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Concrete Microstructure

D.M. Roy

Materials Research Laboratory
The Pennsylvania State University

G.M. Idorn

G.M. Idorn Consult A/S

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2101 Constitution Avenue N.W.
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Related Reports

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Concrete Microstructure: Recommended Revisions to Test Methods (Supplemental Report No. 7)	SHRP-C-339
A Guide to Evaluating Thermal Effects in Concrete Pavements (Curing Tables)	SHRP-C-321
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Cement Paste Aggregate Interface Microstructure (Supplemental Report No. 6)	SHRP-C-629

Contents

List of Figures

List of Tables

Abstract

Durability of concrete in highway systems is a problem of national concern. In order to better understand the mechanisms which intrinsically control durability in highway concrete it is necessary to define and understand those factors which impact concrete microstructure which is a consequence of both its formulation and the processes taking place during mixing, placing and curing. This report documents an investigation of those variables which control cement hydration and consequent microstructural development.

Executive Summary

Deterioration of concrete in highway systems is a problem of national concern. In order to enhance the durability and assess the service lives of concrete highways, it is necessary to consider deterioration processes at their source: Deterioration originates in the concrete at the micro- or sub-microscopic level, i.e. in its microstructure. The microstructure, in turn, is a consequence of the processes taking place during mixing, placing and curing of the concrete.

Many recent studies of concrete failure suggest that inadequate dispersion of cement paste in the original, fresh concrete is an often unrecognized cause of variability of the properties and performance of the concrete. This is manifested by unpredicted variation in the ability of the concrete to restrict the transport of harmful species which permeate or diffuse through hardened concrete and thereby serve as activators of deterioration. Poor dispersion and inhomogeneity during mixing and placing may cause the cement particles to coagulate and cluster in the mix water, resulting in alternating regions of dense and high porosity hardened paste, even in instances where use of a low water/cement (w/c) ratio was intended to provide an ultimately high density microstructure. Packing of the cement particles and aggregate is also extremely important in development of a dense homogeneous microstructure. Thus, the performance of concrete is a direct result of microstructure development during its mixing, setting and hardening process. This research has addressed the development of microstructure and its control of performance with a focus on the early stage processes.

The dispersion of cement particles, mineral admixtures, and aggregate in fresh concrete, and the early stage rheological properties of this mixture are intimately related to the cement hydration process. Dispersion and hydration are often examined separately, but it is necessary to understand and quantify the combined effects. These together control the microstructural development, and as a result the properties and performance of the concrete. Early or retarded setting, excessive bleeding, drying shrinkage, inadequate strength, permeability, and frost damage can be traced to processes occurring on a micro- or sub-microscopic level in the concrete matrix. An understanding of concrete at the micro or sub-microscopic level is the initial and most important step toward achieving the means to control its microstructure.

The study was carried out to address the above factors in five interactive stages with feedback among them. These were:

1. Mixing, Rheology, Strength and Packing
2. Hydration, Maturity and Curing
3. Concrete Microscopy
4. Porosity, Pore Structure and Permeability
5. Revisions to Standards and Test Methods.

Mixing, Rheology, Strength and Packing

Evaluation of packing density of cementitious components combined with rheological studies suggested that maximum workability without bleed water occurs when the porosity of the packed components is just filled with water. This occurs along a boundary between maximum packing in the sand/coarse aggregate system of a concrete and the cement.

A computer model of dry-packed monosized particles was developed. With the expanding role of mineral and chemical admixtures it is felt that the application of this type of modeling can be useful in the modification of current concrete designs leading to a more economic/durable product.

Hydration, Maturity and Curing

Laboratory methods for predicting the rate of hydration of concrete were evaluated and compared with field results. A hydration model has been developed to provide a link between the activation energy determinations and the model developed to predict porosity and permeability. Inputs to this model include the phase composition of the cement and outputs include estimates of heat of hydration, porosity and strength.

Finally, field studies were carried out in concert with adiabatic calorimetry measurements of the concrete mixes. These results have been used to evaluate a commercially available system that predicts maturity. Further, the results of adiabatic calorimetry are useful in evaluating the relevance of the isothermal calorimetric measurements of the heat of hydration of the cement.

Concrete Microscopy

The examination of concrete microstructure either in transmitted or reflected light is a valuable tool in the study of concrete microstructure. Both methods were used in examining concrete specimens. Fluorescent epoxy dye impregnation is a useful technique for enhancing inherent porosity of the pastes, interface porosity and the presence of cracking. Water/cement ratios can be determined by comparing paste porosity with a series of carefully prepared reference samples.

Porosity, Pore Structure and Permeability

A model has been developed for relating porosity to permeability. It was determined that a linear combination of lognormal distributions can be used to describe pore structure. One of these describes small pores while the remaining two describe porosity through which bulk transport occurs. The pore structure model was then integrated into a model for the prediction of permeability.

In the course of this study an experimental apparatus for rapidly determining permeabilities of concrete samples was developed for measuring specimens having permeabilities in the microdarcy to nanodarcy range. This was based on the principle of subjecting the test specimens to a small pressure differential and monitoring both the pressure decay and pressure rise on the inlet and outlet sides respectively in response to the applied pressure pulse.

Revisions to Standards and Test Methods

Pertinent specifications, test methods and standard practices have been reviewed, evaluated and revisions recommended to American Society of Testing and Materials (ASTM), American Concrete Institute (ACI) and American Association of State Highway and Transportation Officials (AASHTO) standards. While no new standards have been suggested, the potential for such does exist based on work completed. Recommendations for possible revision to ASTM microscopy standards have been made.

I.
Mixing, Rheology, Strength, Packing

The primary requirement of fresh concrete is that it should be of such consistency that it can be readily consolidated in forms and around the reinforcement without excessive bleeding or segregation. The workability of fresh concrete, however, plays a significant role in microstructural development and consequent development of properties of hardened concrete. The aggregate proportions and physical properties as well as the microstructure of the cement/water matrix will define the rheological properties of fresh concrete. In many instances, the desired properties of hardened concrete may not be attained because of the difficulty in meeting the fresh concrete workability requirements. Chemical admixtures are often used to increase the workability, whereas mineral admixtures are used to further modify the microstructure of the hardened concrete to meet certain application and/or durability requirements. Effective packing of the blend of solid ingredients is usually contributes favorably to both rheological and durability aspects of concrete.

Mixing, Rheology, Strength

Fresh concrete can be represented by aggregate grains in a continuum of cement particles and water (paste). The aggregate proportions and gradation and physical properties will affect the mechanical properties of the continuum. On the other hand, the microstructure of the continuum will also affect its mechanical properties. Due to the physical characteristics of cement particles, the particulate structure tends to coalesce and eventually encompass the whole sample in a global network of different size flocs or a gigantic floc. Depending on the forces present, this flocculation has a considerable effect on the rheological behavior of fresh concrete. Fluid will be immobilized between the particles that stick together. The floc will have a structure that extends throughout the sample entailing a rigidity which is reflected in elastic behavior and in the generation of a yield stress. Viscoelastic deformation under external forces may take place. Finally, the structure can change reversibly under flow, causing shear thinning and thixotropy. A review of the models presented to explain the behavior is given in App. D. The mechanical behavior of such floc structure is complex due to the continuous change in its structure during hydration. The state of hydration is thus an important factor that must be taken into consideration when dealing with workability aspects of fresh concrete, e.g. slump loss, and time of adding chemical additives and other factors.

The rheological properties of several concrete mixtures were determined by using the traditional slump test and the Tattersall's two-point workability apparatus (Tattersall, Banfill 1983). The slump values were found to correlate with the yield value measured by the second technique. In this report the following are discussed:

1. Materials and Mixtures;
2. Concrete Formulations for Field Applications of Curing Tables;
3. Assessment of the Rheological Properties of Fresh Concrete;
4. Effect of Aggregate (Proportion, Shape and Size) on Rheology;
5. Mineral and Chemical Admixtures;
6. Relationship Between Rheology and Interface Properties.

Materials and Mixtures

Several concrete mixtures spanning a wide range of concrete formulations and covering a significantly large spectrum of variables were prepared. The concrete mixtures were primarily pavement formulations and a few are for bridge piers and bridge decks. The Pennsylvania Department of Transportation (PADOT) guidelines of concrete formulations (Table 1) were followed and the ASTM C192 method for mixing procedure was followed where an Eirich pan mixer was used in mixing all concrete. In order to avoid batch-to-batch variabilities in rheological as well as in subsequent properties, the aggregates and sand used were all brought to saturated surface dry condition before mixing. The components were kept under a constant room temperature of 23°C ±1.5°C and relative humidity of 30% ±5% at all times under sealed conditions. A list of materials used in the present program together with suppliers and chemical compositions are given in App. A. The gradations and physical properties are given in App. B. The mix proportions and properties of the fresh concrete mixtures are given in data sheets complied in App. C.

Concrete Formulations for Field Applications of Curing Tables

Considerable effort was devoted to support of the field work. Four concrete mixtures were made to simulate the concrete formulations used at sites where experiments on the practical applications of curing tables were implemented. The data sheets for these formulations are given in App. C, the materials specifications and suppliers are given in App. A, whereas materials gradation is included in App. B. The 28-day compressive strength and results of the rapid chloride permeability tests are given in Table 2. It is worth noting that several other concrete mixtures were made to assess, specifically, certain workability aspects of the fresh state such as effect of superplasticizers. These mixtures are prefixed with the letter *R* and their data sheets are included in App. C. The four locations are as follows:

1. Concrete pavement slab replacement on Rt. 322 (Seven Mountains), Centre County, PA (S90-20);
2. Concrete pavement slab replacement on Interstate I-80, Clinton County, PA (S90-21);
3. Bridge pier (Faunce Bridge), Clearfield County, PA (S90-22);

Table 1 - PADOT Concrete Formulations

CLASS OF CONCRETE	USE	CEMENT[3] FACTOR (Bags/C.Y.)		MAXIMUM WATER CEMENT RATIO[4] (lbs/lbs)	SLUMP[2] RANGE (INCHES)	MINIMUM MIX[2] DESIGN COMPRESSIVE STRENGTH (PSI)			PROPORTIONS COARSE[1] AGGREGATE SOLID VOLUME (Cu. Ft/Cu. Yd)
						DAYS			
		Min.	Max.			3	7	28	
AAA	Bridge Deck	6.75[5]	8.00	0.43	1-3[5]	–	3600	4500	ACI
AA	Paving	6.25	8.00	0.47[7]	1-3[6]	–	3000	3750	9.93 - 13.10
AA	Structures and Misc.	6.25	8.00	0.47[7]	1-3	–	3000	3750	9.93 - 13.10
A		6.00	8.00	0.50[7]	1-3	–	2750	3300	10.18 - 13.43
C		4.20	7.00	0.66[7]	2-6	–	1500	2000	11.45 - 15.10
H.E.S.		8.00	9.00	0.40[7]	1-3	3000	–	3750	9.10 - 12.00

Table 2
Twenty-eight day compressive strength (MPa) and rapid chloride permeability test results (coulombs).

No.	Mix designation	28-day compressive strength (MPa)	Strength deviation (6 samples) (MPa)	Coulombs passed	
				Concrete	Mortar
1	S89-1	46.03	1.54	1,000	4,752
2	S89-2	44.07	2.98	253	4,104
3	S89-3	45.43	1.49	432	3,406
4	S89-4	46.82	2.45	666	3,744
5	S89-5	48.6	1.31	253	2,502
6	S89-6	44.58	2.44	360	1,919
7	S89-7	45.53	0.84	410	1,879
8	S89-8	51.80	1.35	745	1,602
9	S89-9	44.86	0.60	1,015	10,195
10	S89-10	49.65	0.50	346	1,540
11	S89-11	43.35	0.78	417	2,379
12	S89-12	52.92	1.24	540	3,218
13	S89-13	46.20	2.23	60	176
14	S89-14	46.84	1.78	1,220	4,608
15	S89-15	43.82	2.38	975	3,636
16	S89-16	44.22	1.04	325	8,784
17	S89-17	35.94	0.76	335	3,776
18	S89-18	47.19	0.10	597	2,473
19	S89-19	49.64	0.79	53	2,678
20	S89-20	48.81	1.01	174	1,983
21	S89-21	45.16	1.17	482	2,592
22	S89-22	46.03	0.60	281	2,588
23	S90-1	48.86	2.12	486	2,862
24	S90-2	48.15	1.81	901	4,140
25	S90-3	44.61	1.09	781	3,441
26	S90-4	45.15	2.14	69	316
27	S90-5	42.69	1.27	124	1,490
28	S90-6	46.27	4.53	69	316
29	S90-7	51.83	1.12	21	95
30	S90-8	54.02	0.30	0	74
31	S90-9	47.35	0.30	367	1,897
32	S90-10	47.06	1.05	307	1,660
33	S90-11	49.50	2.16	354	1,498
34	S90-12	38.76	1.30	147	655
35	S90-13	50.45	1.90	300	2,232
36	S90-14	48.84	0.76	226	2,254
37	S90-15	55.58	3.62	0	71
38	S90-16	44.29	3.06	203	918
39	S90-17	40.58	2.20	146	634
40	S90-18	51.46	4.90	158	1,703
41	S90-19	33.60	5.20	--	2,048
42	S90-20	--	--	1,433	--

Table 2. Continued.

No.	Mix designation	28-day compressive strength (MPa)	Strength deviation (6 samples) (MPa)	Coulombs passed	
				Concrete	Mortar
43	S90-21	--	--	551	4,968
44	S90-22	--	--	--	--
45	S90-23	50.10	0.83	2098	10,000
46	S90-24	38.29	2.40	417	3297
47	S90-25	--	--	--	--
48	S90-26	--	--	--	--
49	S90-27	--	--	--	--
50	S90-28	--	--	--	--
51	S90-29	--	--	--	--
52	S90-30	--	--	--	--
53	S90-31	--	--	--	--
54	S90-32	--	--	--	--
55	S90-33	--	--	--	--

4. Concrete pavement slab replacement on Rt. 15 (north of Williamsport), Lycoming County, PA (S90-24).

Due to changes in the PADOT construction plans, the first two experiments were not fully implemented.

Assessment of the Rheological Properties of Fresh Concrete

The assessment of the compliance of concrete mixtures with the placement and consolidation requirement has been traditionally reduced to a simple number of inches as measured by the slump test. Although it suffers from some difficulties and disadvantages, the slump test has remained the oldest and most widely used test on site for its simplicity and the ease with which an experienced worker in the field can develop a link between what a particular concrete looks like and what its slump value would be. Test results may sometimes bear little relation to the actual concrete workability (which is a combination of factors such as mobility, placeability, and cohesiveness).

Tattersall and co-workers developed the two-point workability test and claimed that the workability of concrete cannot be assessed by a single parameter such as the slump value but that it is necessary to provide several points for a better description of workability (Tattersall, Banfill 1983). Using the Tattersall two-point workability apparatus, the concrete mix is subjected to a decreasing shear rate varying from 1.33 to 0.33 revolutions per second and the corresponding torque resistance was determined. When the two values were plotted, a straight line relationship was obtained. A representative example of the shear rate-shear stress curve measured by the two-point apparatus is given in Fig. 1. At lower shear rates the curve tends to deviate from linearity towards higher shear stresses (yield stress). The slope of the line gives the plastic viscosity whereas the intercept with the abscissa gives a value that is proportional to yield stress. The yield stress values were found to correlate inversely with the results of the slump test (Fig. 2).

Effect of Aggregate (Proportion, Shape and Size) on Rheology

At a given aggregate volume fraction, increasing the fine/coarse aggregate ratio will increase the total surface area and more water is needed to maintain a required workability. If the water content is kept constant (same w/c ratio), a decrease in workability is observed with an increasing F/C (fine/coarse) aggregate ratio (Fig. 3).

A more spherical siliceous gravel was found to produce concrete with lower yield stress (higher slump) than the corresponding angular limestone of the same gradation. Furthermore, at a fixed aggregate volume fraction, as the aggregate size increases, the yield stress decreases and the slump increases (higher workability).

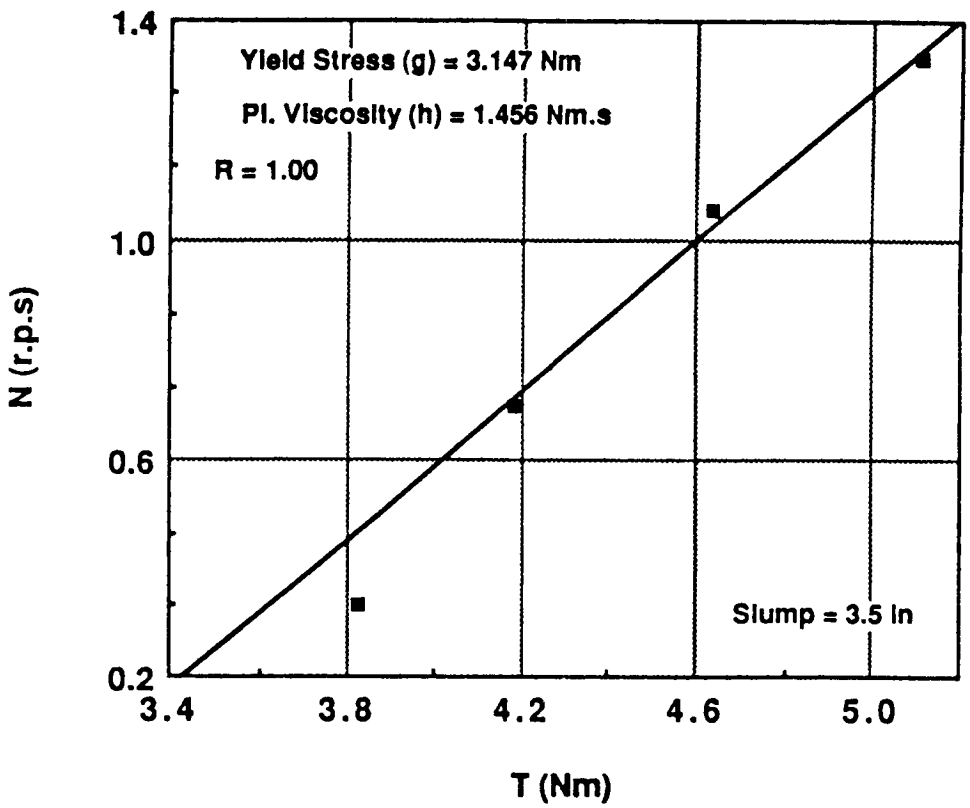


Figure 1. Shear stress-shear rate relationship for concrete (from the two-point workability apparatus).

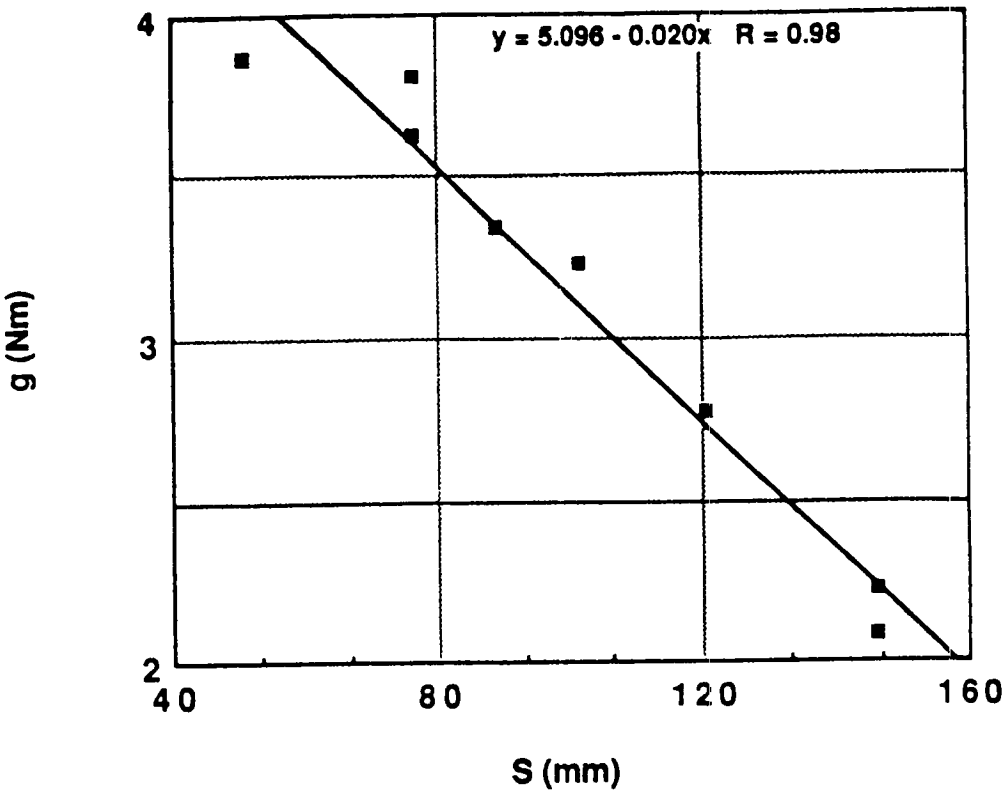


Figure 2. Relationship between the slump value (S) and yield value (g) for Bingham concretes.

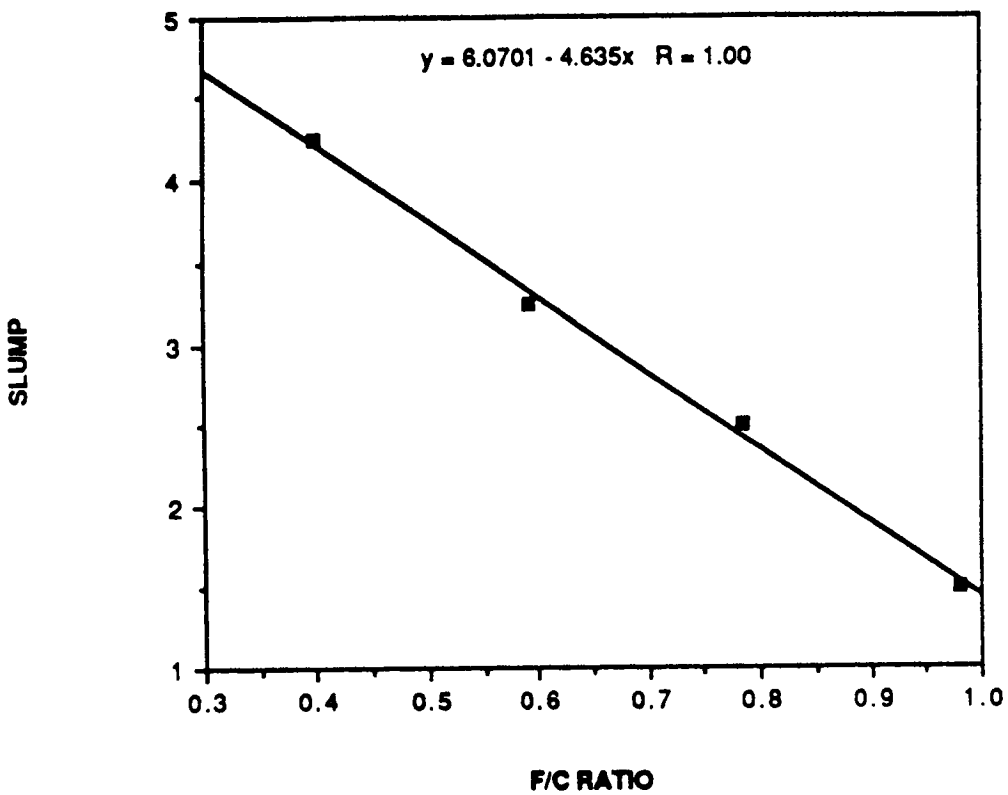


Figure 3. **A representation of the effect of F/C (fine to coarse) aggregate ratio at a given volume fraction (and fixed w/c) on the slump value.**

Mineral and Chemical Admixtures

Several concrete mixtures were made containing various mineral admixtures as well as one high-range water-reducer (superplasticizer) (ASTM C494 Type A), and one retarder (ASTM C494 Type D). The formulations for these concretes are designed as modifications of the mixture S89-1 for pavements to meet certain requirements. The basic role for this type of chemical admixture was to reduce water to cement ratio in an amount as specified in ASTM C494 and maintain the fresh state rheological properties and compressive strength within the specified limits. The basic design requirement for the concretes containing mineral admixtures in this study was to attain, at 28 days' age, a strength equivalent to that of mixture S89-1 plain concrete at the same age. The other general requirements of both AASHTO and PADOT specifications were fulfilled. A summary of the concrete mixtures covering these requirements is given in Table 3 and the data sheets are given in App. C.

It is worth noting that the fly ash-containing mixtures were formulated by replacing a certain weight of the cement with a larger amount of fly ash and the sand content to compensate for the excess fly ash. In these mixtures the favorable effect of fly ash on rheological properties of the concrete mixtures permitted the water reduction that has been favorably reflected in an increase in strength. In this respect, additional water reduction in Class C fly ash-containing mixtures over Class F fly ash-containing mixtures results in early strength gain.

The compressive strength development, as a function of time, indicates that the Class C fly ash has met the strength requirement (with the two replacement levels). Not surprisingly, the Class F ash did not, although its strength (~40 MPa) at 28 days is acceptable. The same relative trends were observed in the Type AAA concrete (formulation for bridge decks) which contains a higher fly ash to cement volume ratio of 0.6 (mixtures S90-17 and S90-18 of App. C). These concrete mixtures were formulated to test the limits of fly ash content, with higher fly ash to cement ratios due to the fact that they are proportioned with higher cement content and attain higher strength compared to Type AA concrete formulations for pavements.

