarized in Figure 5-1.

The following observations can be made from this series of tests:

1. The compressive strength increases as anticipated with increasing moisture content until the moisture content reaches an optimum value. While not exactly at the highest dry density, the optimum moisture contents for highest strength and dry density are fairly close (within 1%). After this optimum value, the compressive strength decreases with increasing moisture content. Thus, the strength behavior with moisture content is similar to that observed for base stabilization specimens. At the optimum moisture content of 10% the compressive strength was 1530 psi.

2. It was found that when similar specimens were cured at room temperature with 12% moisture content, the compressive strength was reduced by approximately 102% from 1080 psi to 535 psi.

This series of tests confirmed the key role of moisture content on strength development, and indicated that the

TABLE 5-4

DETERMINATION OF MAXIMUM COMPRESSIVE STRENGTH FOR ONE DAY CURING

MIX	MOISTURE CONTENT %	COMPRESSIVE STRENGTH psi (a)	DRY DENSITY lb/ft^3
PROPORTIONS:			
Unground coarse pellets #144 20% } by	8.0	825	97.1
Unground fine pellets #145 80% } weight	9.0	1160	97.2
DESIGN MIX (1:8)	9.5	1395	102.2
1 part of portland cement by volume to 8 parts of combined pellets (#144 + #145)	10.0	1530 (b)	100.9 (b)
	10.5	1315	102.8
	11.0	1305 (d)	103.5
	12.0	1080	94.2
	12.0	535 (c)	94.2

(a) Cured in water bath in sealed double plastic bags at 180°F. Average of two specimens.

(b) Average of five specimens.

(c) Cured at room temperature (70 ± 2)°F in sealed double plastic bags.

(d) One specimen.

PROPORTION

Unground coarse pellets #144 20% } by weight
Unground fine pellets #145 80% }

DESIGN MIX (1:8)
One part of Portland Cement by volume to 8 parts of combined pellets

* After one day curing ~~at~~ 180°F in double plastic bag.

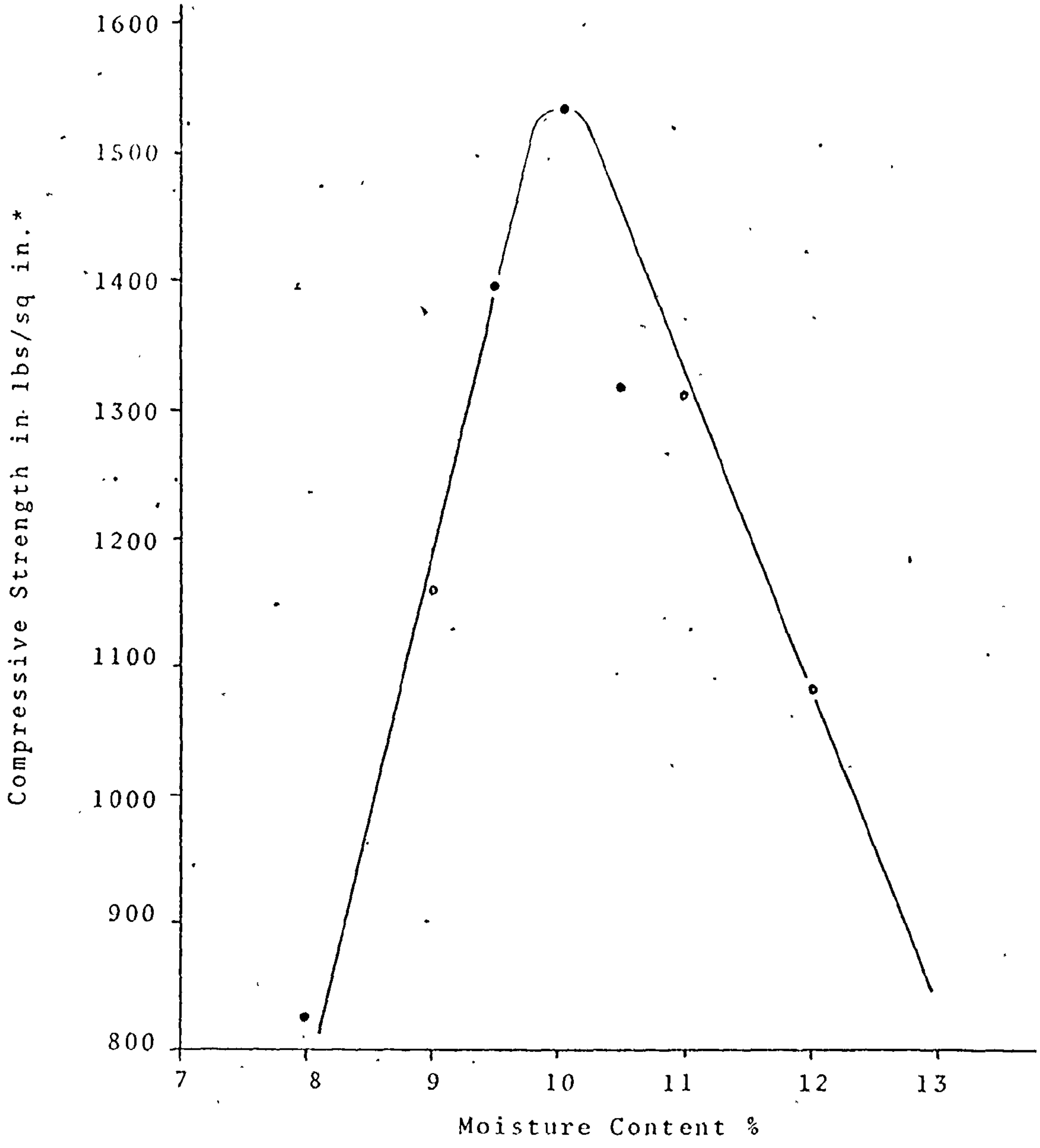


FIGURE 5-1 EFFECT OF MOISTURE CONTENT ON COMPRESSIVE STRENGTH OF BLOCK MIX

block simulation process developed (see Appendix C) was appropriate for such tests.

5-1-3 AUTOCLAVED CURING OF LIGHT-WEIGHT MASONRY BLOCKS USING PELLETIZED SLAG FROM DOFASCO (NATIONAL SLAG LIMITED, HAMILTON)

5-1-3-1 Test Program

This study involved the laboratory investigation (with actual curing in plant) of the potential use of ground and unground pelletized blast furnace slag for making light-weight masonry blocks. The autoclave curing was done at Cooke Concrete Products, Burlington, who co-operated in this particular study. The test program consisted of the three steps summarized in Table 5-5.