The strength development, with time, of the Type AAA concretes containing Class F and Class C fly ashes indicates that the Class C ash formulation meets the requirement, while the Class F does not. It is not surprising that the Class F fly ash mixtures were not as strong. However, this particular behavior of the Class F fly ash mixtures may be a result of an inadequate assessment of the pozzolanic reactivity of this type of fly ash (the basis for formulating these concrete mixtures).

The compressive strength developments, as a function of time, of slag-containing mixtures indicate that these mixtures, except the one with the highest slag (65% AA formulation), have met the strength requirement. Silica fume-containing formulations are always higher in strength than the reference.

Chemical admixtures (superplasticizers and water-reducers) primarily modify the surface charges in the diffuse double layers on surfaces of particles. They tend to diminish the attractive forces between particles and drastically lower the yield stress. The effect of

Table 3
Concrete mixtures for studying the effect of chemical and mineral admixtures.

Mixture	Type	Chemical Admixture Type	Chemical Admixture Amount	Mineral Admixture Type	Mineral Admixture Amount
S89-1	AA	--	--	--	--
S90-14	AAA	D	0.5%	--	--
S89-10	AA	--	--	slag	40%*
S90-5	AA	--	--	slag	65%
S90-16	AAA	D	0.5%	slag	40%
S89-11	AA	--	--	fly ash	f/c = 0.2**
S90-12	AA	--	--	fly ash	f/c = 0.5
S90-17	AAA	D	0.5%	fly ash	f/c = 0.6
S89-12	AA	--	--	C. ash	f/c = 0.2
S90-13	AA	--	--	C. ash	f/c = 0.5
S90-18	AAA	D	0.5%	C. ash	f/c = 0.6
S89-13	AA	A	0.5%	S. fume	7.5%*
S90-7	AA	D	0.5%	S. fume	10%
S90-8	AA	D	0.5%	S. fume	15%
S90-15	AAA	D	1%	S. fume	7.5%
R89-84	AA	A	1.5%	--	--
R89-85	AA	A	2%	--	--
R89-86	AA	A	2.5%	--	--
R89-87	AA	A	1.5%	--	--
R78-88	AA	A	2%	--	--
R89-89	AA	A	2.5%	--	--
R89-90	AA	A	1.5%	--	--
R89-91	AA	A	2%	--	--
R89-92	AA	A	2.5%	--	--
S90-9	AA	D	0.5%	--	--
S90-10	AA	D	1%	--	--
S90-11	AA	D	1.5%	--	--

*Amounts of slag and silica fume reported here are percentage (by weight) replacement of the cement.
**F/C (fly ash/cement) ratios reported are volume ratios.
Fly ash = Class F ash; C. ash = Class C ash; S. fume = silica fume.

chemical admixtures (superplasticizers and normal water-reducers) is more significant at low shear rates (Fig. 4).

Additional discussion of rheology and thixotropy is outlined in App. E.

Relationship Between Rheology and Interface Properties

The interfacial properties are expected to be dependent on the rheological properties of concrete in two ways. First, the aggregate volume fraction and the fine to coarse aggregate ratio will affect the interparticle distance which effects the rheology, and eventually the interfacial zone size and gradation. Second, the water added in excess of that required for minimum workability will affect both rheological and interfacial properties.

Packing and Its Effect on Properties

Standardized formulations for concretes are recommended by such organizations as the Portland Cement Association (PCA), Cement and Concrete Association (CCA), American Concrete Institute (ACI) and others. The results of the research associated with the packing of dry components of the concrete system established the theoretical basis upon which these empirical formulations were developed.

The random arrangement of a polydispersed particle system in a container is defined as the packing density of the powder and represents the volume fraction of the container which is occupied by the solids. Packing densities are always related to volume percentages of the components which are related through density to the masses of the solids being considered.

The results of this modeling demonstrate that the recommended concrete formulations in general occur in the region of maximum dry packing density in the system cement-sand-coarse aggregate. In this region, minor fluctuations in the proportioning of the concrete will have very little if any effect upon the dry packing density (Roy, Scheetz, Malek, et al. 1993).

Evaluation of the effects of packing density of mixtures of particle distributions suggested that the maximum workability without bleed water was achieved when the porosity of the packed powders was just filled with water. This condition occurs along a join drawn between the maximum packing in the sand/coarse aggregate system of a concrete and the cement powder.

With the expanding role of mineral admixtures and chemical admixtures available for concrete formulations, it is clear that the application of this type of modeling can be useful in the development of modifications to the current concrete designs which will function to be either more durable, less expensive or both.

The model used in this report is based upon the work and theoretical presentation of Toufar (1967) and Aims (1968) which was coded for the microcomputer by G.M. Idorn Consult

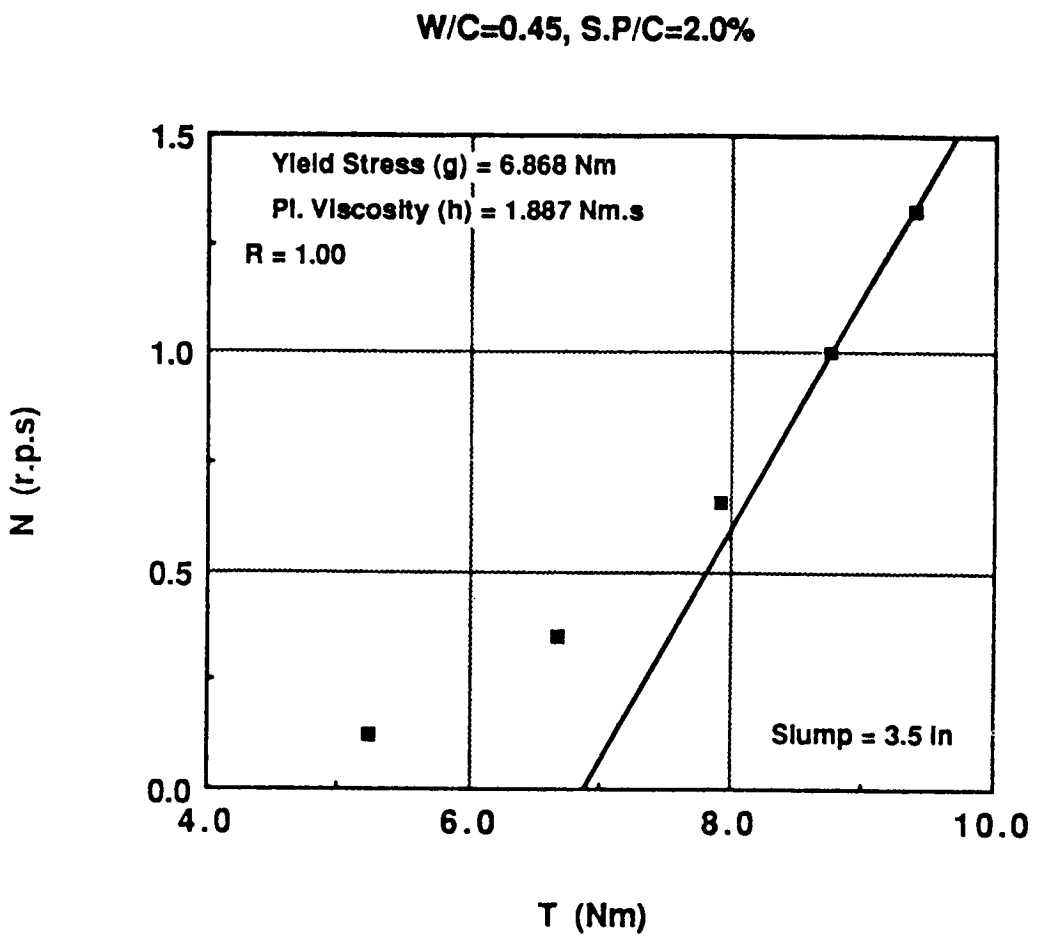


Figure 4. **An example of the shear stress-shear rate relationship of superplasticized concrete.**

A/S. The laboratory verification of the computer code was reported in SHRP-4 (1988). As indicated in this report, the Toufar and Aim model has been adopted for this research program and has been transformed into the status of routine use.

Theoretical Basis of Packing

The model is based upon a random arrangement of a polydispersed particle system in a container which is defined as the packing density of the powder and represents the volume fraction of the container which is occupied by the solids. Packing densities are always related to volume percentages of the components which are related through density to the masses of the solids being considered. With these simple definitions in mind, the packing density can be expressed as:

$$\phi = v_o/v$$

where:

v_o = volume of the container;
v = volume occupied by the solid.

By defining $v_o = 1$, the packing density then becomes:

$$\phi = 1/v$$

Packing density depends upon the particle size distribution, the particle shape and the method by which the particles were packed. Consider two components with diameters d_1 and d_2 such that $d_1 << d_2$ in a mixture with the volume fractions r_1 and r_2 and the maximum packing densities ϕ_1 and ϕ_2.

In the case of a large content of small particles, $r_1 >> r_2$, the mixture will mainly consist of small particles with the large particles discretely distributed in between. The matrix of the small particles has the packing density ϕ_1 and contributes to the specific volume with r_1/ϕ_1. The contribution to the specific volume by the lage particles is r_2. The total volume of the mixture is:

$$v = r_1/\phi_1 + r_2$$

and the packing density of the mixture is:

$$\phi_{mix} = 1/v = 1/(r_1/\phi_1 + r_2).$$

When the volume fraction of the coarse particles is large, $r_1 << r_2$, the small particles are accommodated in voids between the large particles. The specific volume and the packing density of the mixtures are therefore:

$$v = r_2/\phi_2$$

and

$$\phi_{mix} = \phi_2/d_2 \quad .$$

These considerations are based on the assumption that the coarse particles are much larger than the small particles.

When the assumption $d_1 << d_2$ is not valid, the ratio d_1/d_2 will have an effect on the packing density. The small particles may be too large to fit into the voids between the larger particles. Along the walls of the container, the packing densities will be smaller compared to that of the bulk. The magnitude of the "wall effect" will depend on the particle sizes. A similar effect occurs on the surface of large particles in multicomponent systems in which the departure from the bulk packing density is dependent upon the ratio of the small to the large particles.

The above discussion as demonstrated in SHRP-3 (1988) to adequately describe the behavior of polydispersed powder systems even though the original Toufar and Aim publications were developed for monodispersed particles. Further, the characteristic diameter of the particle size distributions for the components of concrete were shown to be adequately described by the D' from the Rosin-Rammler equation:

$$R(D) = e^{-(D/D')n}$$

Objective

The objective of this research was to explore the preliminary experimental observations of the workers at Pennsylvania State University and Idorn Consult that the maximum workability occurs with maximum packing density of the component particles.

Approach

Two widely accepted sources of concrete formulations, the Portland Cement Association (PCA) and the Cement and Concrete Association (CCA) specifications were used as input in order to map out the extent of concrete formulation referenced to a ternary mixture of cement/fine aggregate/coarse aggregate. The PCA specifications are based on different formulations with varying coarse aggregate and water to cement ratios while the CCA specification are based upon cement to fine aggregate versus cement to coarse aggregate ratios. In all cases, the data are based upon volume percentages of components.

This report deals with the correlation of calculated packing densities to the "time-tested" concrete formulations specified by the PCA. The materials that were utilized are materials that were collected specifically for this SHRP program and will therefore represent the data that will directly translate to laboratory practice. These materials are represented by two morphologically distinct coarse aggregates; a rounded to subround and a crushed aggregate.

Observations From Use of Dry Packing Model

The results of modeling recommended concrete formulations with this dry packing program give a theoretical basis for the trial and error establishment of the concrete formulations. For the most part, accepted concrete compositions occur in the vicinity of maximum dry particle packing and further, they occur where variations in the formulations will have minimal impact upon the packing density.

As might be anticipated, packing is influenced primarily by the coarse to fine aggregate packing density; attributable to their relative sizes compared to that of the cement powder. Based on this observation, a loci of optimal packing can be graphically established by locating the maximum packing density for the aggregate and establishing a join between this point and the cement apex in a ternary packing diagram similar to those in the stand-alone report (Roy, Scheetz, Malek, et al. 1993).

The packing model has been used to estimate the differences between extremes of allowable tolerances for fixed aggregate sizes. Following a similar approach, blends of different aggregates and reactive mineral admixtures could be modeled in order to optimize initial packing density. It can also be used to model the effects of different types of aggregates such as river gravels versus crushed prepared stone.

Initial evaluation of the effects of packing density of mixtures of particle distributions suggested that the maximum workability without bleed water was achieved when the porosity of the packed powders was just filled with water. Indeed, variations to the coarse aggregate end of this loci of optimal packing should result in bleed water formation. Deviations to the fine aggregate side of this line should result in either or both separation and bleed water development.

II.
Hydration, Maturity and Curing

In this task laboratory methods for predicting the curing of concrete were evaluated and compared with field results. There are a number of commercially available systems to predict maturity. These rely on assumptions with regard to the rate of curing depending on time and temperature. Relating maturity to curing conditions requires the development of mathematical expressions. These expressions employ the so-called activation energy. The isothermal calorimetry task was performed to more precisely establish the activation energies for portland and blended cements. These data were needed to support maturity model development; facilitate the development of improved hydration models; and provide a basis for comparing isothermally obtained hydration rates with adiabatic rates.

A hydration model was developed to provide a link between the activation energy determinations and the model developed to predict porosity evolution and permeability. Inputs to this model include the phase composition of the cement. Outputs include estimates of heat of hydration, porosity, and strength.

Finally, field studies have been carried out in concert with adiabatic calorimetry. These results have been used to evaluate a commercially available system that predicts maturity. Further, the results of adiabatic calorimetry are useful in evaluating the relevance of the isothermal calorimetric results.

Determination of Activation Energy for Cement Hydration by isothermal calorimetry

There are significant cost savings in allowing expeditious construction practices. With respect to concrete, prediction of the development of properties is crucial. This is often done through the application of the maturity concept. In principle, concretes having the same maturity, as determined by integrating curing time and curing temperatures, should have nominally the same strengths. In order to make such a determination, the strength gain characteristics are related to thermal history. A fundamental assumption in this process is that concrete attains its essential properties more rapidly at elevated temperature than it does at lower temperature. Various models have been developed to predict the relationship between temperature and strength. This relationship is described in terms of an "activation energy"; that is, the energy to start the reaction and overcome a barrier to

reaction/hydration. Models, in which two activation energies are used, one for curing temperatures below approximately 20°C and one for curing temperatures above 20°C are typical. However, the researchers' investigations indicate that a single activation energy is adequate to describe the curing behavior of cement over a range of temperatures from 10° to 65°C. This judgment is based on the results of isothermal calorimetric experiments carried out over this range of temperatures. Indeed, it is based on experiments requiring only one or two days. The values for the activation energy determined by this procedure are in the range of accepted values. Work has been done on portland cement and is being extended to blended cements containing Class F fly ash, Class C fly ash, and silica fume. It will not be possible to complete this study by the end of the SHRP program on microstructure. However, because of the potential importance of these findings, work on this subject will be continued with funding from other sources.

Field Studies: Maturity Model Verification

Two field studies were conducted as part of this program. Both studies were intended to collect thermal data from two different highway-related structures which would serve as actual validation data for the maturity model/curing tables. These two studies included a 34 × 17 × 4 ft., 100-cubic yard bridge pier, used to test behavior of mass concrete, and a highway road patch measuring 6 ft. × 12 ft. × 10 in., to test behavior of a slab.

The location of the bridge pier field experiment was in central Pennsylvania near the town of Faunce. The structure studied is the central bridge pier which was placed on a foundation in the middle of Clearfield Creek. The placement of the foundation was in the middle of this 200 foot-wide stream and at a depth of approximately 6 to 8 ft. below the water surface. The stream is polluted as a result of nearby coal strip mining and was running at 21°C and a pH of 3.5.

The pier was situated on the site in a north-south orientation with the north end of the pier facing downstream. The width of the east-facing side of the pier received substantial exposure to the sun as did the south-facing ballister.

The test sections for the highway road patch field experiment were located along State Route 15 approximately 22 miles north of Williamsport, Pennsylvania, near the crest of the mountain in Steam Valley. Two 6 ft. × 12 ft. slabs in the uphill passing lane were instrumented [number 969-97 and 970-60]. The two slabs were located approximately 40 ft. apart and will be referred to as the uphill and downhill slabs, respectively.

In both of these experiments, thermocouple sensors were embedded in the structures or slabs and the temperatures monitored for the initial 72 hours of curing. These data, along with the concrete supplier's mix data, the data on compressive strength and heats of hydration derived for laboratory activities are being used in a PC-based maturity model.

It has been found that the CIMS software may need to be used in association with CIMS HayBox calorimetry, and that laboratory measurement (adiabatic calorimetry) cannot readily be extended to use in the field in terms of predicting accurately the temperature changes in

concrete with time. However, the predicted temperature changes and the field measured temperature changes in concrete show the same trend. For example, in the bridge pier, about 20 hours after the start of pouring, the temperature reached its peak, as was the difference between the maximum and minimum temperatures in concrete. At about 20 hours after the start of pouring, the steel formwork was removed. The inside temperature began to drop. Eventually the temperature in concrete reached the ambient temperature. The deviation of the predicted temperature changes in concrete from those measured in the field might have been due to heat loss that would occur in the practice. A preliminary study has suggested that further investigation is warranted in terms of developing a general method for predicting temperature change in concrete based on generic adiabatic calorimetry.

Cement Hydration Model

The objective of the cement hydration model is to estimate the influence of composition and other characteristics of the cementitious system on the time-dependent development of engineering properties of cement paste and concrete. A basic model for handling the hydration processes of portland cement minerals and combinations of these has been created. The model delivers, as a function of the initial composition and the maturity of the system, a detailed description of the composition of the cement paste, as well as other data of engineering relevance such as porosity, bound water and heat of hydration.

The model incorporates an estimation of strength because strength is a property of primary engineering interest. Strength estimation is another way to test the concept as well as specific details of the model. Strength is probably the most frequent parameter to characterize a hydration cement system.

It is generally accepted that the strength of a cement-based material is closely related to the porosity of the cement paste (Fig. 5). One of the commonly used exponential expressions is:

$$\sigma = \sigma_o \cdot \exp(-k \cdot p)$$

where: σ = strength
σ_o = strength at zero porosity ("intrinsic strength")
p = porosity
k = constant.

Another is the classical correlation based on gel-space ratio proposed by Powers and Brownyard (1948):

$$\sigma = \sigma_o \cdot x^n$$

where: x = gel-space ratio
n = constant.

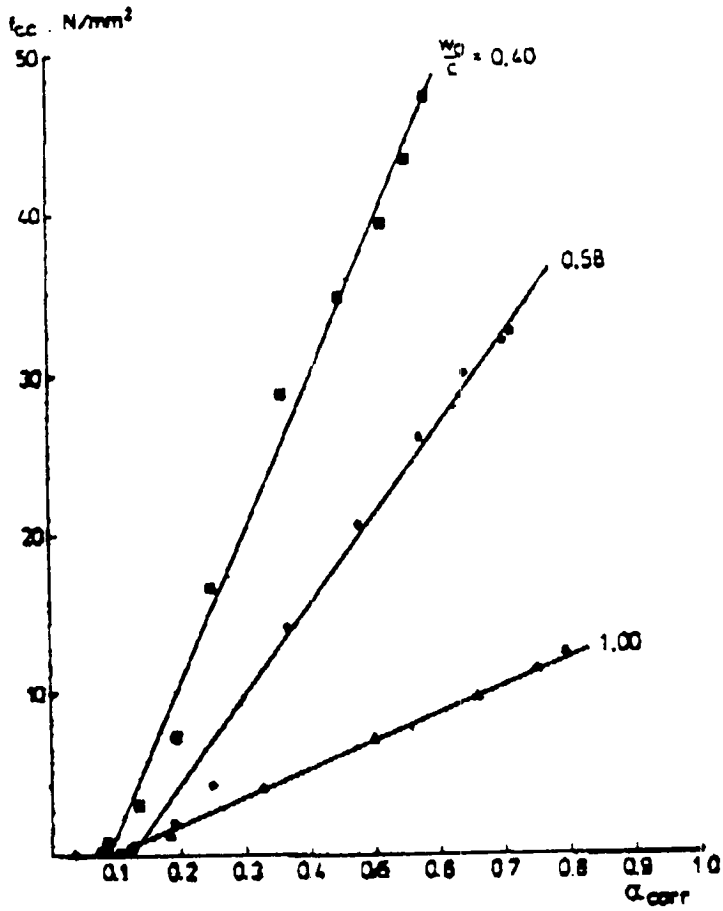


Figure 5. **Example of the close to linear relationship often found experimentally between strength and degree-of-hydration (RILEM 1981).**

From the volumetric description of the cement paste, which is a possible output of the cement hydration model, porosity and gel-space ratio at any maturity (t) can be calculated as follows:

$$p(t) = \frac{V_o - \Sigma v_{\text{solidphases}}(t)}{V_o}$$

$$x(t) = \frac{\Sigma v_{\text{hydrates}}(t)}{V_o - \Sigma v_{\text{anhydrousphases}}(t)}$$

V_o = initial volume of the cement paste.

Test of Strength Function

The strength-function should be able to provide satisfactory estimates of strength as functions of:

initial water/cement ratio
degree of hydration
varying cement compositions.

Tests to investigate the fulfillment of these requirements for the proposed functions have been initiated.

Test for Water/Cement and Degree of Hydration

To test the ability to treat the first two variables, simplified expressions for porosity and gel-space ratio were used:

$$p = \frac{w/c - \Delta V_s \cdot \alpha}{w/c + 1/\rho c}$$

$$x = \frac{N}{1 + w/c \cdot \rho c \cdot 1/\alpha}$$

where: w/c = initial water-to-cement ratio (by weight)
α = degree of hydration (fraction)
ρc = specific gravity of the cement
ΔV_s = solid volume increase by hydration of 1 weight unit of cement
N = hydrate volume produced by 1 volume unit of cement.

The last two terms here are considered constant during the hydration for a specific cement.

They are interlinked by the following expression:

$$N = 1 + \rho c \cdot \Delta V_s$$

In the two strength-functions

$$\sigma = \sigma_o \cdot \exp(-k \cdot p)$$

$$\sigma = \sigma_o \cdot x^n$$

the intrinsic strength is arbitrarily set to 100; k is set to 7 (column R of Table 4) (Jons, Osbaeck 1982); n was found by Powers to vary between 2.5 and 3 for different cements (Powers 1960). However, experience has shown a value of 2 might be a useful alternative. Hence, tests with n = 2.0, 2.5 and 3.0 were run. Results are presented in columns R_2, R_3, and R_4 of Table 4 for n= 2, 2.5 and 3.0, respectively.

Experimental results usually exhibit a nearly linear relationship between strength and degree of hydration as shown in Fig. 5. It is obvious that the gel-space ratio-based functions come closest to that feature and more so for smaller n- values.

A crucial requirement for the strength function is the ability to give a satisfactory estimate of the effect of varying initial w/c ratios. To check that, the strength figures calculated by the functions mentioned above were all normalized with the figures for w/c = 0.50 and compared with relative strength values calculated by strength w/c ratio functions used generally in practice.

One of these is the "law" of Bolomey:

$$\sigma = K_s \cdot (c/w - g)$$

where the constant g usually is put to 0.5 or 0.25 (for air-entrained concrete). Results of the test are presented in columns R_5 and R_6 of Table 4 for g = 0.5 and 0.25 respectively.

Another is the "law" of Feret:

$$\sigma = K_F \cdot \left(\frac{c/\rho o}{c/\rho o + w}\right)^2$$

$$= K_F \left(\frac{1}{1 + (w/c) \cdot \rho_o}\right)^2$$

The results for w/c varying from 0.3 to 1.0 are shown in column R_7 of Table 4.

As can be seen, there is an agreement between the estimates of Bolomey's and Feret's "laws" (Feret-based estimates fall between the two Bolomey estimates).

As for the functions being tested, the estimates based on gel-space ratio using an exponent of 2.0 come very close to the practical "laws" for high values of degree of hydration.

Table 4 **Effect of w/c ratio on strength estimated by different functions. Comparisons made to strength at w/c - 0.50 and at degree of hydration as indicated.**

STRENGTH FUNCTIONS

w/c	a	p	X	R1	R2	R3	R4	R5	R6	R7
.30	.10	.42	.22	269.5	256.9	325.3	411.8	188.9	176.2	175.3
.30	.20	.36	.39	301.1	240.3	299.2	372.5	188.9	176.2	175.3
.30	.30	.29	.54	336.5	226.0	278.3	341.6	188.9	176.2	175.3
.30	.40	.23	.67	376.0	215.6	261.3	316.6	188.9	176.2	175.3
.30	.50	.16	.78	420.1	206.2	247.1	296.1	188.9	176.2	175.3
.30	.60	.10	.88	469.4	198.2	235.1	279.0	188.9	176.2	175.3
.30	.70	.03	.96	524.4	191.3	224.9	264.5	188.9	176.2	175.3
.40	.10	.50	.17	153.2	151.7	168.3	186.8	133.3	128.6	129.8
.40	.20	.45	.31	160.7	147.8	163.0	179.7	133.3	128.6	129.8
.40	.30	.39	.43	168.6	144.5	158.4	173.6	133.3	128.6	129.8
.40	.40	.33	.54	176.0	141.6	154.4	168.4	133.3	128.6	129.8
.40	.50	.20	.64	185.4	139.0	150.9	163.9	133.3	128.6	129.8
.40	.60	.22	.73	194.5	136.7	147.9	159.9	133.3	128.6	129.8
.40	.70	.17	.81	204.0	134.7	145.1	156.4	133.3	128.6	129.8
.40	.80	.11	.88	214.0	132.9	142.7	153.2	133.3	128.6	129.8
.40	.90	.06	.94	224.5	131.3	140.5	150.4	133.3	128.6	129.8
.40	1.0	1.0	1.0	235.4	129.8	138.6	147.9	133.3	128.6	129.8
.50	.10	.56	.13	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.20	.51	.25	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.30	.46	.36	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.40	.42	.44	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.50	.37	.54	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.60	.32	.62	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.70	.27	.70	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.80	.22	.76	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	.90	.17	.82	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.50	1.0	.12	.88	100.0	100.0	100.0	100.0	100.0	100.0	100.0
.60	.10	.61	.11	71.6	70.8	65.0	59.6	77.8	81.0	79.4
.60	.20	.57	.22	69.0	72.1	66.5	61.3	77.8	81.0	79.4
.60	.30	.52	.31	66.5	73.3	67.8	62.6	77.8	81.0	79.4
.60	.40	.48	.39	64.0	74.4	69.1	64.1	77.8	81.0	79.4
.60	.50	.44	.47	61.7	75.4	70.2	65.4	77.8	81.0	79.4
.60	.60	.39	.54	59.4	76.3	71.3	66.6	77.8	81.0	79.4
.60	.70	.35	.61	57.3	77.2	72.3	67.8	77.8	81.0	79.4
.60	.80	.31	.67	55.2	78.0	73.2	68.8	77.8	81.0	79.4
.60	.90	.26	.73	53.1	78.7	74.1	69.8	77.8	81.0	79.4
.60	1.0	.22	.78	51.2	79.4	74.9	70.7	77.8	81.0	79.4

Table 4 **Effect of w/c ratio on strength estimated by different functions. Comparisons made to strength at w/c - 0.50 and at degree of hydration as indicated. Continued**

STRENGTH FUNCTIONS

w/c	a	p	X	R1	R2	R3	R4	R5	R6	R7
.70	.10	.65	.10	54.8	52.8	45.0	39.4	61.9	67.3	64.6
.70	.20	.61	.19	51.2	54.5	46.8	40.2	61.9	67.3	64.6
.70	.30	.57	.27	47.9	56.0	48.5	41.9	61.9	67.3	64.6
.70	.40	.53	.35	44.8	57.5	50.0	43.6	61.9	67.3	64.6
.70	.50	.49	.42	41.9	58.8	51.5	45.1	61.9	67.3	64.6
.70	.60	.45	.48	39.1	60.	52.9	46.6	61.9	67.3	64.6
.70	.70	.41	.54	36.6	61.3	54.3	48.8	61.9	67.3	64.6
.70	.80	.37	.68	34.2	62.5	55.5	49.4	61.9	67.3	64.6
.70	.90	.33	.66	32.0	63.5	56.7	50.6	61.9	67.3	64.6
.70	1.0	.29	.71	29.9	64.6	57.9	51.9	61.9	67.3	64.6
.80	.10	.68	.09	44.0	40.9	32.7	26.1	50.0	57.1	53.5
.80	.20	.64	.17	40.1	42.6	34.4	27.0	50.0	57.1	53.5
.80	.30	.61	.24	36.6	44.2	36.0	29.4	50.0	57.1	53.5
.80	.40	.57	.31	33.4	45.7	37.6	30.9	50.0	57.1	53.5
.80	.50	.54	.37	38.4	47.2	39.1	32.4	50.0	57.1	53.5
.80	.60	.58	.43	27.8	48.6	40.6	33.9	50.0	57.1	53.5
.80	.70	.47	.49	25.3	49.9	42.0	35.3	50.0	57.1	53.5
.80	.80	.43	.54	23.1	51.2	43.3	36.6	50.0	57.1	53.5
.80	.90	.39	.59	21.1	52.4	44.6	37.9	50.0	57.1	53.5
.80	1.0	.36	.64	19.2	53.5	45.8	39.1	50.0	57.1	53.5
.90	.10	.71	.08	36.6	32.6	24.6	18.6	40.7	49.2	45.1
.90	.20	.67	.15	32.7	34.2	26.2	20.0	40.7	49.2	45.1
.90	.30	.64	.22	29.2	35.8	27.7	21.4	40.7	49.2	45.1
.90	.40	.61	.28	26.1	37.3	29.1	22.8	40.7	49.2	45.1
.90	.50	.57	.34	23.3	38.7	30.5	24.1	40.7	49.2	45.1
.90	.60	.54	.39	20.8	40.1	31.9	25.4	40.7	49.2	45.1
.90	.70	.51	.45	18.6	41.4	33.2	26.7	40.7	49.2	45.1
.90	.80	.48	.50	16.6	42.7	34.5	27.9	40.7	49.2	45.1
.90	.90	.44	.54	14.9	43.9	35.7	29.1	40.7	49.2	45.1
.90	1.0	.41	.59	13.3	45.1	36.9	30.3	40.7	49.2	45.1
1.0	.10	.73	.87	31.3	26.5	19.1	13.7	33.3	42.9	38.5
1.0	.20	.70	.13	27.5	28.1	20.4	14.0	33.3	42.9	38.5
1.0	.30	.67	.20	24.1	29.5	21.8	16.1	33.3	42.9	38.5
1.0	.40	.64	.25	21.2	31.0	23.1	17.2	33.3	42.9	38.5
1.0	.50	.61	.31	18.6	32.3	24.4	18.4	33.3	42.9	38.5
1.0	.60	.58	.36	16.3	33.5	25.6	19.5	33.3	42.9	38.5
1.0	.70	.55	.41	14.3	34.9	26.8	20.6	33.3	42.9	38.5
1.0	.80	.52	.46	12.6	36.2	28.0	21.7	33.3	42.9	38.5
1.0	.90	.49	.50	11.1	37.3	29.2	22.8	33.3	42.9	38.5
1.0	1.0	.46	.54	9.7	38.5	30.3	23.9	33.3	42.9	38.5

In this connection it is interesting to note that the law of Feret actually is identical with Powers' gel space ratio based strength function when the degree of hydration = 1 and $n = 2$.

$$\sigma_F = \sigma_o \cdot \left(\frac{1}{1 + w/c \cdot \rho_o \cdot 1/\alpha}\right)^n$$

$$= K_F \cdot \left(\frac{1}{1 + (w/c) \cdot \rho_o}\right)^2$$

Tests for the Effect of Cement Composition

Due to its ability to describe the effect of w/c ratio and degree of hydration in agreement with practical results in general, the strength function based on gel space ratio and an exponent of 2 was used for some preliminary tests on the effect of cement composition.

In these tests, changes in kinetics due to changes in composition were not considered. Despite this simplification the model gave promising results.

Table 5 shows the calculated effect of strength of increasing C_3S by 10% from 50% to 60% with a corresponding decrease in C_2S.

The strength figures are arbitrarily based on a σ_o value of 100, but incidentally the values are close in magnitude to those obtained by strength testing according to the ISO-CEN-method (mortar with s/c = 3 and w/c = 0.5) (Powers, Brownyard 1948). Not only are the 28-day strengths but also the strength levels at 1, 3 and 7 days in close agreement with reality.

The effect predicted by the model is in very good agreement with our own general experience regarding the effect of a C_3S increase on ISO-strengths.

The specific effects of C_3S on ASTM strengths estimated by Blaine et al. (1968) also fall along these lines:

	$\Delta\sigma$/+10% C_3S psi (ASTM C 109)	$\Delta\sigma$/+10% C_3S MPa (ISO-CEN-RILEM)
1d	200	2
3d	400	4
7d	550	5.5
28d	450	4.5

These are average figures for a series of multiple regression analyses based on data on 199 commercially manufactured cements. ASTM strength in psi can be converted to

ISO-strengths in MPa by dividing by 100 (differences in both units and effect of the strength testing system is incorporated in this empirical conversion factor).

Table 6 contains the results of a similar test on the prediction of the effect of a C_3A increase (and corresponding C_4AF decrease) on strength.

Again these values can be compared with values estimated by Blaine et al. by regression analysis:

	$\Delta\sigma$/+10% C_3A psi (ASTM C 109)	$\Delta\sigma$/+10% C_3A MPa (ISO-CEN-RILEM)
1d	200	2
3d	400	4
7d	800-1000	8-10
28d	700-1200	7-12

Considering the fact that no corrections for the effect of composition on the kinetics (α values) have been made, the estimates made by the model must be considered surprisingly good, especially as the reaction kinetics of the interstitial phase (C_3A+C_4AF) is known to be rather sensitive to its composition and to the amount of gypsum added to the cement.

Thus a realistic description of the influence of gypsum on the hydration course and the resulting physical properties must incorporate its influence on the kinetics of the system as well as the influence on the composition of hydrates formed.

Kinetic values for the different clinker mineral are still to be stated as input to the model. An algorithmic treatment of the kinetics is an obvious further step for the development of the model.

Conclusion

Efforts have been made to find an adequate mathematical algorithm to estimate strength from paste composition (porosity). A requirement to such an algorithm is that it should be able to give satisfactory estimates of strength as function of w/c ratio, maturity (degree of hydration) and cement composition.

Preliminary tests have indicated that a function based on the gel-space ratio concept seems to be able to fulfill such requirements.

The function initially used is the following:

$$\sigma = \sigma_o \cdot X^2$$

Table 5 Estimated effect on strength of increasing C_3S by 10% (s_o = 100).

Composition			Δx
C_3S	50	60	+10
C_2S	25	15	-10
C_3A	8	8	
C_4AF	12	12	
Free C	1	1	
CsH_2	4	4	
H	50	50	
Strength			
1d	14.4	17.3	+2.9
3d	23.8	27.9	+4.1
7d	38.4	43.2	+4.8
28d	49.5	54.3	+4.8

Table 6 Estimated effect on strength of increasing C_3A by 10% (s_o = 100).

Composition			Δx
C_3S	50	60	
C_2S	25	25	
C_3A	3	13	+10
C_4AF	17	7	-10
Free C	1	1	
CsH_2	4	4	
H	50	50	
Strength			
1d	14.0	14.7	+0.7
3d	21.9	25.9	+4.0
7d	34.8	42.1	+7.3
28d	45.7	53.3	+7.6

X is the gel-space ratio which is calculated by the hydration model with cement composition, initial w/c-ratio and maturity as input variables. σ_0 ("the intrinsic strength") is a constant, which can be chosen arbitrarily to give values characteristic for the system for which the strength is determined. This will be dependent on the cement-based material being investigated (concrete, mortar, paste) and the size and shape of the specimens used for strength testing. The computer code permitting these applications is appended (App. F).

This code permits the calculation of heat of hydration, porosity and compressive strength based on the hydration of the principal phases in portland cement. The extents of hydration of each of the mineral phases can be adjusted. Therefore, although not explicitly stated, the effects of grinding can be incorporated into the model. At its present stage of development the model cannot directly deal with blended cements. However, it should be possible to integrate this capability into the model with relative ease.

III.
Microstructure

The physical and mechanical properties of portland cement paste, mortars and concretes are a direct result of a series of complex processes taking place during mixing and placing including the hydration reactions. Once the anhydrous cement phases are mixed with water, the developing hydrates fill space between the solids, space originally occupied by the water. The amount of space occupied by the water is related to the original w/c ratio. For example, portland cement paste with a w/c of 0.5 (assuming the density of cement to be 3.3 and that of water to be 1.0) contains 62 volume % of water and therefore has 62 volume % original porosity. Similarly, a paste with a w/c of 0.3 has 50 volume % original porosity. Needless to say, the less space to fill and the denser the microstructure, the stronger the resultant product.

The hydrates which form and fill space are poorly crystalline, foil-like calcium silicate hydrate, more crystalline hexagonal and cubic calcium aluminate and sulfoaluminate hydrates and crystalline calcium hydroxide. As the reaction continues, the developing hydration products become denser, porosity decreases, and physical and mechanical properties performance increase. In terms of microstructure, the interrelationship of packing to mixing, pore structure and property development are reasonably well understood. See Chapters I and IV of this report. However, the interaction of hydrates with nonreactive aggregates found in mortars and concrete and the effect of the interfacial zone are not understood as well.

Microstructure research on this contract has focused on two topics: concrete and tailored interfacial microstructure. Each has had a slightly different emphasis. The emphasis in the concrete work has been on the development and refinement of a particle packing model coupled with a thorough examination of the resulting concrete microstructure using fluorescent microscopy examination of thin sections. The emphasis in the tailored interfacial work has been on computer modeling of packing at interfaces and experimental verification of model predictions. Progress in each of these areas is summarized below.

Modeling and Fluorescent Microscopy Studies of Concrete Microstructure

The following summary highlights only the results of the fluorescent and SEM microscopic studies of concrete. Fluorescent microscopic examination of thin sections of concrete

samples S89-1 to S89-19 has been carried out by G.M. Idorn Consultants (GMIC) and Pennsylvania State University (PSU). Briefly, the method uses paste, mortar or concrete samples impregnated with a fluorescent epoxy to fill cracks, voids and pore space. When these samples are made into thin sections and viewed under fluorescent light in a petrographic microscope, microstructural features and irregularities are highlighted by the variation in intensity of the fluorescence, depending upon the distribution of porosity. An example of an impregnated thin section is given in Fig. 6. The matrix is homogeneous, with only an occasional fine crack at or along an aggregate-paste interface. The reported w/c ratio for this sample is 0.46 (Powers, Brownyard 1948). The method is an extremely powerful one. It may be used to obtain qualitative information such as the location of cracks, homogeneity of particle distribution and, presumed, mixing and general microstructural information. However, quantitative information such as w/c ratio is more difficult to obtain, requiring carefully prepared standards and a skilled operator.

Interfacial Microstructure Simulations and Verifications

The Interface Microstructure report (Roy, Grutzeck, Shi, et al. 1993) contains the results of a computer model simulation of packing of fine particles at an interface, and the results of experiments dealing with the nature of the interfacial zone.

The present computer code is an improvement over existing codes which normally involve adding particles sequentially to an existing accumulation of particles. The current program randomly generates a set of particles above the surface and moves them almost simultaneously towards the surface. During the movement, particle agglomeration may occur. Particle agglomeration can be controlled by varying the sticking probability of particles. The simulation is used to model the initial packing of cement particles in the bulk phase and at the surface of aggregates as a function of sticking probability. The model was used to verify the fact that porosity was higher at the contact between aggregate and paste and then decreased with distance from the interface into the bulk paste. In order to examine interfaces in real samples, experimental work was carried out in four areas.

Thin section work concentrated on concrete properties (Roy, Grutzeck, Scheetz, et al. 1993) and engineered interface samples. In the latter case, slabs of either Tuscarora quartzite or Valentine limestone were mixed with S89 series of concretes and then molded at the center of a 3 × 6 in. cylinder. These were subsequently cured in $Ca(OH)_2$ solutions, cut with a diamond saw, thin sections prepared, and examined with the optical microscope. An example of a typical concrete specimen (S89-4Ma) was given earlier (Fig. 6). Fig. 7 gives an example of an engineered sample (S89-4) cast against a limestone slice. Cracking apparently occurred prior to thin sectioning because the crack is filled with moderately birefringent $Ca(OH)_2$ crystals.

The scanning electron microscope (SEM) was used to examine paste and mortar samples. The mortar samples were designed to contain 50 volume % of both paste and sand (standard ASTM C190 20-30 gradation sand). The mortars and pastes were cured in $Ca(OH)_2$ solution and were sampled as a function of time. Samples were freeze-dried, cut and polished and examined with the backscattered electron (BSE) mode. A typical

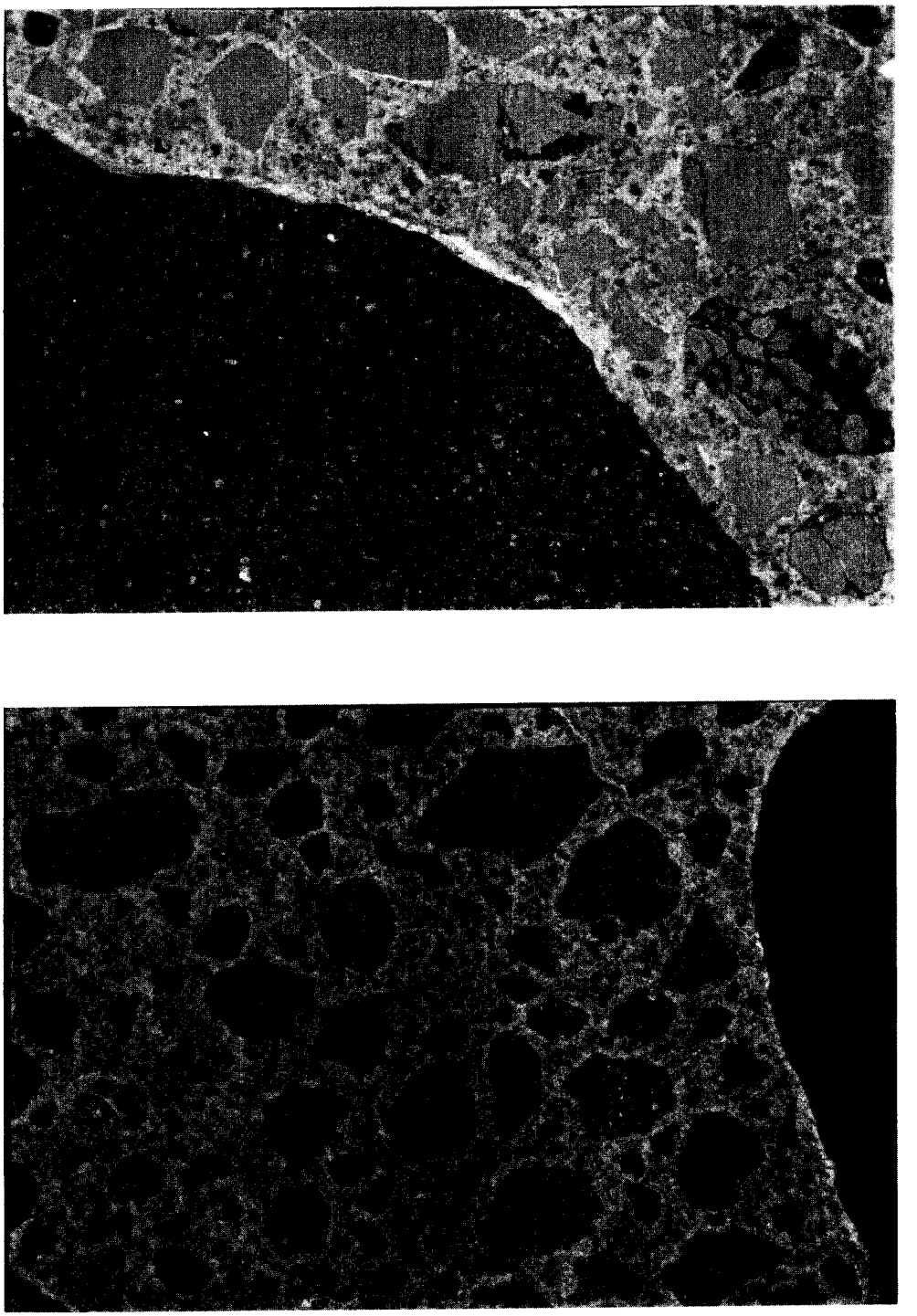


Figure 6. **Fluorescent microscopy images of different portions of SHRP S89-4M concrete cured for 28 days at room temperature in $Ca(OH)_2$ solution. The data suggest that the concrete is well mixed and rather homogeneous. It also suggests that the paste-aggregate contact is variable. In one instance (top) it has a crack-like porous feature whereas in the lower photograph it is totally tight.**

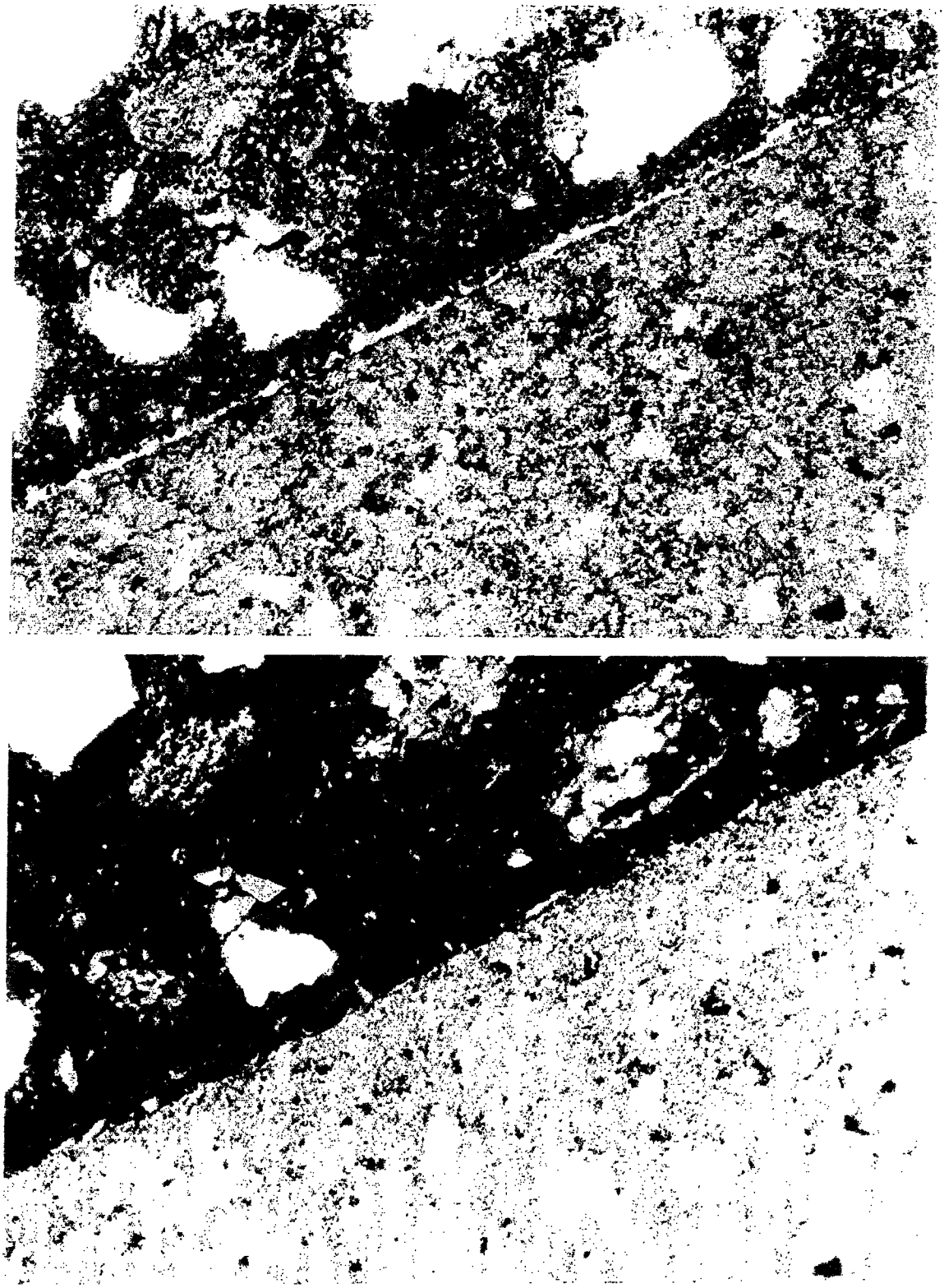


Figure 7. **Micrographs of a S89-4 limestone engineering interface sample showing the interface between the limestone slab and the screened mortar as recorded in ordinary and polarized light (bottom), respectively. The highly birefringent crystals in the crack between the aggregate and the mortar are calcium hydroxide crystals. Their presence indicates that in this case cracking has occurred prior to the preparation of the thin sections. 1.1 × 1.6 mm.**

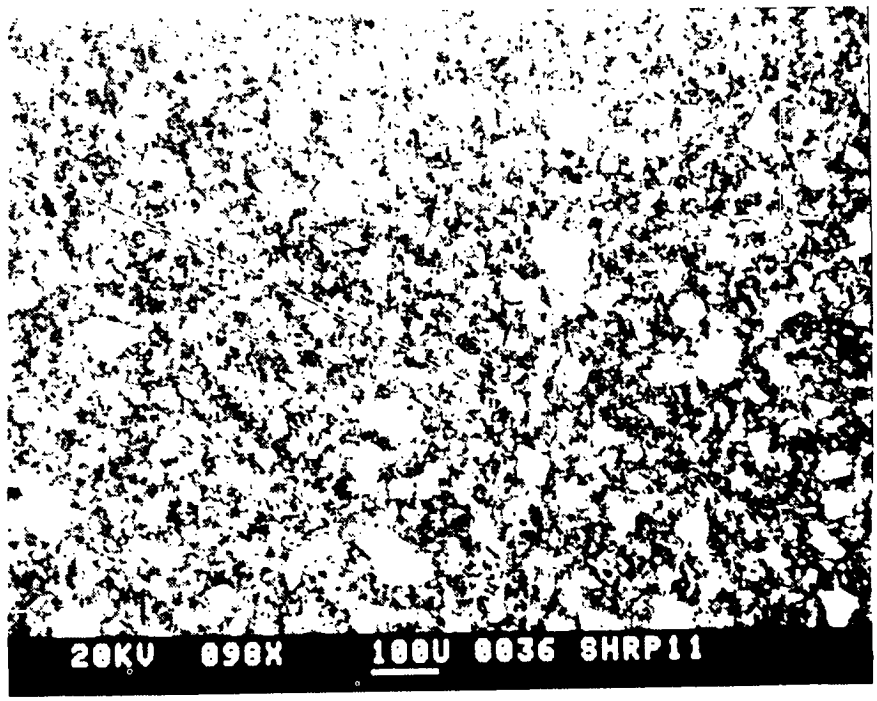
comparison of a paste-mortar pair is given in Fig. 8. It can be seen that cracking associated with the paste is randomly dispersed, while in the mortar it seems to be associated with the interfacial zone. In this instance, the cracking may indicate inherent weakness of the interfacial hydrate-aggregate contact. Quantitative image analysis employing gray level contrast was used to verify the volume percents of paste and aggregate in the mortars and also to investigate the porosity gradients existing around individual sand grains. It was observed that gray levels did in fact vary as a function of distance from the interface within the first 50 μm of hydration product around the sand grains indicating a decrease in porosity with distance from the interface. These same freeze-dried samples were examined as discussed below.