5-1-3-2 Test Procedure

After drying at room temperature, the #143 pelletized slag was ground in the EIRICH R7 intensive mixer to obtain 20% to 21% fines. The grinding characteristics of #143 pelletized slag is shown in Table 5-6 and summarized in Figure 5-2. The combined gradation of the #143 plus #144 pellets when mixed in a 72.5% to 27.5% proportion is also shown in Figure 5-2. This gives a gradation similar to that used for typical light-weight blocks. The apparatus and method used for preparing compressive strength specimens are described in Appendix C.

TABLE 5-5

EXPERIMENTAL PROGRAM FOR STUDYING THE MAKING OF AUTOCLAVED BLOCKS WITH PELLETIZED SLAG

STEP	PURPOSE
1	Grindability in EIRICH R7 intensive mixer
2	Determination of optimum moisture content
3	Autoclaved curing of compressive strength specimens

TABLE 5-6

GRINDING TIMES VS % FINES

MACHINE	-	EIRICH R7 intensive mixer
SPEED	-	2250 rpm (drum running clockwise)
CHARGE	-	150 lbs
MATERIAL	-	Pelletized slag, #143 and #144 Average of two tests in each case

Sieve Size	As received		After 4 min. of grinding #143 pellets	Combined gradation of #143 (ground) & #144 pellets
	#144 pellets	#143 pellets		
	% Passing			
2"	-	100	-	-
3/4"	-	98.2	-	-
3/8"	100	87.9	100	100
#4	49.5	58.5	99.5	85.7
#8	4.6	26.9	91.6	67.6
#16	2.7	11.0	75.5	55.4
#30	2.3	5.1	59.1	43.4
#50	1.9	2.6	43.7	32.2
#100	1.5	1.6	32.1	23.7
% Fines (- #200 Sieve)	0.8	1.1	20.5	15.1

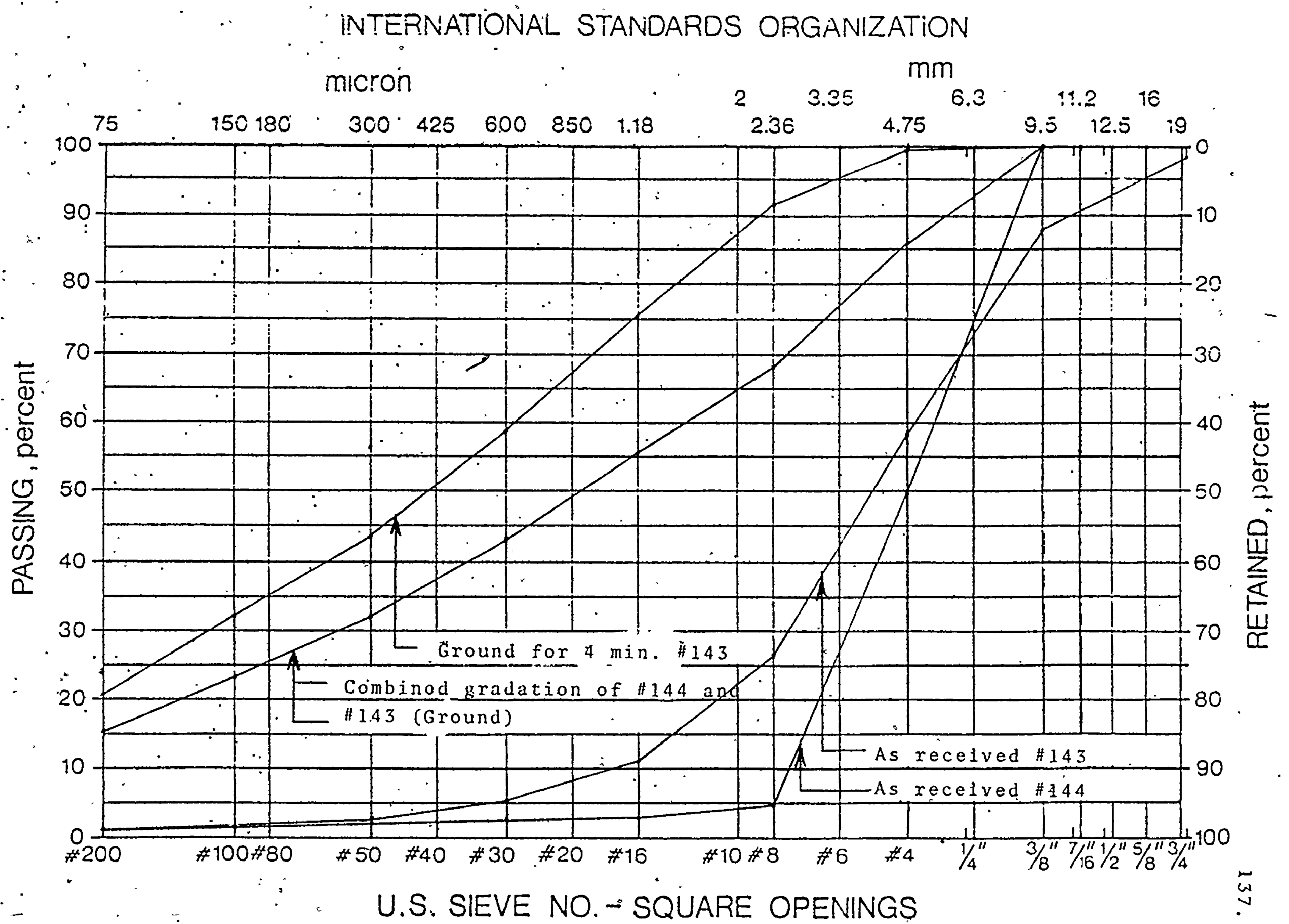


FIGURE 5-2 COMBINED GRADATION OF #144 PELLETIZED SLAG (as received) AND #143 PELLETIZED SLAG (after 4 min. grinding in EIRICH R7)

5-1-3-3 Test Results and Discussion

Step 1 Grindability in Eirich R7 intensive mixer

It should be noted that while the fines for all these specimens were prepared from pellets (#117 for base stabilization and #143, #144 and #145 for block making) supplied over a period of time, that the various fines are extremely similar in chemical and physical properties. The desired fines level of approximately 15% was achieved in 4 minutes grinding time in the Eirich R7. The combined gradation curve is shown in Figure 5-2.

Step 2 Determination of optimum moisture content

In order to determine the optimum moisture content, compressive strength specimens were prepared at different moisture contents and were tested after one day curing in sealed double plastic bags at 180°F with excess moisture available. These test results are shown in Table 5-7 and this information is summarized in Figure 5-3. The mix proportion used was 27.5% #144 unground pellets and 72.5% #143 ground pellets (net fines 15.1%) with moisture added by weight of the total mix. The optimum moisture content was taken to be 7%, since at this moisture content the maximum compressive strength of 292 psi was obtained.

TABLE 5-7

EFFECT OF WATER CONTENT ON COMPRESSIVE STRENGTH SPECIMENS

MIX	DRY DENSITY lb/ft^3	MOISTURE CONTENT %	COMPRESSIVE STRENGTH psi (a)
PROPORTIONS Unground pellets #144 27.5% Ground pellets #143 72.5% (Net Fines 15.1%)	110.5	6	138 (b)
	111.9	7	292
	112.8	8	212
	114.3	9	178
	114.1	10	237
	114.2	11	204 (b)

(a) Average of two specimens

(b) Two specimens were cured, only one could be tested as the other crumbled at the time of testing.

BLOCK

PROPORTIONS:

Ground pellets	#143	72.5%
Unground pellets (Net fines 15.1%)	#143	27.5%

* After one day curing at 180°F sealed in double plastic bags

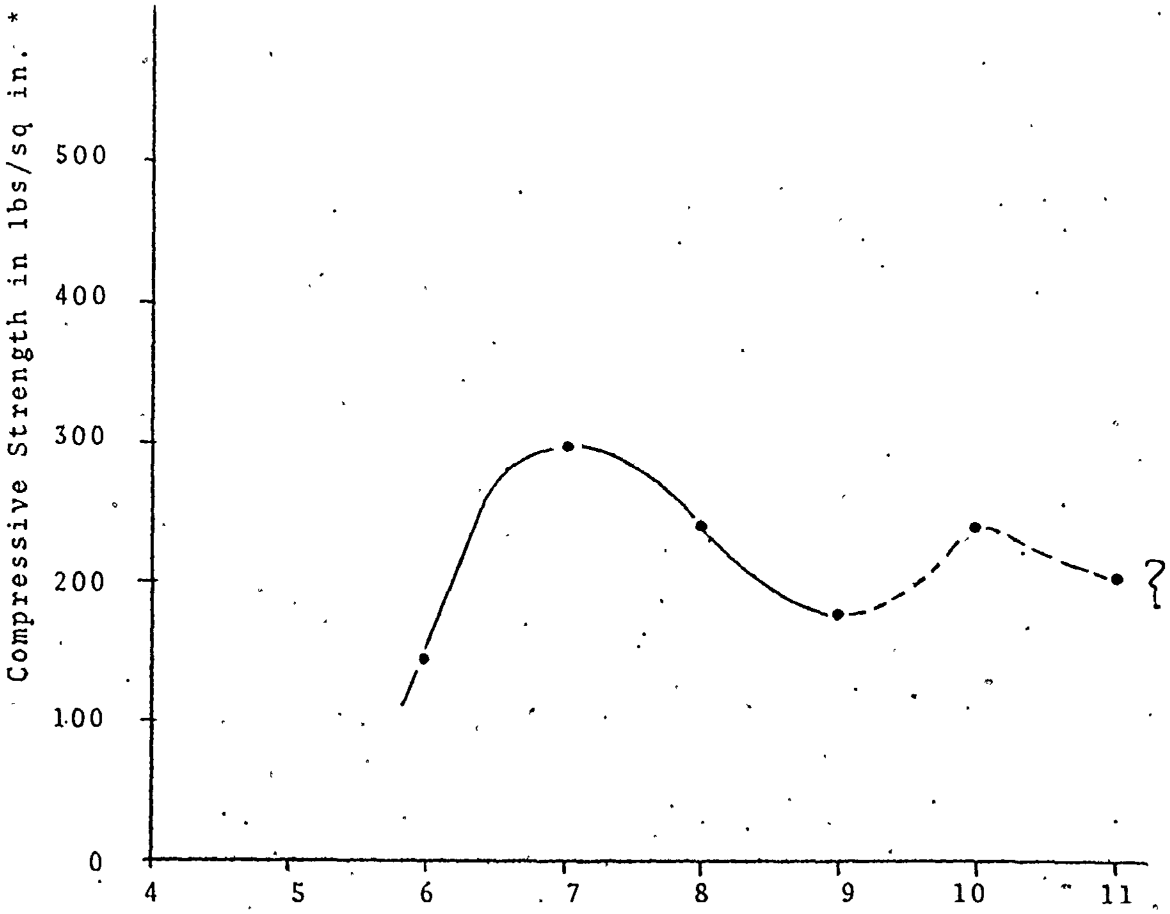


FIGURE 5-3 EFFECT OF MOISTURE CONTENT ON COMPRESSIVE STRENGTH

Step 3 Autoclaving of compressive strength specimens

The compressive strength specimens for plant autoclaving were then prepared at the optimum moisture content of 7%. Three specimens with 15.1% net fines were first cured for 24 hours at 180°F before transporting to Cooke Concrete Products for autoclaving. The autoclaving specimens were then tested for compressive strength in order to determine the influence of autoclaving on compressive strength gain. These test results are shown in Table 5-8 and summarized in Figure 5-4. The specimens were autoclaved for approximately 4 1/2, 9, 13 1/2 and 20 hours to a pressure of 150 psi (350°F).

After the curing process for one day at 180°F and following 4.5 hours in the autoclave at 150 psi there was a strength increase of only 33.9% to 375 psi from 280 psi. However, after curing for 20 hours in the autoclave at 150 psi the strength gain was much larger with a increase of 900% to 2795 psi. Since the minimum aim compressive strength is 2000 psi an autoclaving time of about 12 hours is indicated (Figure 5-4), somewhat longer than current practice.

The autoclaving results are very promising even with the somewhat larger autoclaving time. It is felt that the ground pelletized slag has definite applications in the manufacture of building materials such as masonry blocks and that extensive research should be initiated on this applica-

TABLE 5-8

COMPRESSIVE STRENGTH OF AUTOCLAVED SPECIMENS

(AUTOCLAVED AT 150 psi (350°F))

MIX	AUTOCLAVING TIME-HOURS	COMPRESSIVE STRENGTH psi (a) (b)
PROPORTIONS Unground pellets #144 27.5% Ground pellets #143 72.5% (Net fines 15.1%) Glass Content (d) 82.0% Moisture Content 7.0%	0	280 (c)
	4.50	375
	9.17	1590
	13.67	1990
	20.00	2795 (c)