Mercury-porosimetry data were used to calculate approximate interfacial porosities. A typical result is presented in Fig. 9. In all instances, the mortar porosity was slightly higher than the expected one-half of the paste value. This was attributed to the higher porosity associated with the interface and predicted by our model. By making various assumptions about interfacial thickness (50 μm) and feeding in actual porosity data (paste = 25.5%, mortar = 14.7%) we were able to calculate an interfacial porosity of 37.3% for a cement paste cured 3 days and equivalent 50:50 volume % mortar (SHRP 1-1). Additional interfacial porosities for samples cured 7, 14 and 28 days were calculated to be 32.8, 34.0 and 31.7, respectively.

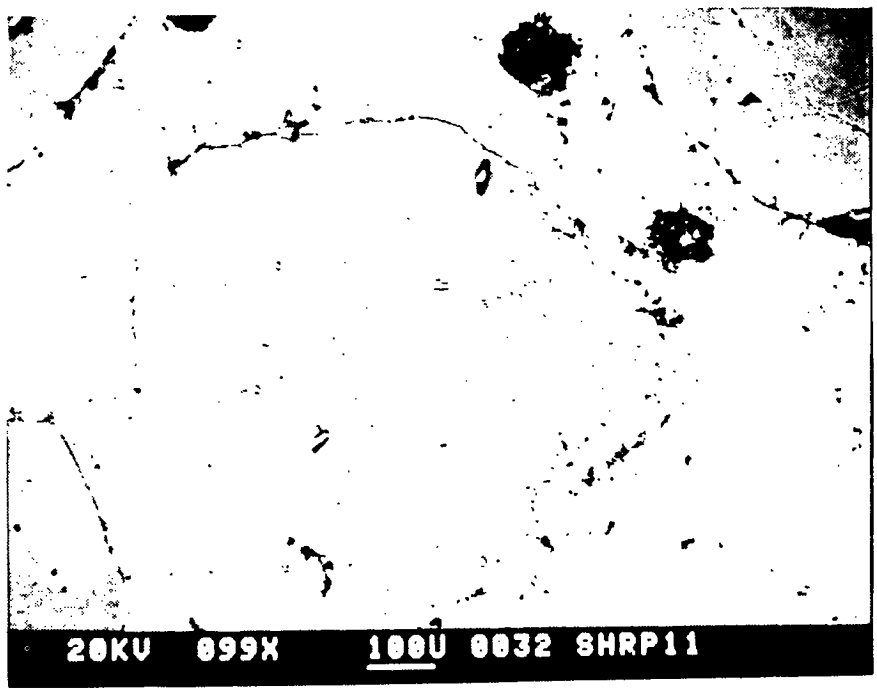
Finally, air permeability measurements have been made on both freeze-dried paste and mortar samples. Typical results for formulation SHRP 1-1, the same cement sample as described above, are presented in Fig. 10. In all instances, the paste permeabilities were higher than the mortar permeabilities; however, once again the mortar value is slightly larger than the expected one-half of the paste value. This is again attributed to the contribution of enhanced porosity at the interface.

Conclusions

Interface porosity is predicted to be higher than bulk paste porosity by the interfacial simulation model. This prediction is in general agreement with previously published data and current findings. However, it was also observed that interfacial samples were extremely sensitive to drying and cracking and questions still exist as to the effect of freeze drying on sample integrity. Further summaries and suggestions for future work in the area of interface research are presented in the Interface Report (Roy, Grutzeck, Shi, et al. 1993).



(a)



(b)

Figure 8. **Typical 100× EBS images of 14-day-old SHRP 1-1 paste (a) and mortar (b) after freeze drying and polishing with 1 μm diamond paste. Cracking is random in (a) and associated with interfaces in (b).**

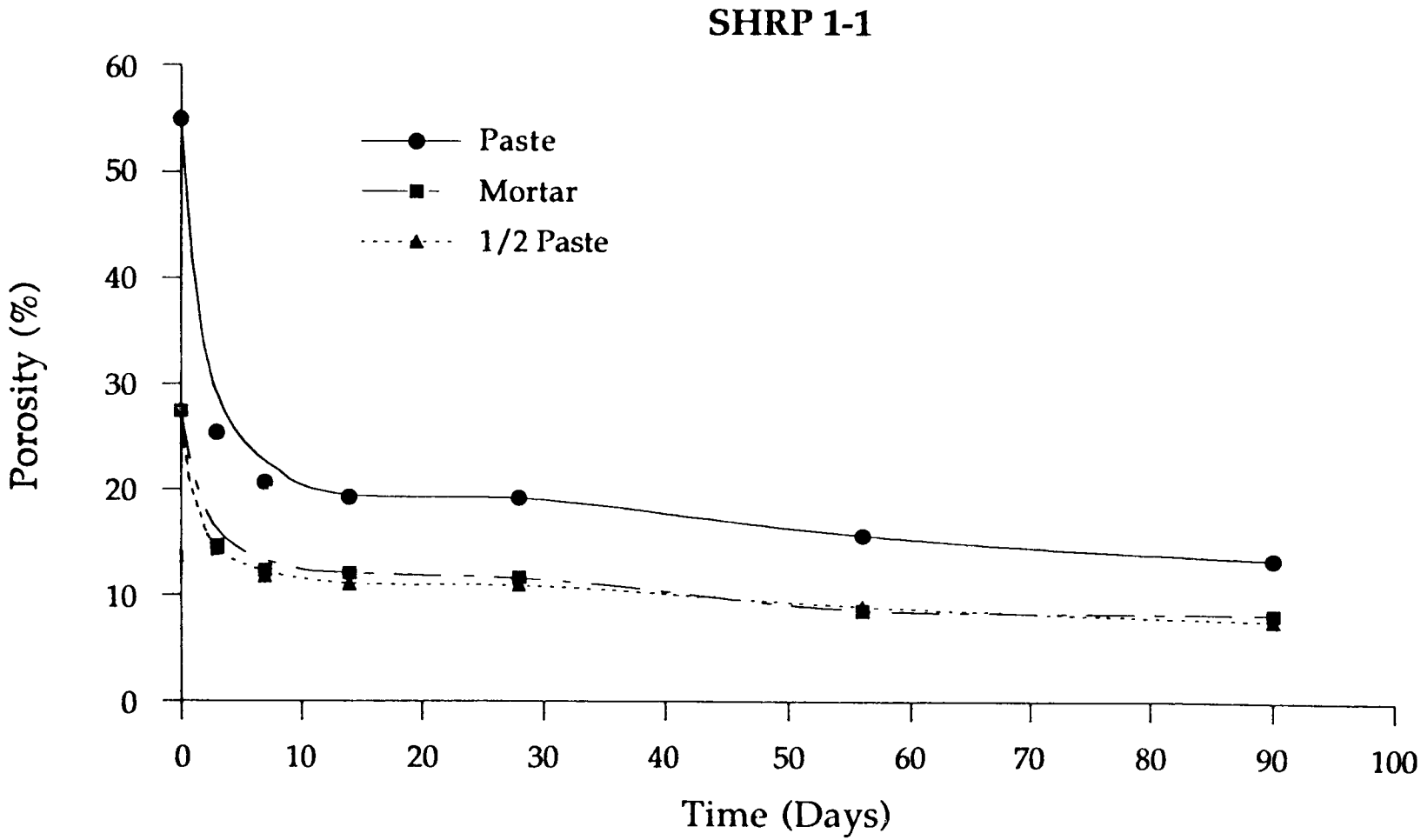


Figure 9. **Typical porosity variations as a function of time measured by mercury porosimetry (SHRP 1-1).**

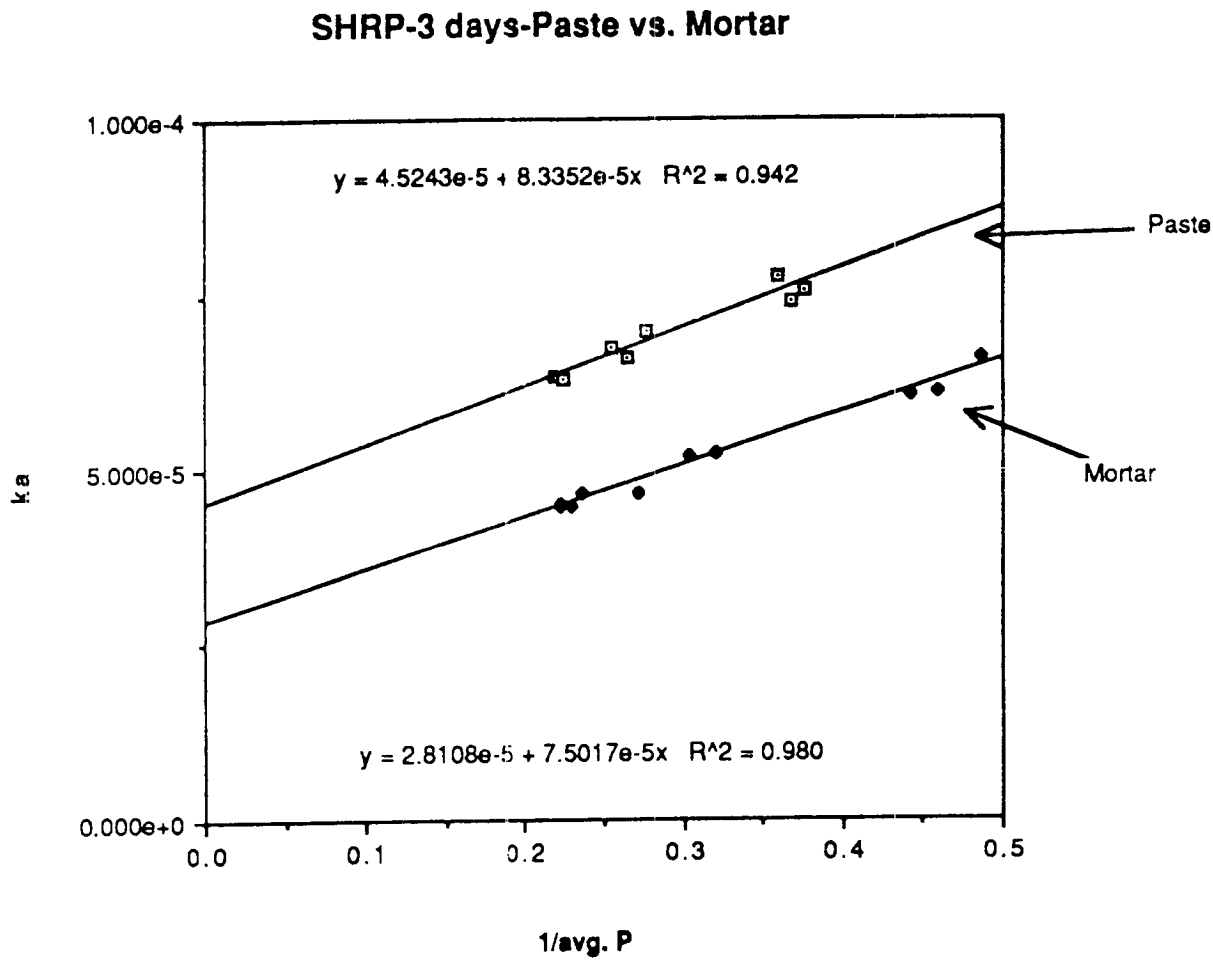


Figure 10. Typical air permeability (k_a) data for 3-day-old freeze-dried SHRP 1-1 paste and mortar samples. The paste and mortar values extrapolated to zero reciprocal pressure (infinite pressure) are 4.52×10^{-5} and 2.81×10^{-5} darcy, respectively. The expected mortar value (50% paste value) would be 2.26×10^{-5}.

IV.
Porosity, Pore Structure, Permeability and Their Relation to Durability

Major conceptual advances have been made in this program relating the pore structure of cement paste, mortar and concrete to permeability. Methodology for measurement of permeability has been advanced. Further, the variations in porosity and permeability with hydration age have been modeled (Roy, Brown et al. 1993; Roy, Scheetz, Sabol et al. 1993). The fundamental exothermal processes which are associated with hydration have been modeled and can be integrated into a predictive tool for establishing maturity. Attendant to the consumption of the anhydrous cement phases, hydration products which confer the needed properties form and this process have been considered in the context of a hydration model. There is a continuous variation in the distribution in the porosity. These variations, too, have been modeled and related to permeability.

Porosity and Pore Structure

Various properties of cement-based materials are affected not only by total porosity but also by the size distribution of the porosity present. In order to model the relationship between pore size distribution and properties, a suitable mathematical descriptor for pore size distribution must first be found. Mercury intrusion porosimetry (MIP) is a commonly used method for determining pore size distributions for the range of pore sizes which significantly effect properties such as permeability. This technique has also been used, as discussed in Chapter III, for measurement of interface porosity. A suitable mathematical descriptor for pore size distributions determined by MIP should be one that not only fits the experimental data but, more importantly, provides the basis for the physical interpretation of pore structure. The pore size distributions in cement pastes and mortars, over the range of pore sizes determined by high pressure MIP, can be described in terms of a multi-modal distribution by using lognormal simulation.

A statistical method has been developed to detect if there is a mixture of two lognormal distributions and to iteratively estimate the parameters in the compound distribution. A similar approach can be applied to a mixture of more than two lognormal distributions. Without the use of a computer program, the iterative estimation of parameters is extremely difficult. However, a graphical method can be used to obtain first degree estimates of

parameters for a compound distribution of two or more lognormal distributions. The method is described in the following section

In order to check the generality of fitting pore size distribution data to a compound lognormal distribution, data from different sources have been examined. Ordinary portland cement paste, blended cement paste, and mortar hydrated for various lengths of time have been examined. The results we have obtained demonstrate that it is reasonable to fit pore size distribution in cementitious materials to a compound lognormal distribution.

Pore size distributions in real materials must exhibit upper and lower bounds. This is the physical basis underlying the model developed by Diamond and Dolch (1972). The upper limit of pore size range used in their model varies with w/c ratio and hydration degree. For cement paste having w/c = 0.4 and cured for 1 day, the pore size range from about 8 nm to 700 nm. For cement paste having the same w/c ratio and cured for 320 days, the range is from about 10 nm to 64 nm. These are roughly the ranges for the second sub-distributions in the compound distribution. This suggests that one lognormal distribution is not adequate if both fine and coarse pores are included. However, limits on pore size must exist in real materials.

We have described a mixture of two lognormal distributions as the basis for describing the pore size distribution obtained by MIP. This was done to describe the distribution of fine pores which were not included in Diamond's model because of the limited intrusion pressures available. We found that a lognormal simulation works well for pore size distributions in both cement pastes and mortars. Thus, a compound distribution containing either two or three lognormal distributions may be used to fit the data. Mathematically this can be true. By fitting data to a compound distribution containing only two lognormal distributions, however, the second linear segment in the compound distribution containing three lognormal distributions is treated as a transition zone between the fine pores and coarse pores. This transition zone can contain more than half of the total pore volume. When a large transition zone occurs, it is difficult to estimate the lognormal parameters. A computer program to iterate the estimation process is required. Because there are five parameters to be manipulated, there may be many combinations of parameters which would produce the same or close quality of fit. As a consequence, unique solutions are often difficult to obtain. This difficulty is reduced by using a mixture of three lognormal distributions instead of two.

Physically, the first sub-distribution of the three may be regarded as describing the size distribution of coarse pores. Pore sizes may extend to include air voids. The third sub-distribution may be regarded as describing the size distribution of fine pores. Pore sizes may extend to gel pores. The middle one represents capillary pores. During initial hydration there is rapid division of large pores to produce smaller ones. This causes the diminution in log(x) of the largest pore with hydration during the first several days. This figure also shows the range of quantile values over which the first sub-distribution extends, effectively extending the first sub-distribution. These rapid changes are also reflected in changes in the weighting factors for the sub-distributions of large and medium pores as a transition occurs from a distribution in pore sizes that is based solely on a physical process to one that is increasingly based on a chemical process.

The three sub-distributions are to be viewed as affecting cementitious materials in quite different ways. The third (finest) sub-distribution usually contributes only about 5% to the total pore volume. Alternatively, in terms of pore numbers, approximately 99% are in this sub-distribution. The calculated median and mean values are approximately 10 nm. However, these data are censored; therefore, only pores over the range of sizes accessible by MIP are considered.

It is the pores that belong to the sub-distribution representing the finest porosity that are created by the hydration process. Because the majority of this porosity exists in the hydration products that are forming, it is these pores that control the kinetics of hydration. Alternatively, from the viewpoint of permeability-pore structure or fracture mechanics-pore structure relationships, the majority of porosity in this range is not important. With respect to permeability, it is well recognized that pores with diameters above a certain size contribute significantly to permeability. As mentioned, it has been observed that this critical pore diameter is near the inflection point on the cumulative pore size distribution curve. As described above, we have demonstrated that this inflection point can be calculated using the compound lognormal model.

Another characteristic that may be important to permeability is the mean square pore diameter, or the second moment of pore diameter distribution. If one combines the classic Darcy's law and Poiseuille's law, one can relate the permeability coefficient k to the mean square pore diameter. Although these assumptions are far from reality, we have observed that a characteristic pore dimension and a tortuosity factor are two indispensable variables in all sensible permeability models. In addition, the mean square pore diameter has been widely selected as the characteristic pore dimension. If the pore diameter distribution can be modeled by a compound lognormal distribution, the mean square pore diameter can be readily determined. Thus, the multiplicative property of the lognormal distribution, which allows the interconversion between volumes and surface areas, allows, in turn, MIP pore volume data to be expressed in appropriate terms. This attribute, coupled with the ability to deconvolute porosity data, suggests that a basis has been identified which may allow a more fundamental understanding of relationships between the behavior of cementitious materials and their pore structures.

Chloride Permeability

The resistance to chloride ion penetration and transport of concretes is an important feature for concrete durability especially in the highway environment. Part of the experimental work included in the current program was directed towards assessment of resistance of concrete to chloride permeability. The results are expected to be useful in connection with water permeability because the test is also rapid. The technique is similar to that described in AASHTO T-227 method for measuring the chloride permeability under the effect of electric field. Concrete and stripped mortar samples (4-in. diameter × 2-in. length) are taken from concrete mixtures cured for 28 days.

The chloride permeability was determined for concrete mixes as well as for the corresponding stripped mortar (mortar derived from concrete by sieving out coarse

aggregate). In addition the measurements were made on concretes and stripped mortars of the concrete formulations for field applications of the curing tables. Furthermore, the chloride permeabilities were determined for mineral admixtures containing concretes as well as their corresponding stripped mortars. Table 2, Chapter I, shows the results of the test (coulombs). The test results lead to the following conclusions:

1. Mortars gave higher chloride permeabilities compared to the corresponding concretes. In addition, at constant cement content, the charges (coulombs) passed increase with decreasing the volume of sand in the mortar. This might signify the fact that chloride permeability takes place primarily through the cement matrix.

2. Higher cement content gives rise to higher chloride permeability. This result holds equally well for both concrete and mortars.

3. At constant cement content, there is a direct correlation between the charge passed through concrete and the fine (sand) to coarse aggregate ratio.

4. Higher w/c ratio gives higher charge passage through both concretes and mortars.

5. Blending with mineral admixtures means reducing the charge passage to various degrees. That this is a true reflection of actual chloride ion penetration under conditions with no applied potential should be verified in further investigations.

Durability Model for Concrete

Taken together, the work carried out on maturity (curing technology), on modeling hydration and on relating porosity and permeability provides the framework for a model for concrete durability. The fundamental exothermal processes which are associated with hydration have been modeled. According to this, a constant activation energy can be applied to calculations involving Type I portland cement over a very broad range of temperature from 10° to 65°C (50° to 149°F). This is significant in that the results of adiabatic calorimetry indicate this is close to the maximum temperature reached when typical concrete ingredients are mixed at room temperature. Therefore, the relative amounts of the mineral phases in cement reacted at various temperatures can be calculated. Thus, this facet of the work can be integrated into a predictive tool for establishing maturity.

The outputs from the calculation of the relative rates of reaction as a function of temperature may be used as inputs to the calculation of the fractional degree of reaction. Attendant to the consumption of the anhydrous cement phases, hydration products form which confer the needed properties. This process has been considered in the context of a hydration model. Among the outputs from the hydration model are the paste strength, the chemical shrinkage and the porosity.

The hydration model can be applied to the prediction of the total porosity. Given assumptions regarding the manner in which this porosity is distributed, the variation in the pore structure with curing can be modeled. This has also been done.

The final step in the process has been to relate the permeability of concrete to the porosity present. This has been accomplished by establishing the appropriate probabilistic basis for modeling porosity and its variation with curing age. For pavements, permeability and durability are intimately connected. Permeability directly controls the ingress and aggressive species which cause concrete deterioration. Thus, in this work we have directly coupled the microstructural variables, which are considered on the microscopic level and their variation, with both time and temperature to bulk transport properties which directly influence concrete durability.

Permeability: Development and Testing of Methodology and Measurement

The durability of concrete is frequently associated with the transport of dissolved species. Such transport usually may be considered to be related to the permeability of the concrete. It is well recognized that transport occurs through a continuous network of pores, which exist in the cementitious matrix of concrete, as well as through the porosity which exists in the interfacial regions between paste and aggregate. It is the objective of this part of the study to describe work leading to rapid and accurate measurement of concrete permeability and the development of the theory to describe permeability of concrete.

Research Approach

The assumption at the onset of this research program was that the single physical property measurement which was best suited as an indicator of quality of concrete was permeability. Mortar samples prepared in this laboratory routinely achieve a permeability to water of <10 nanodarcys which is equivalent to values of 10^{-13} m/s for concrete reported by Hope and Malhotra (1984).

The measurement of very small permeabilities presents special problems for which standard measuring techniques are generally impractical or very difficult to implement in the laboratory and therefore tend to be unreliable (Roy, 1989). If the permeability is very low, long periods of time are required to establish the steady state flow conditions which are for the most part impractical. To overcome these limitations, Brace et al. (1968) introduced a transient flow method to measure permeability of Westerly granite to water. In this experimental design, cylindrical specimens of the granite were contained in a restrained flexible sleeve and connected to an upstream and downstream fluid reservoir. At the start of the experiment, both reservoirs and the specimen were maintained at the same constant pressure. Fluid flow was initiated through the specimen by rapidly establishing a pressure gradient between the upstream and downstream reservoirs. As the pressure began to decay through the sample, it was monitored and from this pressure decay, the permeability was calculated.

The mathematical model presented by Brace et al. (1968) assumed that there is no compressive storage in the rock sample. For the rock type used in these initial experiments, granite, this limiting assumption was indeed justifiable based upon its very low porosity.

However as pointed out by Hsieh et al. (1981), this assumption is invalid for more porous rock types such as shales and argillites and as in the present case, concretes. Hsieh et al. (1981) addressed this question of compressible storage and proceeded to develop the mathematics to calculate permeability by the transient method by independently measuring the porosity and compressibility of the test specimen.

Mathematical Model

In the original report by Brace et al. (1968) the model presented was described as a one-dimensional transient flow equation, the solution of which takes the form of an infinite series. Hsieh et al. (1981) presented an alternative solution to the original Brace mathematical model which relied upon the Laplace transform method. They introduced a dimensionless parameter to describe the upstream and downstream hydraulic heads and two additional dimensionless parameters to describe the compressive storage in terms of the sample to the upstream reservoir and the ratio of the compressive storage in the downstream reservoir to the compressive storage in the upstream reservoir (Roy, Scheetz, Pommersheim et al. 1993).

Based upon these modeling efforts, a detailed review of the mathematics behind the transient method from which the following working equations were drawn. Fig. 11 defines the terminology applied to the analysis of the data from the experiment.

The solution that was followed is:

$$\ln((P_u - P_L)/(P_1 - P_0)) = -(2/v)t'.$$

Plotting $\ln((P_u - P_L)/(P_1 - P_0)$ vs. time yields a slope of alpha which in turn is equal to:

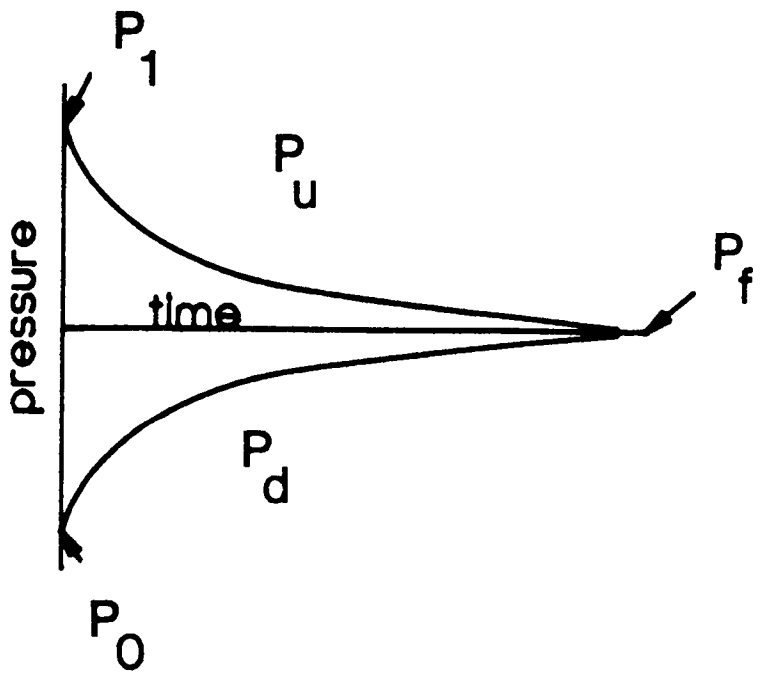
$$\alpha = ((V_p/V_d) + (V_p/V_u))/T$$

$$T = Btul^2/k$$

where:

V_p = volume pores (A x l x e)
V_u = upstream volume of system
V_d = downstream volume of system
T = characteristic time
B = compressibility of fluid
t = time
l = sample length
u = viscosity of fluid
k = permeability
e = porosity
A = cross-sectional area.

Table 7 consists of two parts, typical data for the various parameters in this calculation and a units analysis.



P_u = up-stream pressure
P_d = down-stream pressure
P_f = final equilibrated pressure [~(P_1 + P_0)/2]
P_1 = initial up-stream pressure
P_0 = initial down-stream pressure

Figure 11. Schematic representation of upstream and downstream pressure response as a function of time during the experiment.

Table 7. Values for the parameters in transient permeability calculation.

B = compressibility of water (0.42×10^{-10} $cm^2/gcm/s^2$)
e = porosity (fractional)
V_u = V_d = 1
t' = t/T
T = $Beul^2/k$ (s)
u = viscosity of water (0.01 g/cm s)
l = sample length (cm)
k = permeability (cm^2) {k x (cm^2) × 1.013×10^8 = darcy}

UNITS TEST

$$T = Beul^2/k$$

$$s = [cm^2/(g\ cm/s^2)] \times [g/cm\ s] \times [cm^2/cm^2]$$

Equipment Design

The permeability equipment including the cell was designed and constructed in the Materials Research Laboratory. Fig. 12 represents a schematic drawing of the arrangement of the overall system showing the location of valves, the upstream and downstream reservoirs and the permeability cell. In this design, the pressure pulse is applied to the system by rapidly reducing the pressure from the downstream reservoir. Recovery time from this perturbation is typically on the order of seconds to minutes for samples with micro- and nanodarcy permeabilities and substantially longer for samples with lower flows.

Fig. 13 is a exploded diagram of the cell showing the physical arrangement of the parts. The current cell uses a "Tygon" tube for the sleeving material. This material has been found to be superior to rubber sleeving in that it does not readily puncture under the influence of confining pressure in the presence of surface imperfections in the sample. Three cell types are available which can accommodate samples of 1 in., 2 in. and 3 in. in diameter and lengths varying up to 6 in.

The pressure response of the experiment is monitored electrically with Schaevitz piezoelectric transducers designed to operate over the pressure range of 0 to 1000 psi. The electromotive force (EMF) output of the transducers is monitored on a computer into which a METRABYTE DAS-8 data acquisition and control board was installed.

The computer control of the data acquisition is achieved with a compiled DOS algorithm. The program reads the analog inputs to a file for storage and to which can be appended a

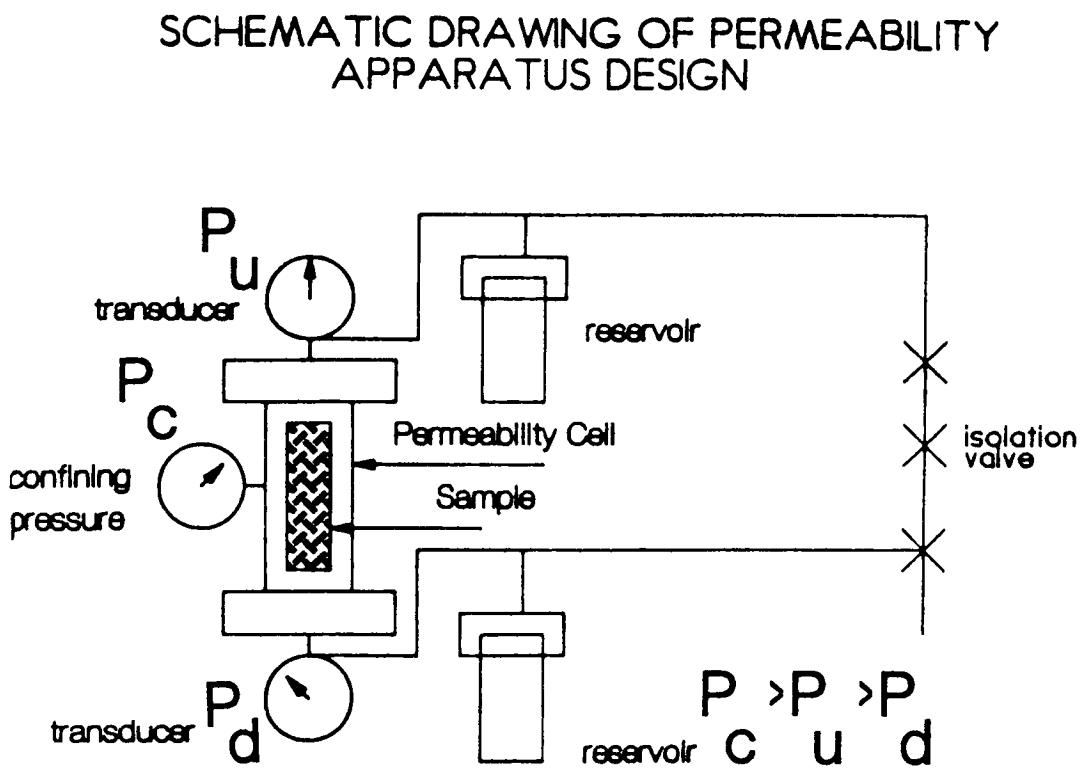


Figure 12. Schematic drawing of permeability apparatus

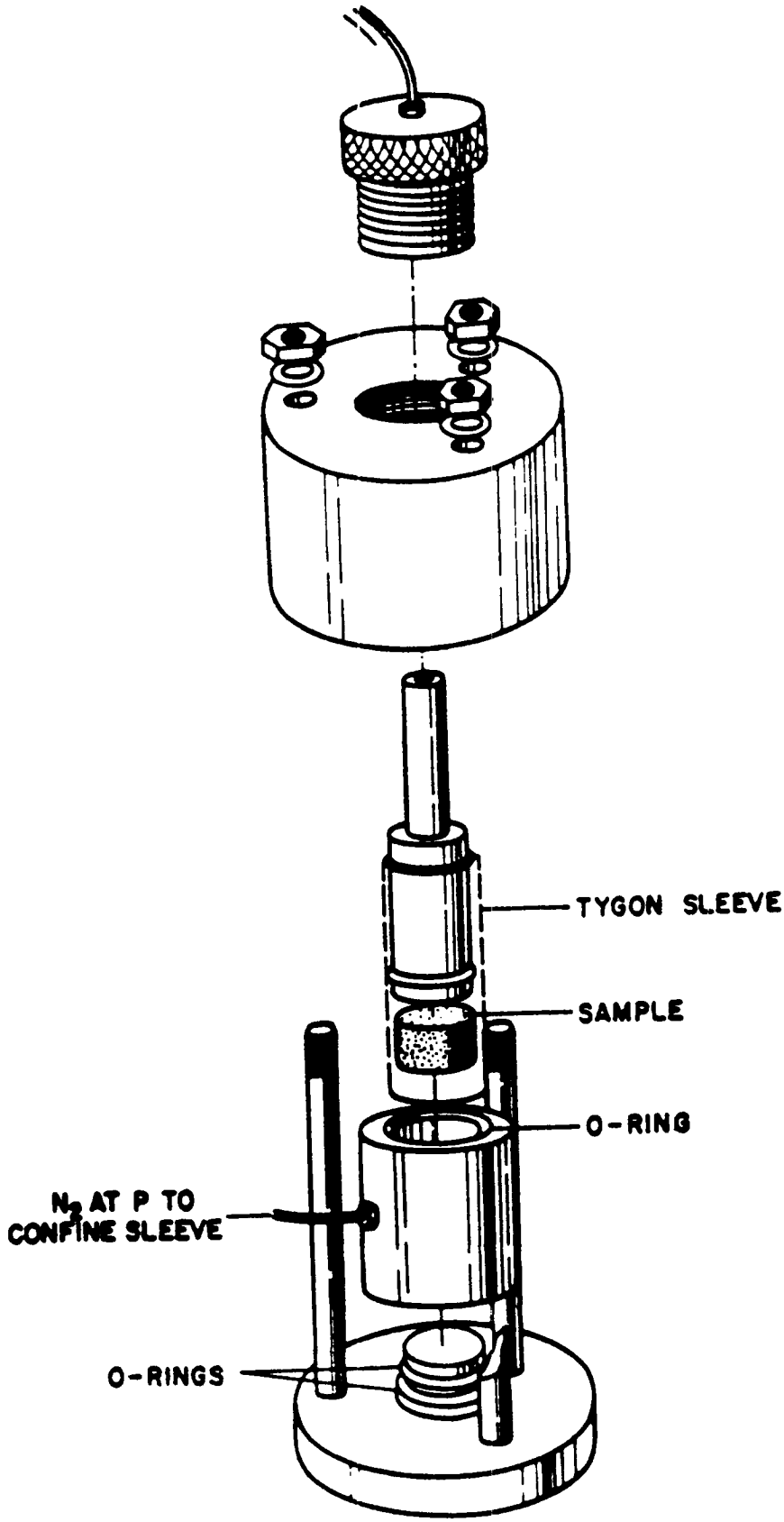


Figure 13. Exploded diagram of permeability cell.

descriptive text file for archiving purposes. Data acquisition time is selected by the operator. The output file of this program is stored separately on a 5.25 in. floppy disc. Further processing is accomplished by reading this raw data into a routine that transforms the raw data into a psi versus time file which can be read into a Lotus 1-2-3 spreadsheet for final data processing.

Sample Handling

For this apparatus to be useful, all specimens to be measured must be fully water saturated and pressure equilibrated before the experiment is initiated. Water saturation for samples with permeabilities in the microdarcy and nanodarcy range is achieved by vacuum impregnation. The sample is placed in the vacuum of a roughing pump for 24 hours before it is immersed in deionized water which was introduced into the vacuum chamber. Pressure equilibration of specimens with lower permeabilities becomes much more difficult. The specimen is then placed in the sleeving material and the cell assembled.

Measurements on several samples of a dense quartzite have resulted in a permeabilities ranging from 3×10^{-7} to 9×10^{-7} darcys. This value is consistent with previous permeability measurements obtained with two different systems: water flow-through and gas permeability, 1.7×10^{-7} and 3.6×10^{-7} darcys, respectively. These data strongly suggest that the apparatus is mechanically functional and that the mathematical interpretation for low porosity specimens is working.

Additional samples of both pastes and mortars have been successfully measured. In conjunction with the apparatus construction, the detailed mathematical relationships building upon the original work of Brace et al. (1968), Lin (1977) and Hsieh et al. (1981) were also developed.

V.
Revisions to Test Methods

From the onset of this project, the researchers have identified existing standards and specifications which might be affected by this investigation. This list is presented in Table 8. As research has been completed, each conclusion has been evaluated with respect to this list of existing standards. In addition, any work that addressed a procedure or topic not currently covered in existing specifications was analyzed and evaluated for possible introduction as a new specification.

To aid in the evaluation process, a set of matrices relating research topic areas to specific test methods or recommended practices was constructed for ASTM, ACI, AASHTO, and PADOT (Roy, Cady et al. 1993).

Criteria for Evaluation and Integration of Research into Specifications

Criteria have been established for detailed, analytic review and evaluation of the research's effect on existing standards and specifications, as well as for recommendations of new standards and specifications. These criteria, can be broken into two groups: those dealing with exact experimental procedure requirements, and those dealing with significance and implementation of research findings.

The primary criterion for evaluating a test method or specification involves the experimental precision and bias of a model's output or the results of experimentation. Where possible, work is evaluated as specified in ASTM C670-88 ("Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials"), ASTM C802-87 ("Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials"), and ASTM E177-86 ("Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods").

Test procedures and model results which satisfy the requirements of the specifications listed above are considered to have passed the precision and bias accountability criterion.

A second criterion involves the relative significance of the findings. While no definitive explanation of "significance" in this context is available, we shall base our estimation of significance on the research team's experience with concrete applications. Thus, a research

Table 8. Candidate test methods, standard specifications, and recommended practices for evaluation.

Type	Description or Title	Method or Spec. No. ASTM	ACI	AASHTO	Typical State DOT (PA)
Test Method	Slump of fresh concrete	C143		T-119	PTM 600
" "	Flexural strength of concrete	C78		T-97	PTM 603
" "	Compressive strength	C39		T-22	PTM 604
" "	Unit weight yield air content of fresh cement	C138		T-121	PTM 613
" "	Air content of fresh concrete	C231		T-152	PTM 615
" "	Time of set	C403		T-179	PTM 632
" "	Compressive strength of mortar	C109		T-106	
" "	Autoclave expansion of cement	C151		T-107	
" "	Normal consistency of cement	C187		T-129	
" "	Fineness of portland cement	C430		1-192	
" "	Bleeding of concrete	C232		T-158	
" "	Splitting tensile strength	C496		T-198	
" "	Chloride permeability			T-277	
" "	Making/curing field test specimens	C31		T-23	
" "	Temperature of fresh concrete	C1064			
" "	Penetration resistance	C803			
" "	Pullout strength		C900		
" "	Rebound number		C805		
" "	Making/curing lab test specimens	C192		T-126	
" "	Project concrete strengths	C918			
" "	Accelerated curing/testing	C684			
Std. Spec.	Physical and chemical requirements for portland cement	C150		M-85	SECT.701
" "	Physical and chemical requirements for blended cement	C395		M-240	"
" "	Ready mixed concrete	C94		M-157	SECT. 704.1
" "	Volumetric batching and continuous mixing	C685		M-241	
" "	Aggregate for concrete	C33			
" "	Aggregate for road/bridge construction		D448		
" "	Concrete admixtures (except AEA)	C494	212.1	M-241	SECT.711.3
" "	Pozzolanic materials	C618			SECT.724.2
" "	Ground blast furnace slag	C989			
Rec. Pract.	Petrographic examination	C856			
" "	Maturity Method for concrete	C1074			
" "	Air-void analysis	C457			
" "	Durable concrete		201.2		
" "	Selecting proportions for normal weight concrete			211.1	
" "	Using admixtures		212.2		
" "	Measuring, mixing, transporting and placing concrete		304		
" "	Hot weather concreting		305		

Table 8. Candidate test methods, standard specifications, and recommended practices for evaluation. (Continued)

Type		Description or Title	Method or Spec. No. ASTM	ACI	AASHTO	Typical State DOT (PA)
"	"	Cold weather concreting		306		
"	"	Curing concrete			308	
"	"	Consolidation of concrete		309		
"	"	Construction of concrete pavements/bases		316		
"	"	Construction of bridge decks		345		

finding which affects a standard or specification which in turn affects many other specifications (e.g. ASTM C33 - "Standard Specification for Concrete Aggregates"), or is deemed critical to at least one important aspect of concrete use and specification (e.g. ACI 211.1 - "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete"), would garner a rating of "high significance."

Similarly, findings considered of lesser use or applicability would be rated "low significance" or "medium significance." Although these ratings are somewhat qualitative, they do allow for a more rigorous analysis and evaluation of findings than would be possible in their absence.

Finally, the implementation of the research findings to specifications and standard practices is evaluated. Certain areas of the research, for example the work performed on activation energy determination, may very easily be transferred to existing standards (in this case, ASTM C1074 "Standard Practice for Estimated Concrete Strength by the Maturity Method"). Such work could be deemed "easily implemented." Other findings, although possibly significant in depth and applicability, may for some reason not be readily integrated in standard specifications and practices. These findings might be termed "difficult to implement."

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Notes

Appendix A
Materials Specifications and Suppliers

A1-a. MATERIALS FOR LABORATORY MIXES:

Cement (1), I-18, ASTM Type I Cement, Keystone Cement Co., Bath, PA

Tricalcium silicate	49.2%
Dicalcium silicate	18.3%
Tricalcium aluminate	12.3%
Tetracalcium aluminoferrite	7.5%
Total alkali (as Na_2O	0.40%
Blaine specific surface, m^2/Kg	200

Cement (2), I-23 and I-25, ASTM Type I Cement, Keystone Cement., Bath, PA
Composition is the same as I-18 above.

Coarse Aggregate (1), #57, #67 and #8 Crushed Limestones, Imbt Co., Oak Hall, PA
(2), #57, #67 and #8 Siliceous Gravel, Genstar Stone Products, Towson, MD

Fine Aggregate (1), ASTM C33 Silica Sand, Lycoming Silica Sand Co., Montoursville, PA (through Centre Concrete, State College, PA)

Fine Aggregate (2), #1, #2 and #3 Siliceous Sand, GenStar Stone Products, Towson, MD

Mineral Admixtures:

Slag, Blue Circle Industries (Atlantic)

Fly Ash: (a) Class F fly ash, B-92, Pennsylvania Power and Light Co., Montoursville, PA;
(b) Class C fly ash, G-07, Rockport Power Plant (through The American Fly Ash Co., IL)

Silica Fume, Elkem Chemicals, Pittsburgh, PA

Chemical Additives

Superplasticizer, Mighty 150, Boremco Specialty Chemicals, MA

Superplasticizer and Retarder, RD-1, Boremco Specialty Chemicals, MA

Air Entraining Agents: (1) MBVR, Master Builders, Cleveland, OH;
MicroAir, Master Builders, Cleveland, OH

Water, municipal water, State College Borough, PA.

A1-b. MATERIALS FOR CONCRETE FORMULATIONS FOR FIELD APPLICATIONS OF CURING TABLES

I. Concrete Pavement Slab Replacement on Rt. 322 (Seven Mountains), Centre County, PA
Contractor: Glenn O. Hawbaker, Inc.

Concrete Supplier: Centre Concrete Co., State College, PA.

Materials Specifications and Suppliers:

Cement, I-26 ASTM Type I Cement, Lone Star Industries, Nazareth, PA

Tricalcium silicate	52.4%
Dicalcium silicate	17.5%
Tricalcium aluminate	11.8%
Tetracalcium aluminoferrite	7.7%
Total alkali (as Na_2O)	0.44%
Blaine specific surface, m^2/Kg	194

Coarse Aggregate, #57 Crushed Limestone, Central Valley Aggregates, Pleasant Gap, PA

Fine Aggregate, ASTM C33 Silica Sand, Lycoming Sand Co., Montoursville, PA

Chemical Additives

MBVR, Air entraining agent, Vinsol Resin, Master Builders, Cleveland, OH

Pozzolith 122N, Water reducer, Master Builders, Cleveland, OH

Pozzolith 133HE, Accelerator, Master Builders, Cleveland, OH

Water, municipal water, State College Borough, PA.

II. Concrete Pavement Batching on Interstate I-80, Clinton County, PA

Contractor: Eastern Industries, Inc.

Concrete Supplier: Central Builders Supply Co., Sunbury-Watsontown, PA

Materials Specifications and Suppliers:

Cement ,I-27 ASTM Type I Cement, Keystone Cement Co., Bath, PA

Tricalcium silicate	49.1%
Dicalcium silicate	18.3%
Tricalcium aluminate	12.3%
Tetracalcium aluminoferrite	7.5%
Total alkali (as Na_2O)	0.43%
Blaine specific surface, m^2/Kg	203

Coarse Aggregate ,#57 Crushed Limestone, Faylor-Middlecreek, Inc., Winfield, PA

Fine Aggregate, ASTM C33 Silica Sand, Central Builders Supply, Co., Point Township, PA

Chemical Additives

MicroAir, Air entraining agent, Master Builders, Cleveland, OH

Pozzolith 100XR, Retarder, Master Builders, Cleveland, OH

Water, well water, American Water Co., PA

III. Bridge Pier (Faunce Bridge), Clearfield County, PA

Contractor: Glenn O. Hawbaker, Inc.

Concrete Supplier: E.M. Brown, Inc., Clearfield, PA

Materials Specifications and Suppliers:

Cement, ASTM Type I Cement, Armstrong Cement Co., Cabot, PA

Tricalcium silicate	60.1%
Dicalcium silicate	11.4%
Tricalcium aluminate	7.9%
Tetracalcium aluminoferrite	13.1%
Total alkali (as Na_2O)	0.43%
Blaine specific surface, m^2/Kg	387

Coarse Aggregate, #57 Crushed Limestone, New Enterprise Stone & Lime Co., Tyrone, PA

Fine Aggregate, ASTM C33 Silica Sand, Lycoming Silica Sand, Fairfield Township, PA

Chemical Additives

MBVR, Air entraining agent, Vinsol Resin, Master Builders, Cleveland, OH

Pozzolith 122N, Water reducer, Master Builders, Cleveland, OH

Water, municipal water, Clearfield County, PA.

IV. Concrete Pavement Slab Replacement on Rt. 15 (North of Williamsport), Lycoming County, PA

Contractor: General Crush, Williamsport, PA

Concrete Supplier: Centre Concrete (Plant 5), Montoursville, PA

Materials Specifications and Suppliers:

Cement, ASTM Type I, Lone Star Industries, Nazareth, PA

Tricalcium silicate	52.4%
Dicalcium silicate	17.5%
Tricalcium aluminate	11.8%
Tetracalcium aluminoferrite	7.7%

Total alkali (as Na_2O) 0.44%

Blaine specific surface, m^2/Kg 194

Coarse Aggregate, #57 Crushed Limestone, Lycoming Silica Sand Co., Salona, PA

Fine Aggregate, ASTM C33 Silica Sand, Lycoming Silica Sand Co., Montoursville, PA

Chemical Additives

MBVR, Air entraining agent, Vinsol Resin, Master Builders, Cleveland, OH

Pozzolith 122N, Water reducer, Master Builders, Cleveland, OH

Water, private well, Lycoming, PA

Appendix B
Aggregate Gradations

A2a AGGREGATE GRADATIONS FOR LABORATORY BATCHES

Table A-2.1
Sands gradation.

	Sieve No.	Aperture (in)	Lycoming
1	1.5 in	1.5	
2	1 in	1	
3	3/4 in	.75	
4	1/2 in	.5	
5	3/8 in	.375	100.00
6	# 4	.187	97.40
7	# 8	.0937	83.00
8	# 16	.0469	71.70
9	# 30	.0234	56.20
10	# 50	.0117	20.70
11	# 100	.0059	3.90
12			
13	Fin. Modulus		2.67

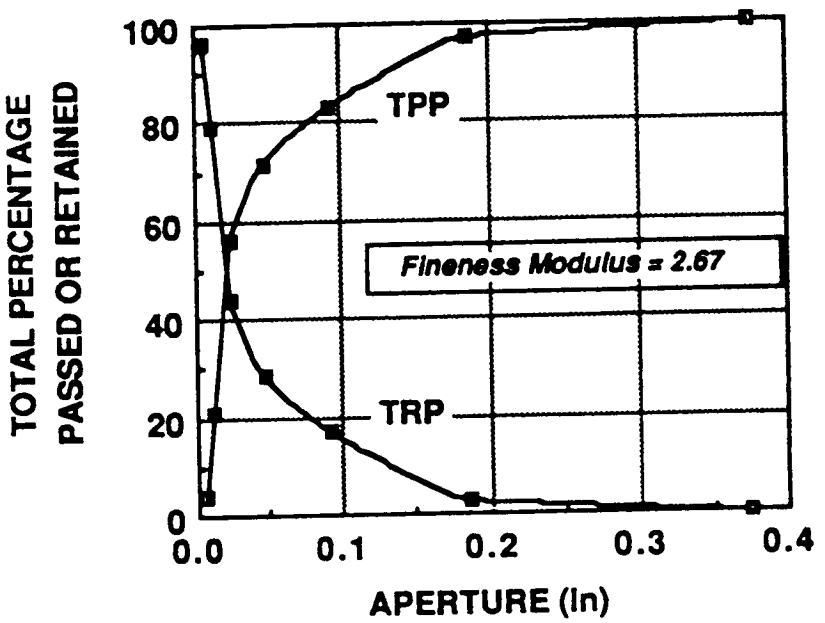

Figure A2-1. Lycoming sand gradation curve.

Table A-2.2
Towson sands gradations.