(a) Curing for 24 hours at 180°F before autoclaving

(b) Average of three specimens

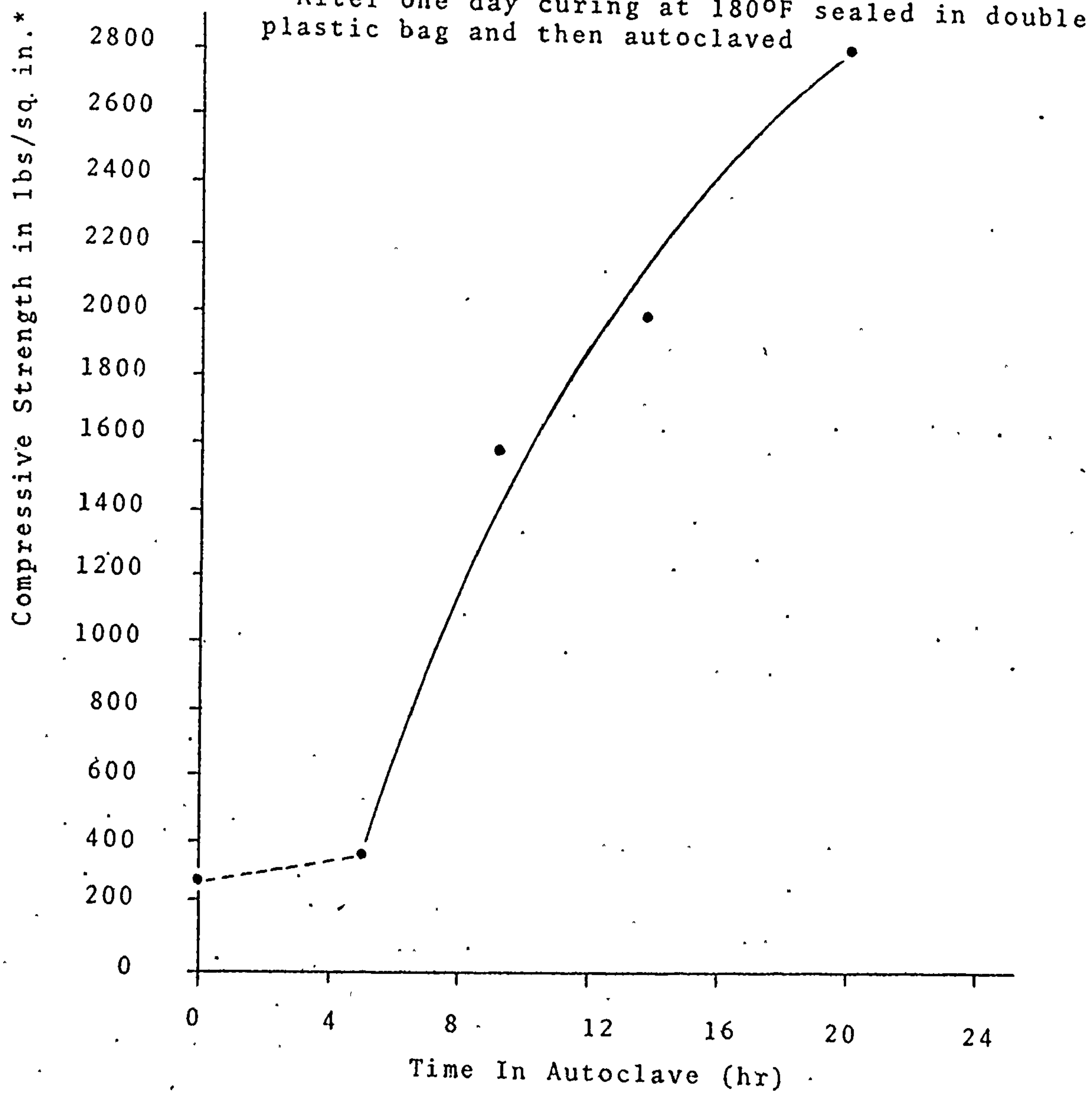
(c) Average of four specimens

(d) McMaster Method, Appendix A

BLOCK

PROPORTIONS:

Ground pellets	#143	72.5%	
Unground pellets (Net fines 15.1%)	#144	27.5%	
Water content		7.0%	(Optimum)



* After one day curing at 180°F sealed in double plastic bag and then autoclaved

FIGURE 5-4 EFFECT ON COMPRESSIVE STRENGTH DUE TO CURING IN AUTOCLAVE tion of ground pelletized slag as a cementitious material. Cooke Concrete Products Limited found the results of great interest in their efforts to decrease the cost of cementitious material and would participate in a extended study*. Thus, the range of applications for pelletized slag has been extended to include the large area of masonry unit manufacturing, particularly as a cementitious component of lightweight blocks.

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* Since completion of this study, D. Hooton has extended the research in late October 1976, prototype block runs were successfully completed at Cooke Concrete Products, Limited.

6 CONCLUSIONS AND RECOMMENDATIONS

6-1 CONCLUSIONS

The prime findings of this study on the utilization of pelletized slags in cementitious applications (base stabilization and masonry blocks) are summarized in the following section.

It was found for the limited number of slags investigated no clear relationship exists between stabilized base compressive strengths and the various hydraulic moduli which are based on chemical composition. However, there were differences in glass content which would have an influence on strength development and the number of slags and specimens were limited. Of course, basicity ratio greater than unity are important, but all moduli incorporate this to some extent. Therefore, in order to determine if some relationship actually does exist between stabilized base compressive strengths and the various moduli as claimed by many researchers, several pelletized glassy slag of the same glass content but with different chemical compositions, should be studied. Based on this study, it is currently recommended that a performance type specification for the base stabilization process be adopted since the relationship between strength and factors such as fineness, moduli, glass content, and activators appears difficult, if at all possible, to establish. A specified strength (and curing conditions) allows the base stabilization process to be utilized without undue concern for the hydraulicity factors.

The phosphorus pelletized slag was not suitable for cementitious use in base stabilization or aggregate for the making of light-weight blocks. This poor performance undoubtedly related to the minor element constituents such as P_2O_5 and fluorine which influences with hydraulic reactions. The use of activators, (hydrated lime and sodium carbonate) did not result in much improvement for the base stabilization process. Of course, bulk applications will continue to form an outlet for this byproduct.

The Finnish pelletized slags did not meet the minimum required compressive strengths for stabilized base construction.. However, they probably would be satisfactory with some activation. A range of possible activators should be tried if base stabilization uses for this slag are still contemplated.

The pelletized slag from DOFASCO was found to be very suitable for base stabilizaion and the manufacture of autoclaved masonry blocks, as this slag has good cementitious properties without activators. The influence of normal curing at 70°F (i.e. typical of summer field conditions) had some retardation in base stabilization strengths over the previously examined accelerated curing at 100°F. Typically, 14 to 16 days field curing would be required to develop adequate strengths, which is quite acceptable from a construction view point. Further, the additions of more fines (-#200 in the ground slag) gives high strengths, and in addition, increased resistance to freeze-thaw cycles. From these findings, it is clear that the base stabilization process is technically feasible and there will be no problem with curing or durability.

The equipment and procedures developed for the simulation of autoclaved masonry block manufacture enables product strength development to be checked while the results are of an initial nature, it is clear that while the length of autoclaving is critical, that satisfactory strengths (typically 2000 psi) are readily achieved. Since completion of this initial work on autoclaved masonry blocks using pelletized slag as cementitious material and aggregate, actual blocks have been manufactured successfully at Cooke Concrete Products Limited.