	Sieve No.	Aperture (in)	#1	#2	#3
1	1.5 in	1.5			
2	1 in	1			
3	3/4 in	.75			
4	1/2 in	.5			
5	3/8 in.	.375	100.00	100	100.00
6	# 4	.187	93.83	99.82	98.68
7	# 8	.0937	69.16	95.50	97.16
8	# 16	.0469	47.26	82.88	88.98
9	# 30	.0234	26.00	62.32	75.23
10	# 50	.0117	8.08	28.68	58.13
11	#100	.0059	1.85	3.09	15.84
12					
13	Fin. Modulus		3.54	2.28	1.66

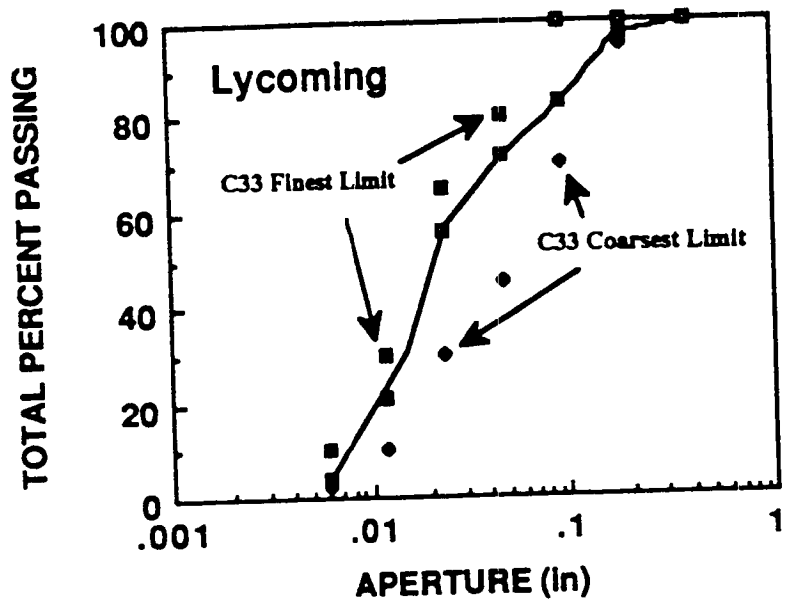

Figure A2-2. Lycoming sand gradation with respect to C33 specifications.

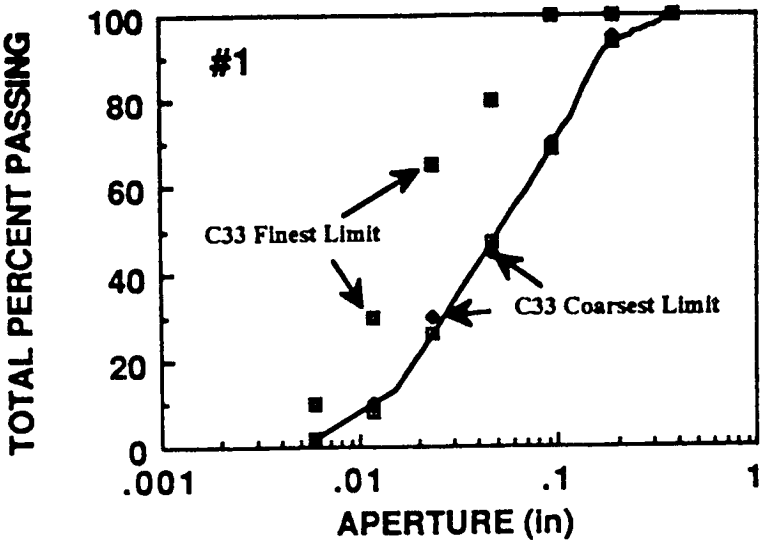

Figure A2-3. #1 sand gradation with respect to C33 specifications.

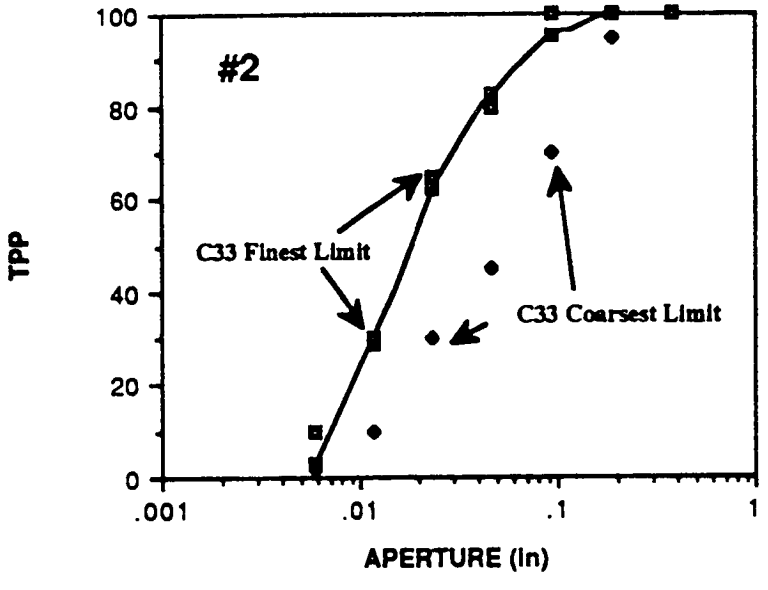

Figure A2-4. #2 sand gradation with respect to C33 specifications.

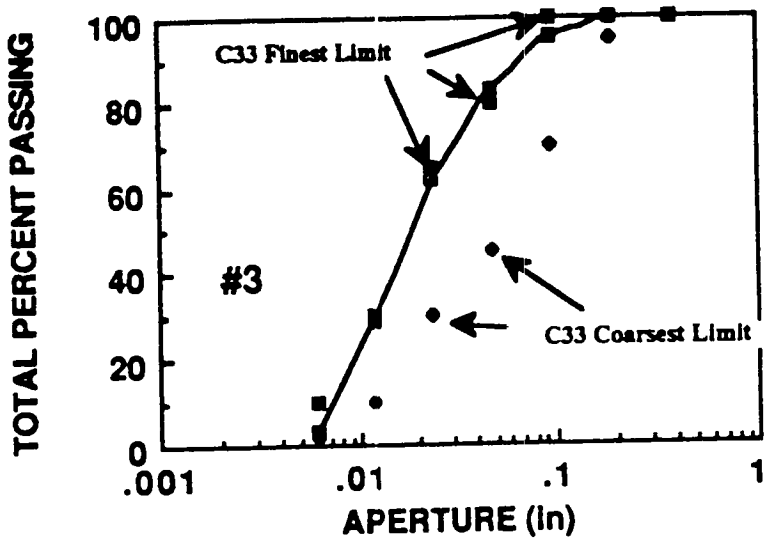

Figure A2-5. #3 sand gradation with respect to C33 specifications.

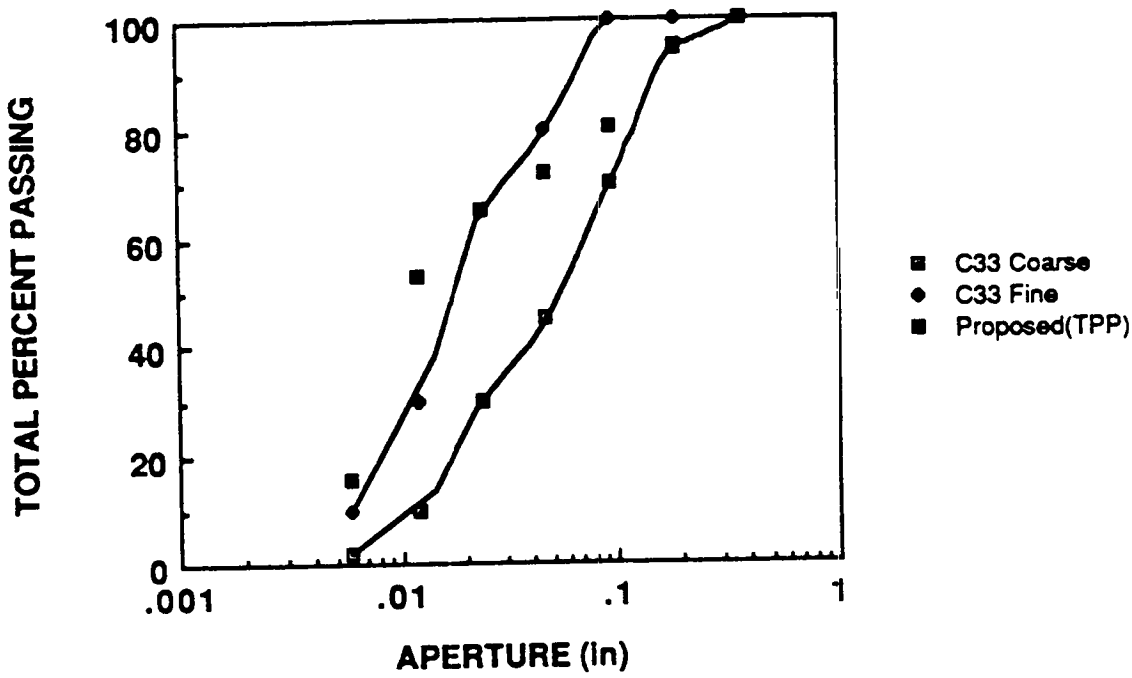

Figure A2-6. Blended sand gradation with respect to C33 specifications.

Table A2-3
#57 limestone gradation.

	Sieve No.	Aperture (in)	Imbt
1	1.5 in	1.5	100.00
2	1 in	1	99.67
3	3/4 in	.75	
4	1/2 in	.5	45.32
5	3/8 in	.375	
6	# 4	.187	1.27
7	# 8	.0937	0.60
8	# 16	.0469	
9	# 30	.0234	
10	# 50	.0117	
11	# 100	.0059	
12			
13	Fin. Modulus		7.51

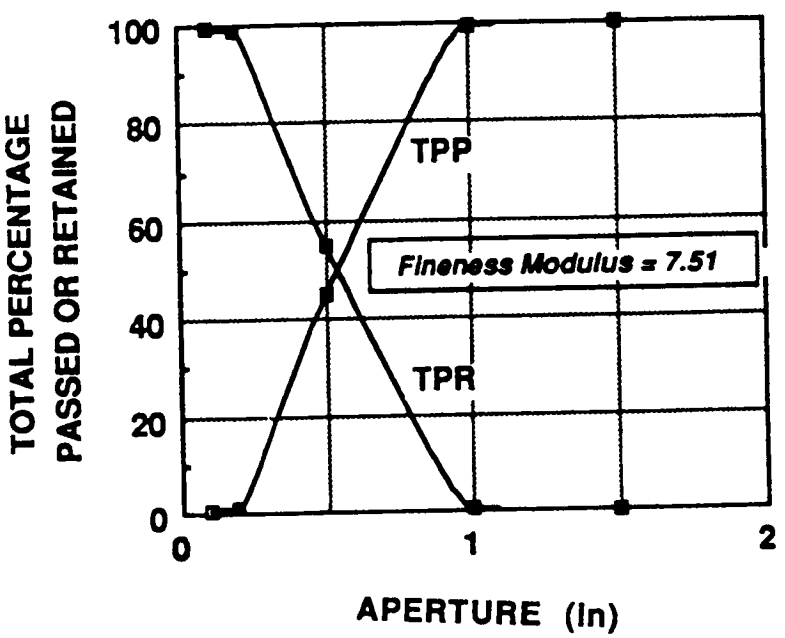

Figure A2-7. #57 limestone gradation curve.

Table A2-4
#67 and #8 limestone gradation.

	Sieve No.	Aperture (in)	#67 limestone	#8 limestone
1	1.5 in	1.5		
2	1 in	1	100	
3	3/4 in	75	99.44	
4	1/2 in	.5		100
5	3/8 in	.375	29.44	95.24
6	# 4	.187	.54	7.3
7	# 8	.0937	.26	1.5
8	# 16	.0469		.86
9	# 30	.0234		
10	# 50	.0117		
11	# 100	.0059		
12				
13	Fin. Modulus		7.20	5.95

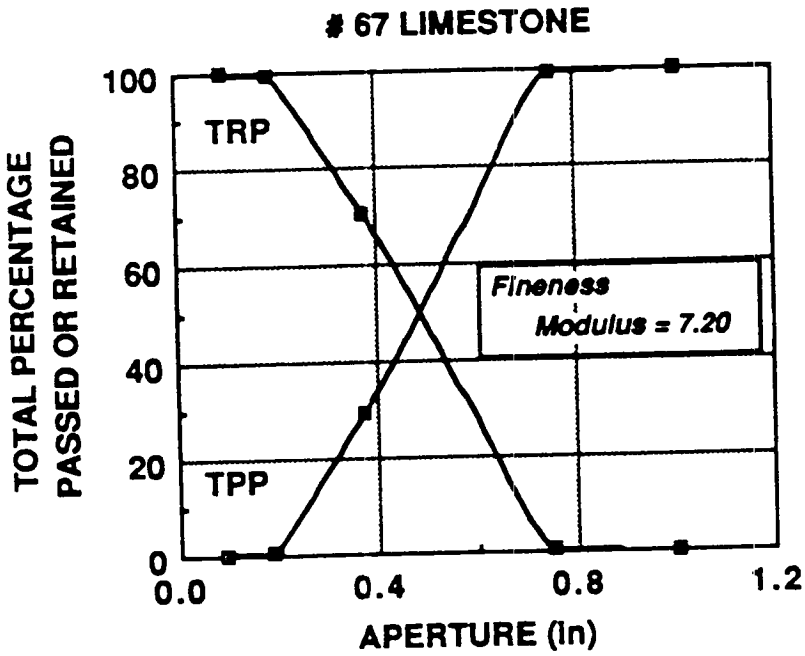

Figure A2-8. #67 limestone gradation curve.

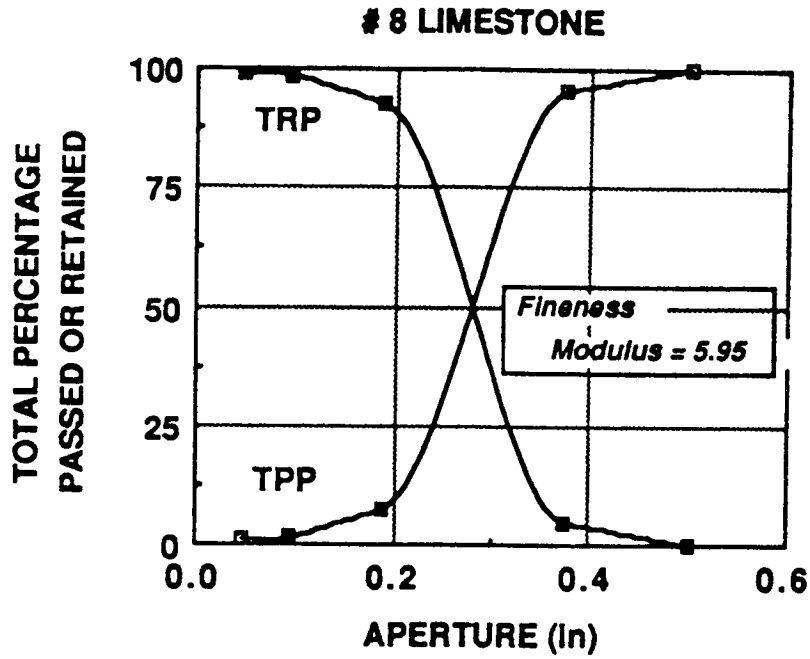

Figure A2-9. #8 limestone gradation curve.

Table A2-5
Gravel gradations.

	Sieve No.	Aperture (in)	#57 gravel	#67 gravel	#8 gravel
1	1.5 in	1.5	100.00		
2	1 in	1	100.00	100	
3	3/4 in	.75		96.31	
4	1/2 in	.5	32.08		100
5	3/8 in.	.375		31.68	92.4
6	# 4	.187	1.79	10.58	4.05
7	# 8	.0937	1.35	6.04	1.06
8	# 16	.0469			
9	# 30	.0234			
10	# 50	.0117			
11	#100	.0059			
12					
13	Fin. Modulus		7.48	7.33	5.99

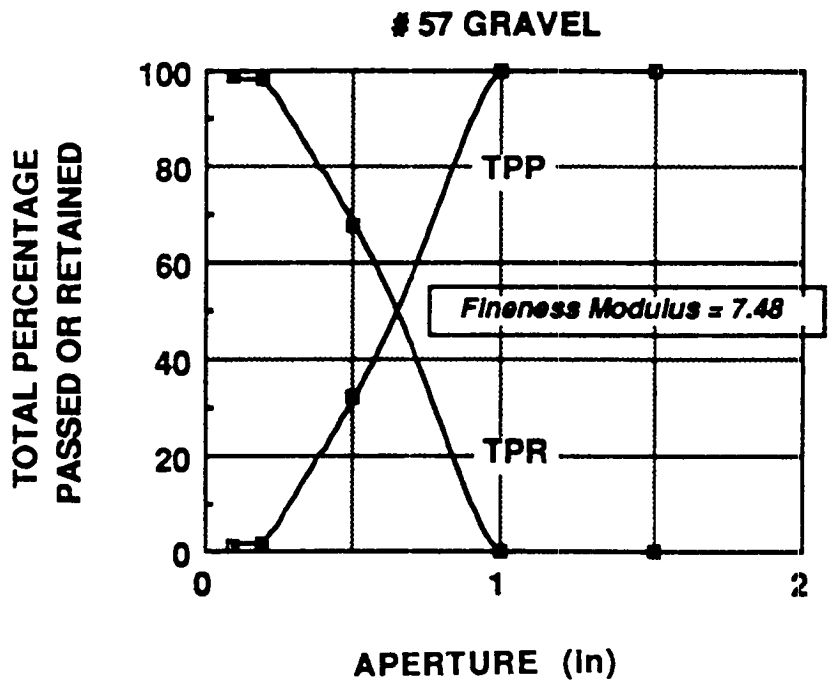

Figure A2-10. #57 gravel gradation curve.

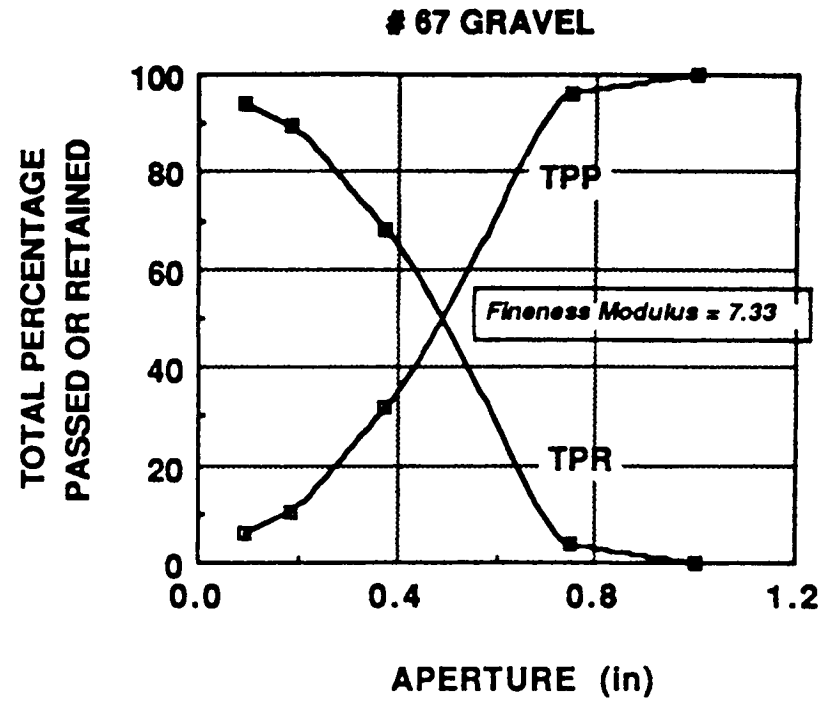

Figure A2-11. #67 gravel gradation curve.

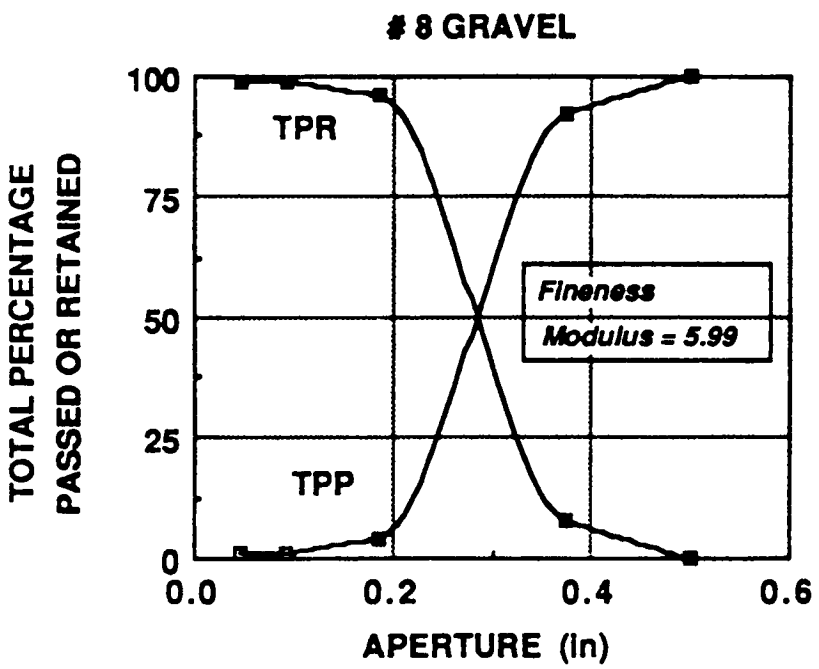

Figure A2-12. #8 gravel gradation curve.

A-2b AGGREGATE GRADATIONS FOR CONCRETE FORMULATIONS FOR FIELD APPLICATIONS OF THE CURING TABLES

Table A2-6
Sand gradations.

	Sieve No.	Aperture (in)	Rt. 322	I-80	Faunce Bridge	Rt. 15
1	1.5 in	1.5				
2	1 in	1				
3	3/4 in	.75				
4	1/2 in	.5				
5	3/8 in.	.375	100.00	100.00	100.00	100.00
6	# 4	.187	96.20	96.21	94.87	95.83
7	# 8	.0937	81.35	74.56	71.07	77.42
8	# 16	.0469	72.12	61.23	58.56	65.28
9	# 30	.0234	55.45	48.96	43.84	50.92
10	# 50	.0117	22.19	19.02	12.75	17.87
11	#100	.0059	4.07	4.01	2.49	3.08
12						
13	Fin. Modulus		2.69	2.96	3.16	2.90

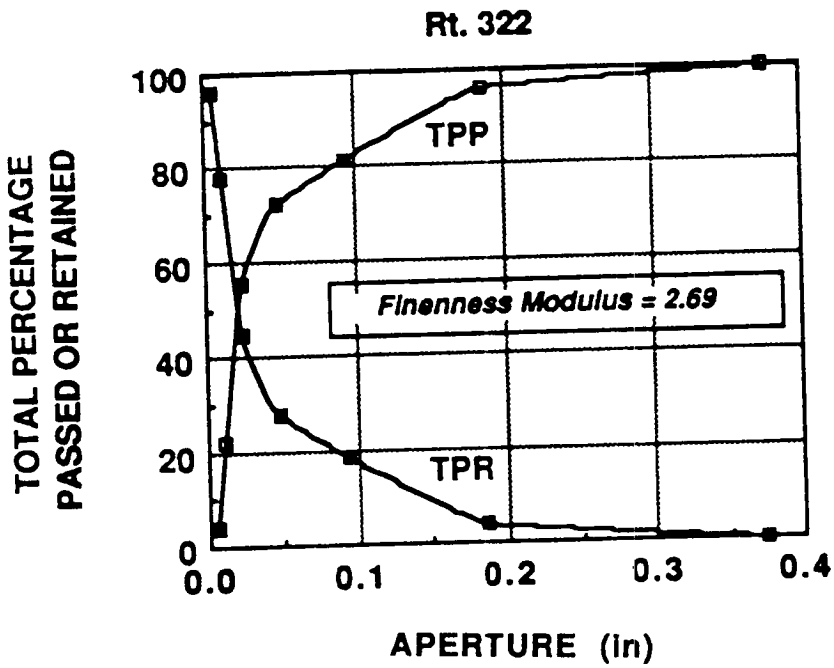

Figure A2-13. Rt. 322 sand gradation curve.

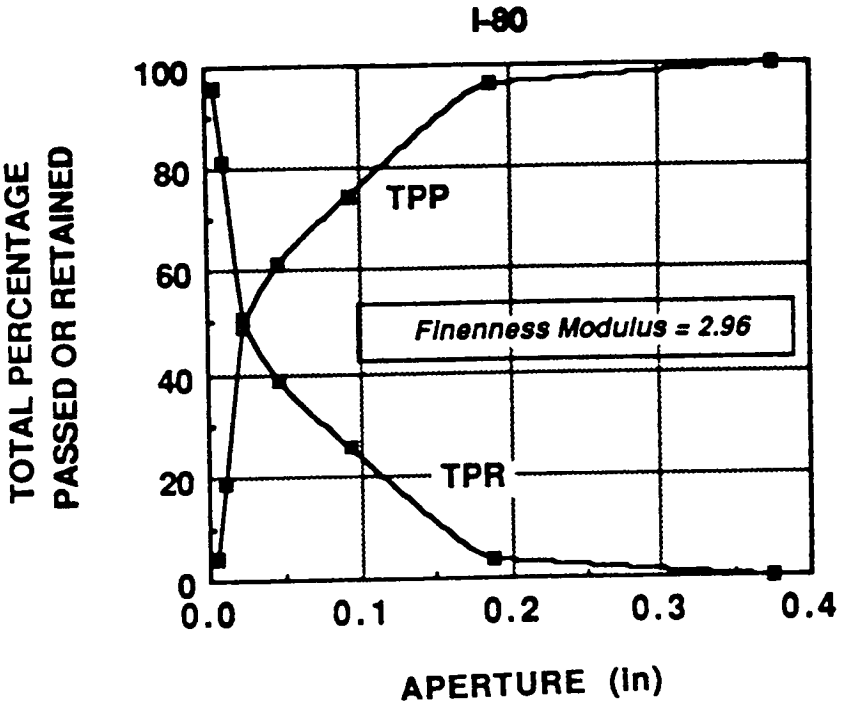

Figure A2-14. I-80 sand gradation curve.