6-2 RECOMMENDATIONS

Some of the findings are of a preliminary nature and require confirmation and extention. Recommendations for future studies can be summarized as follows:

(a) A further integrated examination of the factors influencing hydraulicity-chemical composition (moduli), glass content, fineness, and activators (if necessary) for a wide range of pelletized blast furnace slags;

(b) The use of other agregates for the bulk constituent in the base stabilization process;

(c) Field applications and related testing of the laboratory developed base stabilization process (including rate of curing); and

(d) Testing of actual autoclaved blocks manufactured at a commercial plant.

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APPENDIX A

GLASS COUNT DETERMINATION

A. SOUTH AFRICAN PROCEDURE

1. Sample preparation

A representative sample of the granulated slag clinker shall be dried and ground to the following gradation.

Sieve Size	Per cent Passing
230	100
325	0

2. Slide Preparation

A slide shall be prepared by placing one or two drops of oil of camphor (camphorated oil) on the clean slide. Introduce to this sufficient graded ground slag (Item 1) so that when dispersed in the oil and viewed under the microscope approximately 70 (seventy) individual particles can be counted per quadrant of the cross hairs.

3. Microscope

The microscope shall have the following minimum requirements:

Magnification: 100 - 200
Coarse and fine focusing
Adjustable cross hairs in the eyepiece

Transmitted light
Orange filter (OG2)
Cross Nicols polarization.

4. Method of Count

The prepared slide shall be viewed under the microscope through the transmitted light modified by the orange filter. The crossed Nicols is not in use at this time.

A quadrant total particle count is taken, assumed to be representative of the total viewing area and multiplied by four (4).

The crossed Nicols is inserted and a total view count is taken of all orange transluscent particles, care being taken to count individual separate orange transluscent particles and making allowances for particles that are partially transluscent and opaque. The orange transluscent particles are assumed to be crystalline; the opaque particles glass.

5. Determination of Percentage

$$\% \text{ Glass} = \frac{100\ (\text{total particles - crystalline orange transluscent particles})}{\text{total particles}}$$

e.g.: 70 particles per quadrant 70 x 4 = 280

Total particles

9 individual and partial proportioned to individual

Transluscent particles

$$\% \text{ Glass} = \frac{100\ (280 - 9 = 271)}{280} = 97\%$$

6. Items 4 and 5 should be repeated four times to ensure a more representative count.

This method is not recommended for samples of high crystalline count.

B. McMASTER METHOD

Microscope

While an Olympus Trinocular Model ECE Tr-1 microscope has been used, any microscope with the polarizing features indicated will be suitable. The microscope is equipped with a Model LSE high power interchangeable illuminator, eyepiece of PO-10X (polarizing), and objectives of 4X, 10X, 40X, and 100X. The lower polarizing element is carefully adjusted to ensure that cross-polarization can be achieved, and the eyepiece can be adjusted quickly from plane to cross-polarized light.

Preparation of Slide Specimens

Representative samples are mixed and quartered down to approximately 0.04 lb (15 to 20 g), and this material is then totally ground to various sizes such as #100-#200 (minus No. 100 (150μm) to plus No. 200 (75μm)), #200-#325, and #325-#400. A very small amount of the desired size is then sprinkled on a microscope slide. A drop of ethylene glycol ($HOCH_2CH_2OH$) is applied to the centre portion of the sprinkled specimen. A cover plate is then placed on top of the specimen. The ethylene glycol then spreads below the cover plate by capillary attraction. After this occurs, the cover plate is gently sheared to form a uniform, single layer of particles. Care must be taken to avoid air bubbles forming. Prepared slides should be labelled and handled carefully.

Examination of Specimens

The prepared specimen slide is mounted on the stage of the microscope which has fine vernier horizontal movement controls. The specimen is then examined under plane and cross-polarized light. Glass is amorphous and does not transmit cross-polarized light, but crystalline materials do and tend to glow and show birefringence. The determination of glass content is based on the average of two or three counts of 40 individual particles which appear at the cross-hair as the specimen is moved along one axis by the horizontal venier. The glass content of individual particles is estimated to the nearest ten percent by checking each particle (if necessary) under plane and cross-polarized light. The specimen is moved from one end of the cover to the other along one line, and on reaching the end is switched to another line, and so on until the required number of particles has been examined.

Application of Method

The eyepiece of PO-10X is combined with the appropriate objective according to Table 1 to get the optimum magnification for glass content determinations on various sizes. The examination of minus No. 400 (38μm) sizes is difficult since at a magnification of 1000X the glass content of individual particles is not well defined. Particles in the #200-#325 (75μm to 45μm) range are mainly used at a magnification of 400X since this size and magnification give a reliable glass content determination for each particle.

The procedure outlined is essentially that given in Ref. 42.

TABLE 1 - Magnifications for glass content determinations

Particle Size	Objective	Magnification[a]
#50-#100 #100-#200	10X	100X
#200-#325 #325-#400	40X	400X
-#400	100X	1000X

[a] With PO-10X eyepiece

APPENDIX B

MODULI FOR EVALUATION OF HYDRAULICITY

1. <u>Parker and Nurse</u>: [55]

$$M = \frac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3} \qquad (3\text{-}1)$$

and % strength $(S)_{90} = 0.38G(M - 0.72) + 75$ (3-2)

A detailed discussion concerning moduli 3-1 and 3-2 is given in Chapter 3. Parker and Nurse also indicated two other strength criteria:

% strength = $90.3 + 0.18G - 1.05(Al_2O_3 + TiO_2)$ (B-1)

% strength = $0.18GR + 67.5$ (B-2)

where G = % glass content determined by microscope analysis

$$R = \frac{CaO + (\text{less } CaO \text{ for } CaS)}{SiO_2}$$

However, they prefer the strength relationship (3-2) for reasons detailed in Reference 55: supported by other researchers; better for alumina influence; and closer representation of slag limits.

2. <u>Cheron and Lardinois</u>

$$\frac{\frac{CaO}{56} + \frac{MgO}{40} + \frac{Al_2O_3}{102}}{\frac{SiO_2}{60}} \geqq 1.0 \qquad (B\text{-}3)\,[16]$$

Cheron and Lardinois [16] found that modulus (B-3) proposed by Tetmayer displayed a linear relationship between the index and compressive strength.

3. Old ASTM and Germany

$$\frac{CaO + MgO + 1/3\ Al_2O_3}{SiO_2 + 2/3\ Al_2O_3} \geq 1.0 \qquad (B\text{-}4)$$

[8,18,27,37, 39,43,54,55]

Modulus (B-4) appears in a tentative ASTM specification (C205-48T) which disappeared in the amendment to ASTM C595-72. This modulus has been adopted for granulated slag to be ground with portland cement in Germany.

4. DIN 1164 (1967), Germany

$$\frac{CaO + MgO + Al_2O_3}{SiO_2} \geq 1.0 \qquad (B\text{-}5)$$

[1,7,23,27,37, 39,43,54]

This modulus is currently used in Germany and appears in the specification DIN 1164: 1967. The Cemsave cement company in U.K. uses this modulus as their standard. Scunthorpe [1] granulated slag gave an index of 2.0 indicating that the reactivity of the slag can be classified as good.

5. Keil

$$\frac{CaO + CaS + 1/2\ MgO + Al_2O_3}{SiO_2 + MnO} \geq 1.5 \qquad (B\text{-}6)$$

[7,8,27,37,38 39,43,55]

According to Keil [37], the hydraulic property of modulus (B-6) is medium if the value is less than

1.5, good between 1.5 and 1.9 and very good greater than 1.9. The essential difference in the moduli (B-4) to (B-6) is the transfer of Al_2O_3 in its full amount to the numerator and the effect of S and MnO.

6. Budnikov

$$Q = \frac{CaO + MgO + Al_2O_3}{SiO_2 + MnO} \geqq 1.0 \qquad \text{(B-7)} \; [39]$$

According to Kholin and Royak [39], Budnikov proposed this modulus to characterise the quality of slag.

7. 4707 - 1953, Hungary

$$\frac{CaO + MgO}{SiO_2 + Al_2O_3} \leqq 1.0 \qquad \text{(B-8)} \; [7,11,38,39]$$

According to Hungarian standard specification 4707 - 1953 [7], the value should be equal to or less than one.

8. Cementation Index

$$\frac{2.8\ SiO_2 + 1.1\ Al_2O_3 + 0.7\ F_2O_3}{CaO + 1.4\ MgO} \qquad \text{(B-9)} \; [11, 22]$$

The modulus (B-9) is termed the cementation index and has the following limits:

Product	Hydraulic Index Limits
(a) Slow setting and high in tensile strength	1.00 - 1.15
(b) Most natural cement	1.15 - 1.60
(c) Relatively low limed natural cement	1.60 - 2.00

(d) Feeble in hydraulic properties as the value approaches 3.00, the product can be considered as artificial pozzolanas	2.00 - 3.00

9. Hydraulic Index

$$\frac{SiO_2 + Al_2O_3}{CaO} \qquad (B\text{-}10)$$

[7, 22]

The hydraulic index, calculated by the modulus (B-10) may be used as a basis for classifying cementing materials according to their hydraulic activity. In this modulus, no allowance is made for the action of either MgO or Fe_2O_3, and an assumption is being made that silica and alumina are interchangeable, i.e., 10% silica will have exactly the same effect as 10% alumina.

Product	Hydraulic Index Limits
(a) Common lime, quick lime	Less than 0.10
(b) Feebly hydraulic lime	0.10 - 0.20
(c) Eminently hydraulic lime	0.20 - 0.40
(d) Portland cement	0.40 - 0.60
(e) Natural cement	0.60 - 1.50
(f) Weak natural cement	1.50 - 3.00
(g) Pozzolanas, etc.	> 3.00

According to Biezok [7], the Hydraulic Index should be between 0.70 to 0.90 for the manufacture of blast furnace slag cements.

10. F - Value

$$\text{F - Value} = \frac{CaO + 0.5\ MgO + Al_2O_3}{SiO_2 + MnO} \qquad \text{(B-11)}\ [60]$$

F - Value greater than 1.9 did not show appreciably higher strengths. Thus conclusions were based on 28 day strength development, using five slags, containing 20% clinker, 7% anhydrite and 73% granulated blast furnace slag. For appraising the adverse effect of FeO and MnO on the strength evaluation separately, Schröder [60] indicated that Sopora has proposed to square the MnO content in modulus (B-11).

11. Keil's Hydraulic Index

For assessing the contribution to strength made by granulated slag a "hydraulic index" is recommended by Keil [37]. This is based on a comparison of the compressive strengths at 28 days of mortars as follows:

$$\text{Hydraulic Index} \left(\frac{70}{30}\right) = \left(\frac{a-c}{b-c}\right) \times 100 \qquad \text{(B-12)}\ [37, 43]$$

Where a = the strength developed by the mortars of portland slag cement;

b = the strength developed by portland cement mortars alone;

c = the strength developed by the portland cement and ground quartz sand (sand ground to a specific surface of 4,000 cm^2/g, by air-permeability method) cement mortars; and

70/30 = indicates that the portland cement by
weight of total cement is 30%

This index does not include the chemical composition and is found to vary with the proportion of slag present in the cement, say 50/50, 30/70, etc. Mortars of low water-cement ratio must not be used. This method for testing hydraulic or pozzolanic reactivity is given in ASTM C595 - 72 in terms of the "pozzolanic activity test".

APPENDIX C

A. APPARATUS USED FOR SIMULATING MASONRY BLOCK MANUFACTURE

A simple and inexpensive apparatus was developed for simulating the manufacture of masonry blocks as shown in Figures C-1, C-2 and C-3. The complete assembly of the apparatus used for making the compressive strength specimens is shown in the photograph of Figure C-3. Figure C-4 shows the process of making the compressive strength specimens and the apparatus used for removing specimens from the cylinder is shown in Figure C-5 and C-6.

B. PREPARATION OF SPECIMENS

After arranging the apparatus as shown in Figures C-1 and C-3 without the top 2 1/2" diameter by 5 1/8" solid cylinder in place, more than one-third of the 2 15/16" diameter by 5" hollow cylinder was filled with pre-mixed material. Then the 2 1/2" diameter by 5 1/8" solid cylinder was put into the hollow cylinder so that it rested on the mix. Ten blows were then applied to the solid cylinder using a 10 lb hammer and 12 inch drop (Figure C-4). The 1 5/16" x 7/16" x 2" metal spacer blocks were then