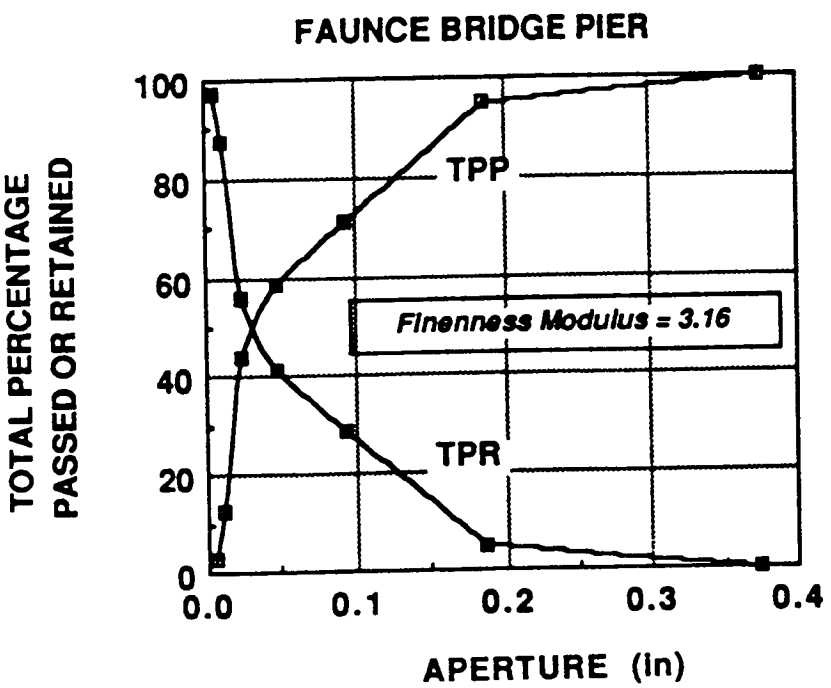

Figure A2-15. Faunce Bridge pier sand gradation curve.

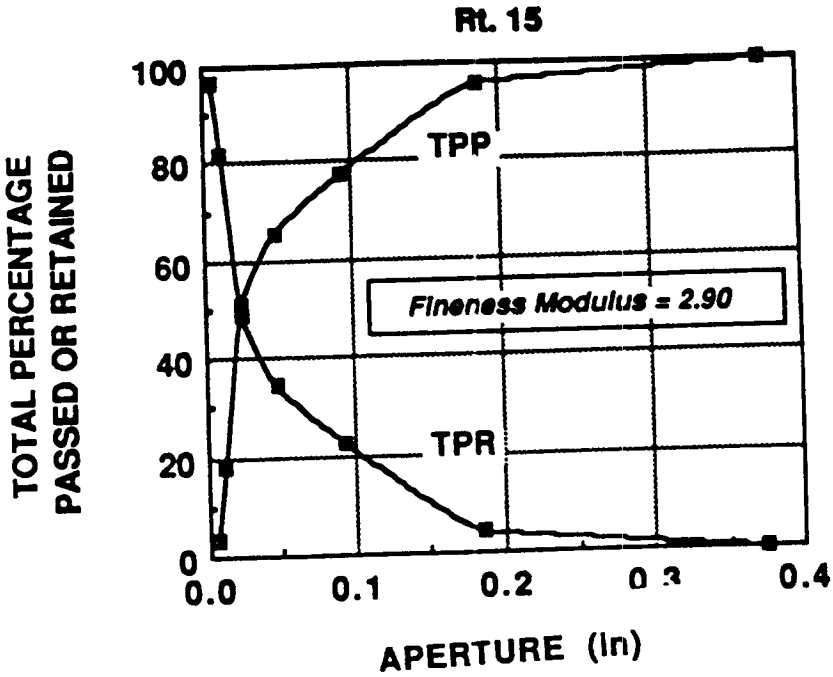

Figure A2-16. Rt. 15 sand gradation curve.

Table A2-7
#57 limestone gradations.

	Sieve No.	Aperture (in)	Rt. 322	I-80	Faunce Bridge	Rt. 15
1	1.5 in	1.5	100.00	100.00	100.00	100.00
2	1 in	1	99.52	99.62	99.70	99.06
3	3/4 in	.75				
4	1/2 in	.5	32.21	30.23	27.15	28.98
5	3/8 in.	.375				
6	# 4	.187	1.30	1.56	0.81	2.32
7	# 8	.0937	0.56	0.48	0.37	1.00
8	# 16	.0469				
9	# 30	.0234				
10	# 50	.0117				
11	#100	.0059				
12						
13	Fin. Modulus		7.49	7.50	7.52	7.54

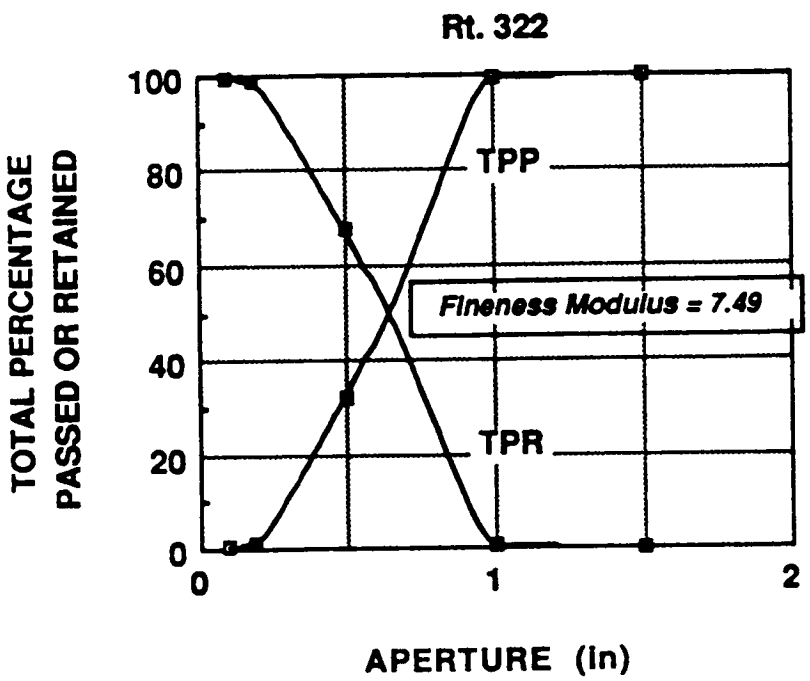

Figure A2-17. Rt. 322 #57 limestone gradation curve.

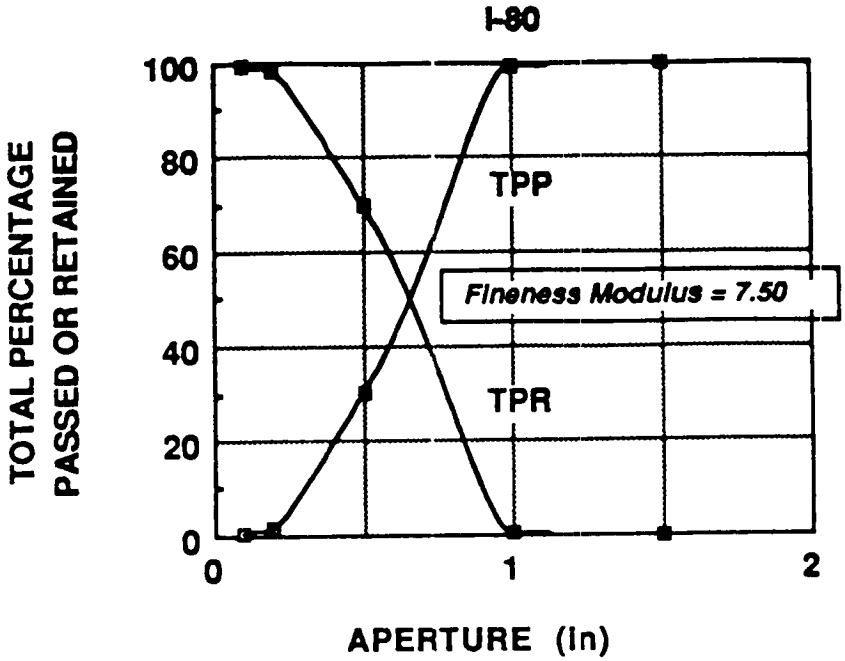

Figure A2-18. I-80 #57 limestone gradation curve.

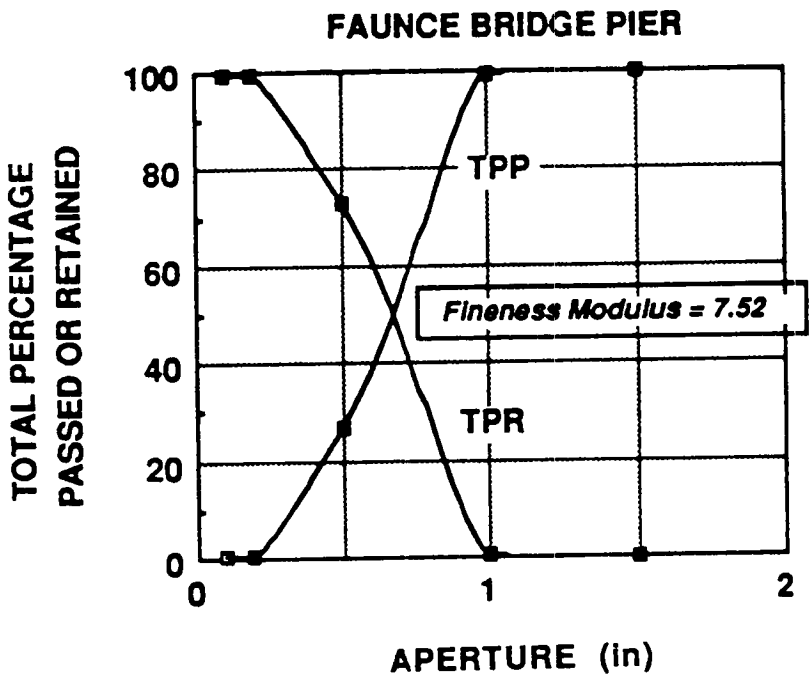

Figure A2-19. Faunce Bridge pier #57 limestone gradation curve.

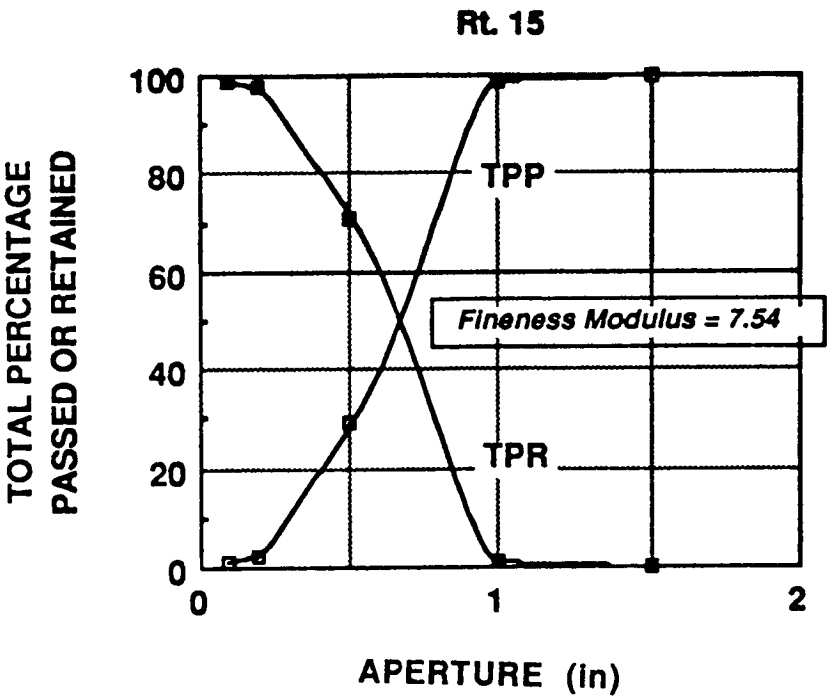

Figure A2-20. Rt. 15 #57 limestone gradation curve.

Appendix C
Concrete Formulations and Data Sheets

Mixing Data (SHRP)

Mix Identification No.: ____ **S 89 - 1** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 3-28-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	32.20 / 16.73
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	51.77 / 26.89
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	93.40 / 48.52
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	15.13 / 7.86

Mixing Data: Mixing Date:_ 3-28-89_Mixer Used: Eirich Pan Mixing Time:_9:30 am__
Temp.: 23 ± 1.5°C W/C= 0.47

Pre-set Properties:

		Method
Slump	4.25 in.	____ ASTM C 143___
Density	148.35 lb/cu ft	____ ASTM C 138___
Air Content	1.5 %	____ ASTM C 231___
Setting Time: Initial:	5.50 hrs.	____ ASTM C 403___
Final :	8.00 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-1-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ____ ASTM C 39 ____
B. S 89-1-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 89-1-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-1-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 89-1-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate __

Testing Dates:(1d)Mar. 29, (3d)Mar. 31, (7d)April 4, (14d)April 11, (28d)April 25-89

28-Day Compressive Strength: 46.03 MPa ($\sigma_{6\ Samples}$ = 1.54 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 2 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 4 - 4 -89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	36.20 / 18.42
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	37.05 / 18.85
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	106.26 / 54.07
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.01 / 8.66

Mixing Data: Mixing Date:_ 4 - 4 -89_Mixer Used: Eirich Pan Mixing Time:_4:00 pm__
Temp.: 23 ± 1.5°C W/C= 0.47

Pre-set Properties:

	Method
Slump_____2.50 in. _____	____ ASTM C 143___
Density___ 152.16 lb/cu ft ____.	____ ASTM C 138___
Air Content_____ 0.8 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.00 hrs. __	____ ASTM C 403___
Final :__ 6.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-2- C_{28} Compressive Strength ____ ASTM C 39 ____
B. S 89-2- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-2- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-2-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-2-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: May 2-89

28-Day Compressive Strength: 44.07 MPa ($\sigma_{6\ Samples}$ = 2.98 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ **S 89 - 3** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 4 -11 -89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	36.21 / 18.97
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	57.10 / 29.91
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	80.55 / 42.20
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.02 / 8.92

Mixing Data: Mixing Date:_ 4 -11-89_Mixer Used: Eirich Pan Mixing Time:_4:00 pm__
Temp.: 23 ± 1.5°C W/C= 0.47

Pre-set Properties:

		Method
Slump	3.50 in.	____ ASTM C 143___
Density	149..13 lb/cu ft	____ ASTM C 138___
Air Content	0.8 %	____ ASTM C 231___
Setting Time Initial:	6.25 hrs.	____ ASTM C 403___
Final :	8.00 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-3- C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 89-3- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-3- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-3-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-3-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: May 9-89

28-Day Compressive Strength: 45.43 MPa ($\sigma_{6\ Samples}$ = 1.49 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 4 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 4 -14-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	36.20 / 19.03
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	75.70 / 39.80
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	61.26 / 32.21
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.02 / 8.95

Mixing Data: Mixing Date:_ 4 -14-89_Mixer Used: Eirich Pan Mixing Time:11:15 pm__
Temp.: 23 ± 1.5°C W/C= 0.47

Pre-set Properties:

	Method
Slump_____2.00 in. _____	____ ASTM C 143___
Density___ 146.15 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.8 % _____	____ ASTM C 231___
Setting Time Initial:__ 6.00 hrs. __	____ ASTM C 403___
Final :__ 8.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-4- C_{28} Compressive Strength _____
B. S 89-4- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-4- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-4-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-4-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate
F._____
G._____

Testing Date: May 12-89

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 5 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 5 - 2 -89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	28.29 / 14.36
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	48.56 / 24.65
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	106.27 / 53.95
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticiser	_____	0.56* / 0.28
	_____	_____	_____/_____
Water	_____	_____	13.30 / 6.75

Mixing Data: Mixing Date:_ 5 -2-89_Mixer Used: Eirich Pan Mixing Time:_10:30 am__
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

	Method
Slump_____2.75 in._____	____ ASTM C 143___
Density___ 151.78 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.2 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.67 hrs. __	____ ASTM C 403___
Final :__ 7.33 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-5- C_{28} Compressive Strength ____ ASTM C 39 ___
B. S 89-5- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-5- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-5-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-5-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: May 30-89

28-Day Compressive Strength: 48.60 MPa ($\sigma_{6\ Samples}$ = 1.31 MPa)

Notes: * 2% by weight of the cement _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 6 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 5 - 9 -89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	28.29 / 14.44
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	73.32 / 37.43
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	80.55 / 41.12
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticiser	_____	0.42* / 0.21
	_____	_____	_____/_____
Water	_____	_____	13.29 / 6.79

Mixing Data: Mixing Date:_ 5 -9-89_Mixer Used: Eirich Pan Mixing Time:_9:30 am__
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

	Method
Slump_____3.50 in. _____	____ ASTM C 143___
Density___ 149.42 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 2.0 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.75 hrs. __	____ ASTM C 403___
Final :__ 6.67 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-6- C_{28} Compressive Strength ____ ASTM C 39 ____
B. S 89-6- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-6- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-6-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-6-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: June 6-89

28-Day Compressive Strength: 44.58 MPa ($\sigma_{6\ Samples}$ = 2.44 MPa)

Notes: * 1.50% by weight of the cement _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 7 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 5-11 -89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	28.29 / 14.47
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	89.20 / 45.62
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	64.09 / 32.78
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticiser	_____	0.63* / 0.32
	_____	_____	_____/_____
Water	_____	_____	13.30 / 6.80

Mixing Data: Mixing Date:_ 5 -11-89_Mixer Used: Eirich Pan Mixing Time:_11:10 am_
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

		Method
Slump	3.50 in.	____ ASTM C 143___
Density	147.74 lb/cu ft	____ ASTM C 138___
Air Content	2.8 %	____ ASTM C 231___
Setting Time Initial:	6.30 hrs.	____ ASTM C 403___
Final :	8.25 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-7- C_{28} Compressive Strength ____ ASTM C 39 ____
B. S 89-7- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-7- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-7-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-7-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: June 8-89

28-Day Compressive Strength: 45.53 MPa ($\sigma_{6\ Samples}$ = 0.84 MPa)

Notes: * 2.25% by weight of the cement _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 - 8 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 6 -13 -89 _ ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	32.25 / 16.44
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	57.02 / 29.07
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	93.04 / 47.43
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticizer	_____	0.32*/ 0.16
	_____	_____	_____/_____
Water	_____	_____	13.54 / 6.90

Mixing Data: Mixing Date:_ 6-13-89_Mixer Used: Eirich Pan Mixing Time:_2:30 pm__
Temp.: 23 ± 1.5°C, W/C = 0.42

Pre-set Properties:

	Method
Slump_____4.00 in. _____	____ ASTM C 143___
Density___ 152.98 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.0 % _____	____ ASTM C 231___
Setting Time Initial:__ 4.75 hrs. __	____ ASTM C 403___
Final :__ 6.80 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-8- C_{28} Compressive Strength ____ ASTM C 39 ___
B. S 89-8- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-8- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-8-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-8-I Interface, (a)**, (b) Regular with aggregate

Testing Date: July 11-89

28-Day Compressive Strength: 51.80 MPa ($\sigma_{6\ Samples}$ = 1.35 MPa)

Notes: * 1% by weight of the cement., ** Engineered samples without aggregate were not prepared upon task leader's request.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 89 - 9** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 6 -15 -89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	24.81 / 16.92
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	36.77 / 25.08
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	71.85 / 36.89
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	13.15 / 8.97

Mixing Data: Mixing Date:_ 6-15-89_Mixer Used: Eirich Pan Mixing Time:_10:45 am__
Temp.: 23 ± 1.5°C, W/C = 0.53.

Pre-set Properties:

	Method
Slump_____5.00 in. _____	____ ASTM C 143___
Density___ 148.84 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 0.6 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.75 hrs. __	____ ASTM C 403___
Final :__ 7.90 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-9- C_{28}	Compressive Strength ___ ASTM C 39 ____
B. S 89-9- K_{28}	Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-9- $Ø_{28}$	Porosity. (a) MIP, (B) ASTM _____
D. S 89-9-M_{28}	Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-9-I	Interface, (a)*,(b) Regular with aggregate

Testing Date: July 13-89

28-Day Compressive Strength: 44.86 MPa ($\sigma_{6\ Samples}$ = 0.60 MPa)

Notes: * Engineered samples without aggregate were not prepared upon task leader's request.

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -10 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 6-26-89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	22.32 / 10.03
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	60.12 / 27.01
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.42
Min. Admix.	_____Newcem Slag_____	____ G-24 ____	14.88 / 6.68
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.49 / 7.86

Mixing Data: Mixing Date:_ 6-26-89_Mixer Used: Eirich Pan Mixing Time:_10:10 am_
Temp.: 23 ± 1.5°C, W/(C+S) = 0.47

Pre-set Properties:

	Method
Slump_____2.75 in. _____	____ ASTM C 143___
Density___ 149.52 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.2 % _____	____ ASTM C 231___
Setting Time Initial:__ 4.33 hrs. __	____ ASTM C 403___
Final :__ 6.66 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-10-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-10-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 89-10-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-10-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 89-10-I Interface, (a)*,(b) Regular with aggregate __

Testing Dates:(1d)June 27, (3d)June 29, (7d)July 3, (14d)July 10, (28d)July 24-89

28-Day Compressive Strength: 49.65 MPa ($\sigma_{6\ Samples}$ = 0.50 MPa)

Notes: * Engineered samples without aggregates were not prepared upon task leader's request.

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -11 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 8- 1-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	31.63 / 14.24
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	59.62 / 26.84
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.53
Min. Admix.	____ Class-F Fly Ash* ___	____ B-92 ____	6.33 / 2.85
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.08 / 7.69

Mixing Data: Mixing Date:_ 8- 1-89_Mixer Used: Eirich Pan Mixing Time:_10:15 am__
Temp.: 23 ± 1.5°C W/(C+F)= 0.45 F/C=0.20

Pre-set Properties:

	Method
Slump_____1.50 in. _____	____ ASTM C 143___
Density___ 149.42 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.2 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.10 hrs. __	____ ASTM C 403___
Final :__ 7.25 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-11-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 89-11-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 89-11-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-11-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 89-11-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate __

Testing Dates:(1d)Aug. 2, (3d)Aug. 4, (7d)Aug. 8, (14d)Aug. 15, (28d)Aug. 29-89

28-Day Compressive Strength: 43.35 MPa ($\sigma_{6\ Samples}$ = 0.78 MPa)

Notes: * Pennsylvania Power and Light Co.(Montour Plant) fly ash.

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -12 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 8- 8-89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	31.63 / 14.24
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	60.45 / 27.21
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.52
Min. Admix.	____ Class-C Fly Ash* ___	____ G-07 ____	6.33 / 2.85
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	15.94 / 7.18

Mixing Data: Mixing Date:_ 8- 8-89_Mixer Used: Eirich Pan Mixing Time:_10:45 am__
Temp.: 23 ± 1.5°C W/(C+F)= 0.42 F/C=0.20

Pre-set Properties:

	Method
Slump_____1.00 in. _____	____ ASTM C 143___
Density___ 152.21 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.5 % _____	____ ASTM C 231___
Setting Time Initial:__ 4.75 hrs. __	____ ASTM C 403___
Final :__ 6.25 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-12-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-12-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 89-12-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-12-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 89-12-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate __

Testing Dates:(1d)Aug. 9, (3d)Aug. 11, (7d)Aug. 15, (14d)Aug. 22, (28d)Sept. 5-89

28-Day Compressive Strength: 52.92 MPa ($\sigma_{6\ Samples}$ = 1.24 MPa)

Notes: * Rockport fly ash. _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -13 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 8-15 -89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	34.42 / 15.46
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	59.93 / 26.92
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.42
Min. Admix.	__ Micro Silica Fume* ___	____ G-15 ____	2.79 / 1.25
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticizer	_____	0.20 / 0.09**
	_____	_____	_____/_____
Water	_____	_____	17.49 / 7.86

Mixing Data: Mixing Date:_ 8-15-89_Mixer Used: Eirich Pan Mixing Time:_10:28 am__
Temp.: 23 ± 1.5°C W/(C+S.F.)= 0.47

Pre-set Properties:

	Method
Slump_____1.50 in. _____	____ ASTM C 143___
Density___ 150.33 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.3 % _____	____ ASTM C 231___
Setting Time Initial:__ 3.50 hrs. __	____ ASTM C 403___
Final :__ 4.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold___
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-13-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-13-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 89-13-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-13-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 89-13-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate __

Testing Dates:(1d)Aug. 16, (3d)Aug. 18, (7d)Aug. 22, (14d)Aug. 29, (28d)Sept. 12-89

28-Day Compressive Strength: 46.2 MPa ($\sigma_{6\ Samples}$ = 2.23 MPa)

Notes: * Elkem Chemicals. ** 0.5% by weight of the cementitious materials.