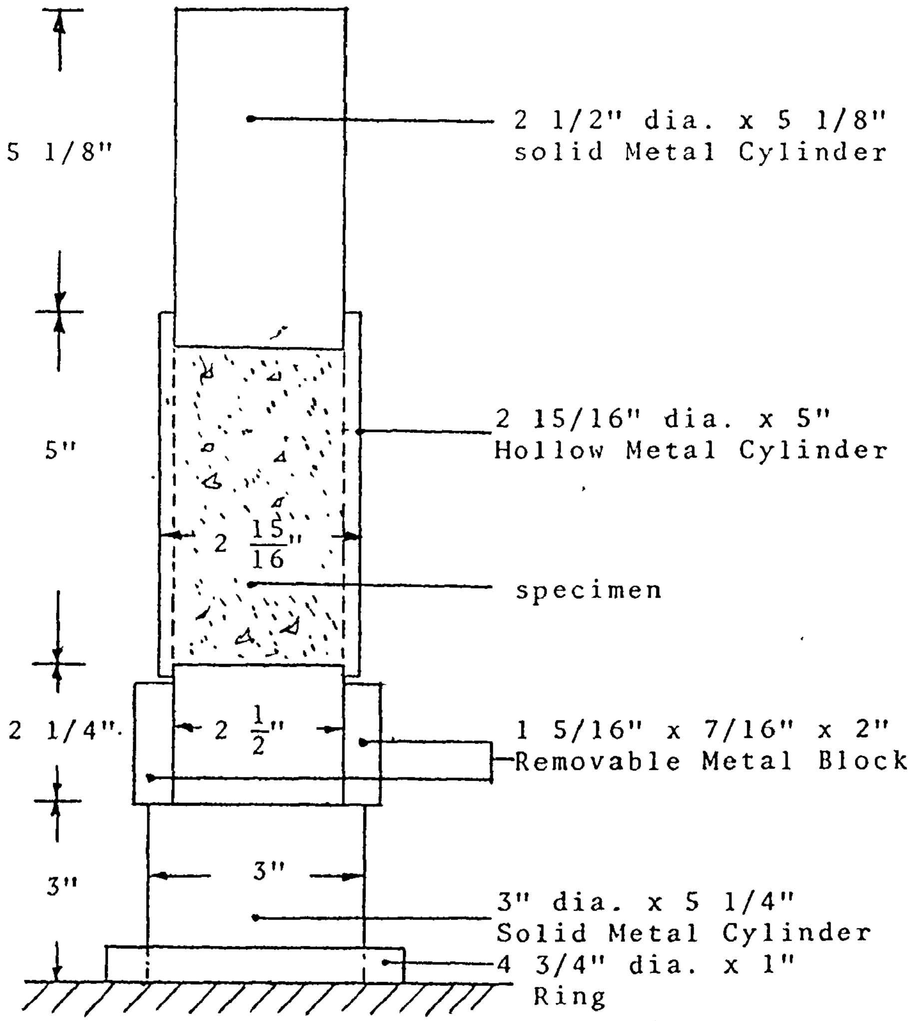

FIGURE C-1 APPARATUS USED FOR MAKING COMPRESSIVE STRENGTH SPECIMEN TO SIMULATE BLOCK MANUFACTURE

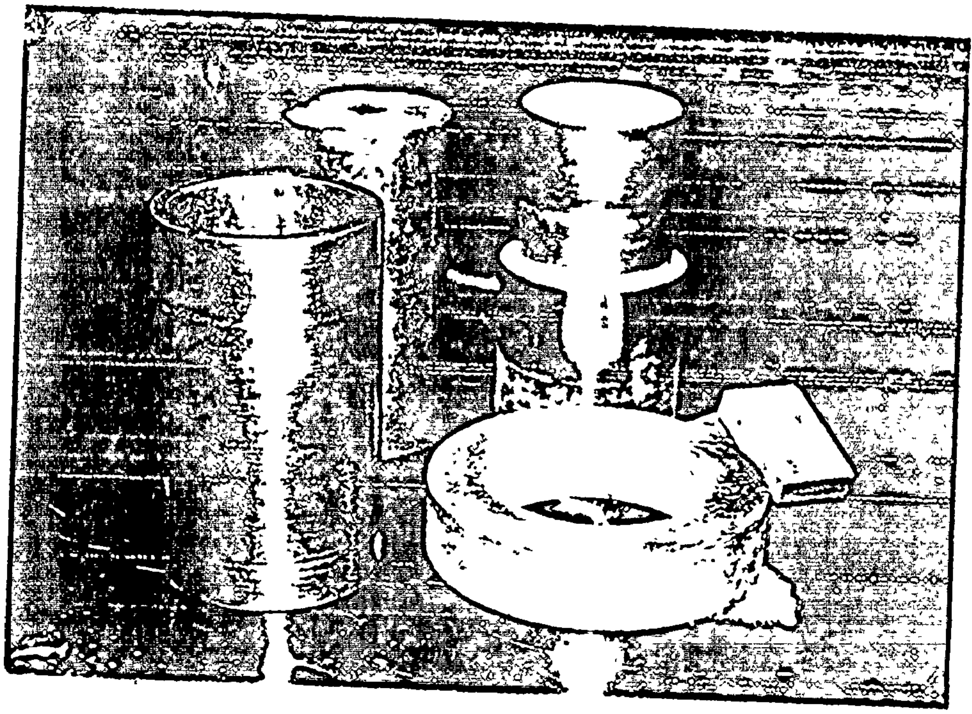

FIGURE C-2 PHOTOGRAPH OF APPARATUS
USED FOR MAKING MASONRY BLOCKS

FIGURE C-3 PHOTOGRAPH OF COMPLETE ASSEMBLY OF APPARATUS USED FOR MAKING COMPRESSIVE STRENGTH SPECIMENS

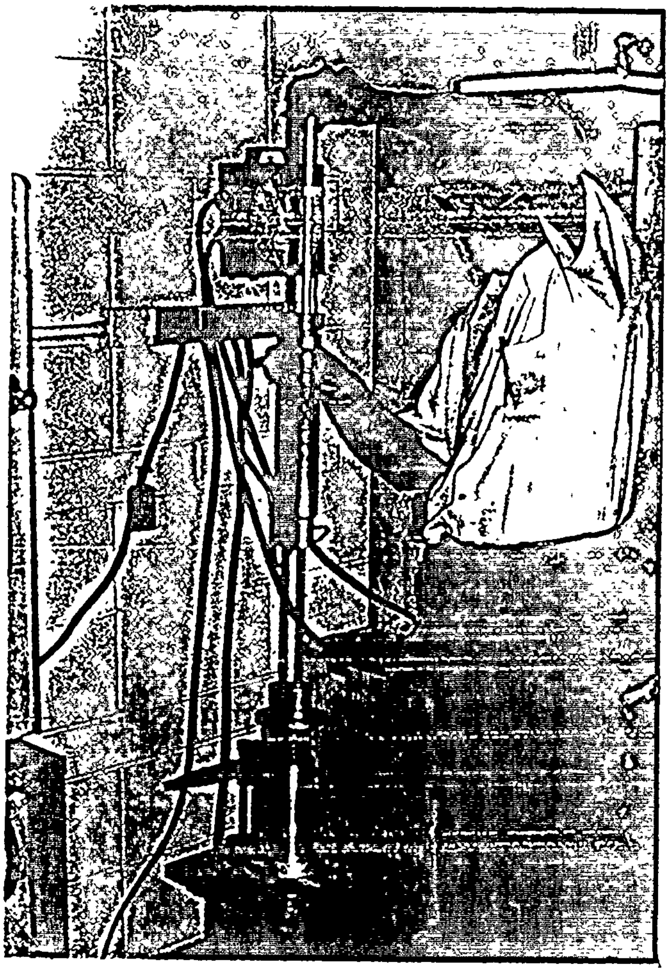

FIGURE C-4 PROCESS OF MAKING COMPRESSIVE STRENGTH SPECIMENS

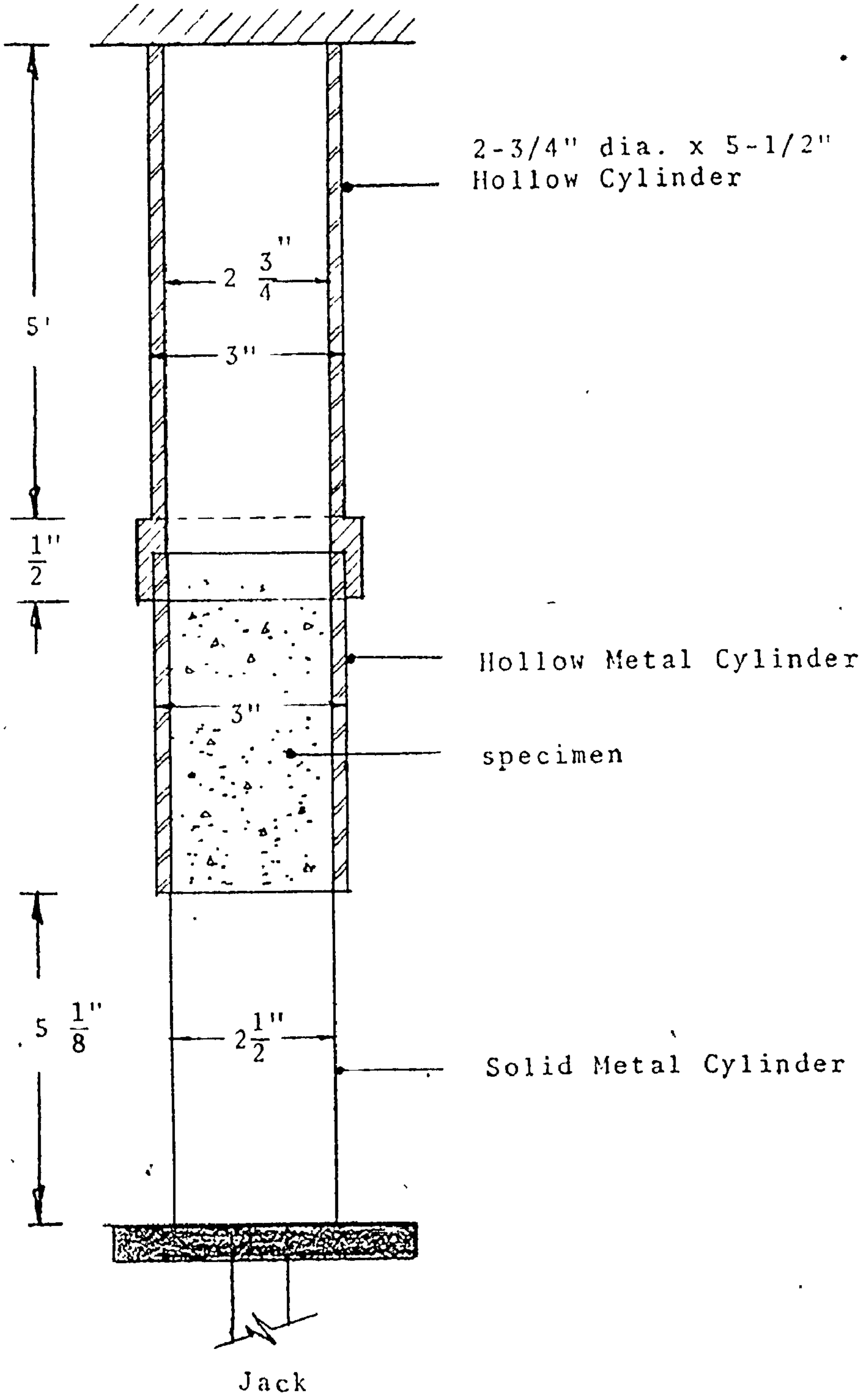

FIGURE C-5 APPARATUS USED FOR REMOVING SPECIMENS FROM CYLINDER

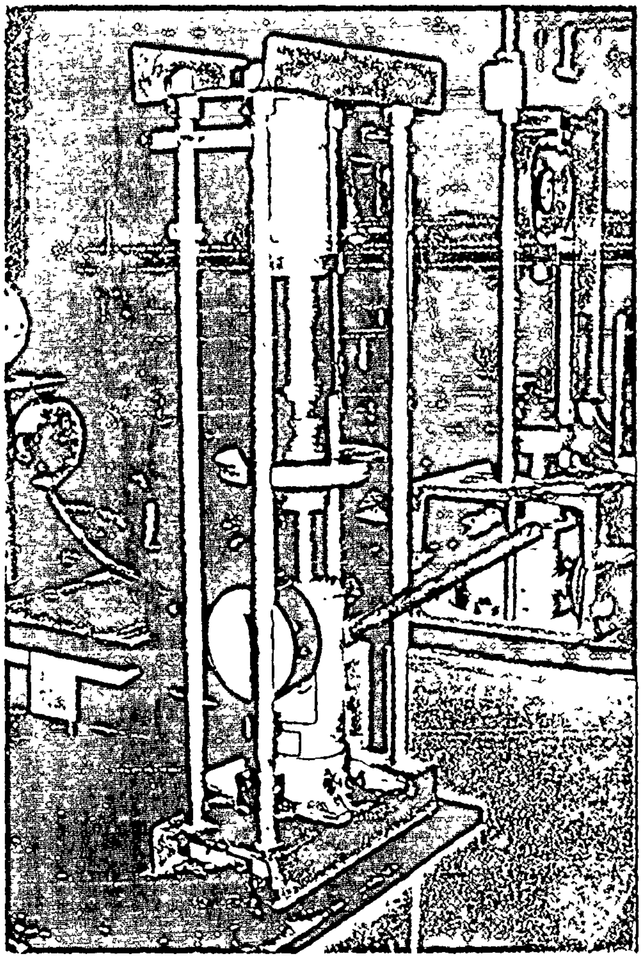

FIGURE C-6 PHOTOGRAPH OF APPARATUS USED
FOR REMOVING SPECIMEN FROM
CYLINDER

removed and 15 more blows given for a total of 25 blows (i.e. 10 blows as single plunger and 15 blows as a double plunger). The complete specimen is then prepared by compacting two more layers with the same compactive efforts. Other compactive efforts can be employed by using a heavier hammer or more blows, etc. The compactive effort adopted gave reasonable product densities compared to the actual manufacturing process.

C. REMOVING SPECIMENS FROM THE MOLD

The hollow cylinder is placed at one end of the mold and the solid sylinder is placed at the other end as shown in Figure C-5 and the specimen is jacked into the hollow cylinder as shown in Figure C-6.