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -14 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 8 - 28 -89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	12.38 / 16.84
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	19.91 / 27.08
Coarse Agg.	Crushed Limestone/ #8 (SSD)	_____	35.40 / 48.16
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	5.82 / 7.92

Mixing Data: Mixing Date:_ 8-28-89_Mixer Used: Eirich Pan Mixing Time:_11:10 am_
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

	Method
Slump_____1.00 in. _____	____ ASTM C 143___
Density___ 148.79 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.8 % _____	____ ASTM C 231___
Setting Time Initial:_____	____ ASTM C 403___
Final :_____	

Curing Conditions: Precure* Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-14- C_{28}
B. S 89-14- K_{28}
C. S 89-14- $Ø_{28}$
D. S 89-14-M_{28}
E. S 89-14-I

Compressive Strength ___ ASTM C 39 ____
Perm.(a)Impulse,(b)Chloride,(c)Standard
Porosity. (a) MIP, (B) ASTM _____
Microscopic Examination, (a) GMIC, (b) MRL/PSU
Interface, (a)**,(b) Regular with aggregate

Testing Date: September 25-89

28-Day Compressive Strength: 46.84 MPa ($\sigma_{6\ Samples}$ = 1.78 MPa)

Notes: * Samples have been slightly vibrated during molding. _____
** Engineered samples without aggregate were not prepared. _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -15 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 8-28-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	37.14 / 16.87
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	59.73 / 27.14
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	105.78 / 48.06
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.46. / 7.93

Mixing Data: Mixing Date:_ 8-28-89_Mixer Used: Eirich Pan Mixing Time:_9:10 am__
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

		Method
Slump	2.75 in.	____ ASTM C 143___
Density	147.93 lb/cu ft	____ ASTM C 138___
Air Content	1.6 %	____ ASTM C 231___
Setting Time Initial:	3.83 hrs.	____ ASTM C 403___
Final :	5.17 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-15-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____

B. S 89-15-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard

C. S 89-15-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____

D. S 89-15-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __

E. S 89-15-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate __

Testing Dates:(1d)Aug. 29, (3d)Aug. 31, (7d)Sept. 4, (14d)Sept. 11, (28d)Sept 25-89

28-Day Compressive Strength: 43.82 MPa ($\sigma_{6\ Samples}$ = 2.38 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ **S 89 -16** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 8 - 28 -89 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	12.38 / 16.84
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	19.91 / 27.08
Coarse Agg.	Towson Siliceous Gravel/#8(SSD)	_____	35.40 / 48.16
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	5.82 / 7.92

Mixing Data: Mixing Date:_ 8-28-89_Mixer Used: Eirich Pan Mixing Time:_10:40 am_
Temp.: 23 ± 1.5°C W/C = 0.47

Pre-set Properties:

	Method
Slump_____1.00 in. _____	____ ASTM C 143___
Density___ 148.84 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 2.00 % _____	____ ASTM C 231___
Setting Time Initial:_____	____ ASTM C 403___
Final :_____	

Curing Conditions: Precure* Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-16- C_{28}
B. S 89-16- K_{28}
C. S 89-16- $Ø_{28}$
D. S 89-16-M_{28}
E. S 89-16-I

Compressive Strength ____ ASTM C 39 ___
Perm.(a)Impulse,(b)Chloride,(c)Standard
Porosity. (a) MIP, (B) ASTM _____
Microscopic Examination, (a) GMIC, (b) MRL/PSU
Interface, (a)**,(b) Regular with aggregate

Testing Date: September 25-89

28-Day Compressive Strength: 44.22 MPa ($\sigma_{6\ Samples}$ = 1.04 MPa)

Notes: * Samples have been slightly vibrated during molding._____
** Engineered samples without aggregate were not prepared. _____

Mixing Data (SHRP)

Mix Identification No.: ____ **S 89 -17** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 11-17-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	20.90 / 19.07
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	18.68 / 17.05
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	60.18 / 54.92
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	9.82 / 8.96

Mixing Data: Mixing Date:11-17-89_Mixer Used: Eirich Pan Mixing Time:_10:00 am__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

	Method
Slump_____6.50 in. _____	____ ASTM C 143___
Density___ 152.16 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 0.8 % _____	____ ASTM C 231___
Setting Time Initial:_____ hrs. __	____ ASTM C 403___
Final :_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-17- C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 89-17- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-17- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-17-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-17-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: December 15-89

28-Day Compressive Strength: 35.94 MPa ($\sigma_{6\ Samples}$ = 0.76 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -18 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 12-20-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	20.90 / 19.12
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	32.94 / 30.14
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	45.63 / 41.75
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	9.83 / 8.99

Mixing Data: Mixing Date:12-20-89_Mixer Used: Eirich Pan Mixing Time:_10:00 am__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

	Method
Slump_____3.25 in. _____	____ ASTM C 143___
Density___ 150.95 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.5 % _____	____ ASTM C 231___
Setting Time Initial:_____ hrs. __	____ ASTM C 403___
Final :_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-18- C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-18- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-18- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-18-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-18-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: January 17-90

28-Day Compressive Strength: 47.19 MPa ($\sigma_{6\ Samples}$ = 0.10 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -19 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 12-20-89 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	20.90 / 19.16
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	43.67 / 40.02
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	34.70 / 31.81
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	9.83 / 9.01

Mixing Data: Mixing Date:12-20-89_Mixer Used: Eirich Pan Mixing Time:_10:00 am__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

		Method
Slump	2.25 in.	____ ASTM C 143___
Density	151.85 lb/cu ft	____ ASTM C 138___
Air Content	1.5 %	____ ASTM C 231___
Setting Time Initial:	_____ hrs. __	____ ASTM C 403___
Final :	_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-19- C_{28} Compressive Strength ____ ASTM C 39 ____
B. S 89-19- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-19- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-19-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-19-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: January 17-90

28-Day Compressive Strength: 49.64 MPa ($\sigma_{6\ Samples}$ = 0.79 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -20 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 1 - 4 - 90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	10.88 / 14.46
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	18.67 / 24.81
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	40.35 / 53.63
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticizer	_____	0.22 / 0.29
	_____	_____	_____/_____
Water	_____	_____	5.12 / 6.80

Mixing Data: Mixing Date:1 - 4 -90_Mixer Used: Eirich Pan Mixing Time:_10:00 am__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

	Method
Slump_____7.00 in. _____	____ ASTM C 143___
Density___ 150.29 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.5 % _____	____ ASTM C 231___
Setting Time Initial:_____ hrs. __	____ ASTM C 403___
Final :_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-20- C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 89-20- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-20- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-20-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-20-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: February 1-90

28-Day Compressive Strength: 48.81 MPa ($\sigma_{6\ Samples}$ = 1.01 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -21 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 2 - 7 - 90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	10.88 / 14.53
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	28.20 / 37.68
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	30.42 / 40.65
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticizer	_____	0.22 / 0.29
	_____	_____	_____/_____
Water	_____	_____	5.12 / 6.84

Mixing Data: Mixing Date:2 - 7 -90_Mixer Used: Eirich Pan Mixing Time:_10:00 am__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

	Method
Slump_____9.00 in. _____	____ ASTM C 143___
Density___ 148.83 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.5 % _____	____ ASTM C 231___
Setting Time Initial:_____ hrs. __	____ ASTM C 403___
Final :_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-21- C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-21- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-21- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-21-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-21-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: March 7-90

28-Day Compressive Strength: 45.16 MPa ($\sigma_{6\ Samples}$ = 1.17 MPa)

Notes: _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 89 -22 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 2 - 7 - 90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	10.88 / 14.43
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	43.98 / 46.40
Coarse Agg.	Towson Siliceous Gravel/#67(SSD)	_____	24.20 / 32.10
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Mighty 150 Superplasticizer	_____	0.22 / 0.29
	_____	_____	_____/_____
Water	_____	_____	5.12 / 6.79

Mixing Data: Mixing Date:2 - 7 -90_Mixer Used: Eirich Pan Mixing Time:_1:00 pm__
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

		Method
Slump	2.25 in.	____ ASTM C 143___
Density	147.24 lb/cu ft	____ ASTM C 138___
Air Content	1.6 %	____ ASTM C 231___
Setting Time Initial:	hrs.	____ ASTM C 403___
Final :	hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 89-22- C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 89-22- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 89-22- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 89-22-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 89-22-I Interface, (a) Engineered without aggregate,(b) Regular with aggregate

Testing Date: March 7-90

28-Day Compressive Strength: 46.03 MPa ($\sigma_{6\ Samples}$ = 0.60 MPa)

Notes: _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 84 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 - 6 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.28
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	45.34 / 29.88
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	75.60 / 49.82
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.326* / 0.21
	_____	_____	_____ /_____
Water	_____	_____	9.14 / 6.02

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 0.00 in.__ Unit Weight _____ lb/cu ft__ Air Content_____ %

W/C = 0.365

Notes: * 1.5% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 85 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 - 7 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.28
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	45.34 / 29.88
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	75.60 / 49.82
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.436* / 0.29
	_____	_____	_____ /_____
Water	_____	_____	9.14 / 6.02

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 0.75 in.__ Unit Weight _____ lb/cu ft__ Air Content_____ %

W/C = 0.365

Notes: * 2.0% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 86 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 - 8 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.28
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	45.34 / 29.88
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	75.60 / 49.82
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.454* / 0.36
	_____	_____	_____ /_____
Water	_____	_____	9.14 / 6.02

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 5.75 in.__ Unit Weight 153.72 lb/cu ft__ Air Content___1.5 % ___

W/C = 0.365

Notes: * 2.5% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 87 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 - 9 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.33
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.90 / 29.70
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.84 / 49.50
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.326* / 0.21
	_____	_____	_____ /_____
Water	_____	_____	9.79 / 6.47

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 0.75 in.__ Unit Weight ___ lb/cu ft__ Air Content_____ % ___

W/C = 0.394

Notes: * 1.5% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 88 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 -10 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.33
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.90 / 29.70
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.84 / 49.50
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.436* / 0.29
	_____	_____	_____ /_____
Water	_____	_____	9.79 / 6.47

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 3.50 in.__ Unit Weight ___ 154.20 lb/cu ft__ Air Content__ 1.80 % ___

W/C = 0.394

Notes: * 2.0% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 89 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 -11 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.33
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.90 / 29.70
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.84 / 49.50
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.544* / 0.36
	_____	_____	_____ /_____
Water	_____	_____	9.79 / 6.47

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 7.00 in.__ Unit Weight _____ lb/cu ft__ Air Content_____ % ___

W/C = 0.394

Notes: * 2.5% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 90 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 -12 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.44
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.00 / 29.33
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.10 / 49.40
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.326* / 0.21
	_____	_____	_____ /_____
Water	_____	_____	10.23 / 6.82

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 6.50 in.__ Unit Weight _____ lb/cu ft__ Air Content_____ % ___

W/C = 0.417

Notes: * 1.5% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 91 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 -13 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.44
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.00 / 29.33
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.10 / 49.40
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.436* / 0.29
	_____	_____	_____ /_____
Water	_____	_____	10.23 / 6.82

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 7.25 in.__ Unit Weight __ 153.72 lb/cu ft__ Air Content__ 1.5 % ___

W/C = 0.417

Notes: * 2.0% by weight of the cement. _____

Concrete Rheology Data (SHRP)

Mix Identification No.: __ R 89 - 92 __ Originated by: __ R.I.A.MALEK
Date: ___ 5 -14 -89 __

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-18 ____	21.67 / 14.44
Fine Agg.	Lycoming Sand/ASTM C33(DRY)	_____	44.00 / 29.33
Coarse Agg.	Crushed Limestone/#67(DRY)	_____	74.10 / 49.40
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	____ Superplasticizer ___	__ Mighty-150__	0.544* / 0.36
	_____	_____	_____ /_____
Water	_____	_____	10.23 / 6.82

Mixing Data: Mixer Used: Eirich Pan Mixing Time: 10:00 am__ Temp.: 23 ± 1.5°C

Fresh Properties:

Slump __ 8.00 in.__ Unit Weight _____ lb/cu ft__ Air Content_____ % ___

W/C = 0.417

Notes: * 2.5% by weight of the cement. _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 1 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 2-13-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	37.21 /16.66
Fine Aggregate	Towson Sand #1 *(SSD)	_____	62.24 / 27.78
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.27
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	16.26 / 7.28

Mixing Data: Mixing Date:_ 2-13-90_Mixer Used: Eirich Pan Mixing Time:_10:10 am_
Temp.: 23 ± 1.5°C, W/C = 0.437

Pre-set Properties:

	Method
Slump_____ 1.50 in. _____	____ ASTM C 143___
Density___ 154.40 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 1.40 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.00 hrs. __	____ ASTM C 403___
Final :__ 6.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-1-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-1-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-1-$\emptyset_2$,$\emptyset_3$,$\emptyset_7$,$\emptyset_{14}$,$\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-1-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-1-I Interface, (a)Engineered, (b) Regular with aggregate __

Testing Dates:(1d)Feb. 14,(3d)Feb. 16,(7d)Feb. 20,(14d)Feb. 27,(28d)March 13-90

28-Day Compressive Strength: 48.86 MPa ($\sigma_{6\ Samples}$ = 2.12 MPa)

Notes: * Fineness Modulus = 3.54 . _____

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 - 2** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 2-15-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	37.21 /16.57
Fine Aggregate	Towson Sand #2 *(SSD)	_____	62.24 / 27.63
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.00
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.49 / 7.79

Mixing Data: Mixing Date:_ 2-15-90_Mixer Used: Eirich Pan Mixing Time:_10:00 am_
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

		Method
Slump_____	1.50 in. _____	____ ASTM C 143___
Density___	148.60 lb/cu ft ____	____ ASTM C 138___
Air Content_____	1.50 % _____	____ ASTM C 231___
Setting Time Initial:__	5.00 hrs. __	____ ASTM C 403___
Final :__	6.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-2-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-2-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-2-$Ø_2$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-2-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-2-I Interface, (a)Engineered, (b) Regular with aggregate __

Testing Dates:(1d)Feb. 16,(3d)Feb. 19,(7d)Feb. 23,(14d)March 1,(28d)March 15-90

28-Day Compressive Strength: 48.15 MPa ($\sigma_{6\ Samples}$ = 1.81 MPa)

Notes: * Fineness Modulus = 2.28 . _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 3 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 2-20-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	37.21 /16.62
Fine Aggregate	Towson Sand/[Blend]* (SSD)	_____	62.04 / 27.71
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.14
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	16.86 / 7.53

Mixing Data: Mixing Date:_ 2-20-90_Mixer Used: Eirich Pan Mixing Time:_ 9:10 am_
Temp.: 23 ± 1.5°C, W/C = 0.453

Pre-set Properties:

	Method
Slump_____ 3.50 in. _____	____ ASTM C 143___
Density___ 151.60 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.20 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.00 hrs. __	____ ASTM C 403___
Final :__ 7.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-3-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-3-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-3-$Ø_2$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-3-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-3-I Interface, (a)Engineered, (b) Regular with aggregate __

Testing Dates:(1d)Feb. 21,(3d)Feb. 23,(7d)Feb. 27,(14d)March 6,(28d)March 20-90

28-Day Compressive Strength: 44.61 MPa ($\sigma_{6\ Samples}$ = 1.09 MPa)

Notes: * A blend of 31.40% #1 Sand + 68.60% # 2 Sand (Fineness Modulus = 2.60) .

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 4 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 2-20-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	37.21 /14.17
Fine Aggregate	Towson Sand #3 *(SSD)	_____	57.61 / 26.15
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.93
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	__ Superplasticizer ___	__ Mighty 150 _	0.20** / 0.09
	_____	_____	_____/_____
Water	_____	_____	16.86 / 7.94

Mixing Data: Mixing Date:_ 2-20-90_Mixer Used: Eirich Pan Mixing Time:_ 11:10 am_
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

		Method
Slump_____	2.75 in. _____	____ ASTM C 143___
Density___	150.80 lb/cu ft ____	____ ASTM C 138___
Air Content_____	1.10 % _____	____ ASTM C 231___
Setting Time Initial:__	5.25 hrs. __	____ ASTM C 403___
Final :__	7.25 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-4-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-4-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-4-$Ø_2$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-4-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-4-I Interface, (a)Engineered, (b) Regular with aggregate __

Testing Dates:(1d)Feb. 21,(3d)Feb. 23,(7d)Feb. 27,(14d)March 6,(28d)March 20-90

28-Day Compressive Strength: 45.15 MPa ($\sigma_{6\ Samples}$ = 2.14 MPa)

Notes: * Fineness Modulus = 1.66. ** 0.50% by weight of the cement.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 5 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 3-27-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	13.03 / 5.85
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	60.12 / 27.01
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 48.42
Min. Admix.	_____Newcem Slag_____	____ G-24 ____	24.18*/ 10.86
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	17.49 / 7.86

Mixing Data: Mixing Date:_ 3-27-90_Mixer Used: Eirich Pan Mixing Time:_10:10 am_
Temp.: 23 ± 1.5°C, W/(C+S) = 0.47

Pre-set Properties:

	Method
Slump_____ 1.00 in. _____	____ ASTM C 143___
Density___ 148.96 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 1.9 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.50 hrs. __	____ ASTM C 403___
Final :__ 7.50 hrs. __	

Curing Conditions: Precure Time initl. 48 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 48 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-5-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-5-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-5-$Ø_2$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-5-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-5-I Interface, (a)Engineered, (b) Regular with aggregate __

Testing Dates:(2d)March 29,(3d)March 30,(7d)April 3,(14d)April 10,(28d)April 24-90

28-Day Compressive Strength: 42.69 MPa ($\sigma_{6\ Samples}$ = 1.27 MPa)

Notes: * 65% by weight replacement of the cement . _____

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 - 6*** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 4-10-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	25.43 / 10.97
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	58.76 / 25.35
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	135.12 / 58.30
Min. Admix.	_____	_____	_____ / _____
Admixtures	Mighty 150 Superplasticizer	_____	0.5** / 0.22
Water	_____	_____	11.95 / 5.16

Mixing Data: Mixing Date:_ 4-10-90_Mixer Used: Eirich Pan Mixing Time:_11:00 am_
Temp.: 23 ± 1.5°C, W/C = 0.47

Pre-set Properties:

		Method
Slump_____	1.00 in.***_____	____ ASTM C 143___
Density___	154.67 lb/cu ft ____	____ ASTM C 138___
Air Content_____	1.1 % _____	____ ASTM C 231___
Setting Time Initial:__	4.00 hrs. _ Final :__ 6.00 hrs. _	ASTM C 403_

Curing Conditions: Precure Time initl. 48 hrs Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 48 hrs.Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-6-C_2,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-6-K_2,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-6-$\emptyset_2$,$\emptyset_3$,$\emptyset_7$,$\emptyset_{14}$,$\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-6-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU __
E. S 90-6-I Interface, (a)****,(b) Regular with aggregate __

Testing Dates:(2d)April 12,(3d) April 13,(7d)April 17,(14d)April 24,(28d)May 8-90

28-Day Compressive Strength: 46.27 MPa ($\sigma_{6\ Samples}$ = 4.53 MPa)

Notes: * Formulation corresponds to maximum packing in GMIC ternary packing diagram for #67 limestone. ** 0.5% by weight of the cement . **** Continued to show zero slump with increasing amount of superplasticizer, untill started to shear at 0.5%.
**** Engineered samples not prepared

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 7 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 6- 5 -90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	29.02 / 15.07
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	51.64 / 26.58
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	93.42 / 48.65
Min. Admix.	__ Micro Silica Fume* ___	____ G-15 ____	3.22 / 1.67
	_____	_____	_____/_____
Admixtures	Superplasticizer & Retarder	____ RD-1____	0.16 / 0.08**
Water	_____	_____	15.16 / 7.90

Mixing Data: Mixing Date:_ 6- 5-90_Mixer Used: Eirich Pan Mixing Time:_ 9:45 am__
Temp.: 23 ± 1.5°C W/(C+S.F.)= 0.47

Pre-set Properties:

	Method
Slump_____2.25 in. _____	____ ASTM C 143___
Density___ 150.16 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 1.1 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.25 hrs. __	____ ASTM C 403___
Final :__ 7.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold___
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-7-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-7-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-7-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-7-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-7-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate __

Testing Dates:(1d)June. 6, (3d) June. 8, (7d)June. 12, (14d)June. 19, (28d)July. 3-90

28-Day Compressive Strength: 51.83 MPa ($\sigma_{6\ Samples}$ = 1.12 MPa)

Notes: * Elkem Chemicals. ** 0.5% by weight of the cementitious materials.
+ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 - 8** ___ Originated by: __ **R.I.A.MALEK** _
Date: ____ 5-29 -90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	27.40 / 14.27
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	51.04 / 26.58
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	93.42 / 48.65
Min. Admix.	__ Micro Silica Fume* ___	____ G-15 ____	4.84 / 2.52
	_____	_____	_____/_____
Admixtures	Superplasticizer & Retarder	____ RD-1____	0.16 / 0.08**
Water	_____	_____	15.16 / 7.90

Mixing Data: Mixing Date:_ 5-29-90_Mixer Used: Eirich Pan Mixing Time:_11:41 am__
Temp.: 23 ± 1.5°C W/(C+S.F.)= 0.47

Pre-set Properties:

		Method
Slump	1.25 in.	____ ASTM C 143___
Density	149.76 lb/cu ft	____ ASTM C 138___
Air Content	1.1 %	____ ASTM C 231___
Setting Time Initial:	5.33 hrs.	____ ASTM C 403___
Final :	7.33 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold___
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-7-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-7-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-7-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-7-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-7-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate __

Testing Dates:(1d)May. 30, (3d) June. 1, (7d)June. 5, (14d)June. 12, (28d)June. 26-90

28-Day Compressive Strength: 54.02 MPa ($\sigma_{6\ Samples}$ = 0.30 MPa)

Notes: * Elkem Chemicals. ** 0.5% by weight of the cementitious materials.
+ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 - 9 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 6 - 21-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	12.40 / 16.45
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	21.93 / 29.09
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.78 / 47.47
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Superplasticizer & Retarder	____ RD-1____	0.06*/ 0.08
	_____	_____	_____/_____
Water	_____	_____	5.21 / 6.91

Mixing Data: Mixing Date:_ 6 - 21-90_Mixer Used: Eirich Pan Mixing Time:12:35 pm__
Temp.: 23 ± 1.5°C W/C= 0.42

Pre-set Properties:

		Method
Slump	0.50 in.	____ ASTM C 143___
Density	155.34 lb/cu ft	____ ASTM C 138___
Air Content	1.75%	____ ASTM C 231___
Setting Time Initial:	4.00 hrs.	____ ASTM C 403___
Final :	5.75 hrs.	

Curing Conditions: `Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-9- C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-9- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-9- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-9-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-9-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate

Testing Date: July 19-90

28-Day Compressive Strength: 47.35 MPa ($\sigma_{6\ Samples}$ = 0.30 MPa)

Notes: * 0.5 % by weight of the cement + Not prepared _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -10 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 6 - 21-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	12.40 / 16.44
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	21.93 / 29.07
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.78 / 47.43
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Superplasticizer & Retarder	____ RD-1____	0.12*/ 0.16
	_____	_____	_____/_____
Water	_____	_____	5.21 / 6.91

Mixing Data: Mixing Date:_ 6 - 21-90_Mixer Used: Eirich Pan Mixing Time: 1:25 pm__
Temp.: 23 ± 1.5°C W/C= 0.42

Pre-set Properties:

		Method
Slump	3.75 in.	____ ASTM C 143___
Density	153.74 lb/cu ft	____ ASTM C 138___
Air Content	1.3%	____ ASTM C 231___
Setting Time Initial:	4.20 hrs.	____ ASTM C 403___
Final :	5.50 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-10- C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-10- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-10- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-10-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-10-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate

Testing Date: July 19-90

28-Day Compressive Strength: 47.06 MPa ($\sigma_{6\ Samples}$ = 1.05 MPa)

Notes: * 1.0 % by weight of the cement + Not prepared _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -11 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 6 - 21-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	12.40 / 16.44
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	21.93 / 29.07
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.78 / 47.43
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	Superplasticizer & Retarder	____ RD-1____	0.18*/ 0.24
	_____	_____	_____/_____
Water	_____	_____	5.21 / 6.91

Mixing Data: Mixing Date:_ 6 - 21-90_Mixer Used: Eirich Pan Mixing Time: 2:50 pm__
Temp.: 23 ± 1.5°C W/C= 0.42

Pre-set Properties:

		Method
Slump	7.50 in.	____ ASTM C 143___
Density	154.54 lb/cu ft	____ ASTM C 138___
Air Content	1.45%	____ ASTM C 231___
Setting Time Initial:	4.45 hrs.	____ ASTM C 403___
Final :	6.50 hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-11- C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-11- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-11- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-11-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-11-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate

Testing Date: July 19-90

28-Day Compressive Strength: 49.50 MPa ($\sigma_{6\ Samples}$ = 2.16 MPa)

Notes: * 1.5 % by weight of the cement + Not prepared _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -12 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 6-28-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	26.25 / 12.75
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	54.32 / 26.38
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	100.00 / 48.56
Min. Admix.	____ Class-F Fly Ash* ___	____ B-92 ____	9.83 / 4.77
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	15.53 / 7.54

Mixing Data: Mixing Date:_ 6-28-90_Mixer Used: Eirich Pan Mixing Time:_12:40 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.43 F/C=0.375

Pre-set Properties:

	Method
Slump_____1.25 in. _____	____ ASTM C 143___
Density___ 150.29 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.5 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.33 hrs. __	____ ASTM C 403___
Final :__ 6.75 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-12-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____

B. S 90-12-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard

C. S 90-12-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____

D. S 90-12-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___

E. S 90-12-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate __

Testing Dates:(1d)June. 29, (3d)July. 1, (7d)July. 5, (14d)July. 12, (28d)July. 26-90

28-Day Compressive Strength: 38.76 MPa ($\sigma_{6\ Samples}$ = 1.30 MPa)

Notes: * Pennsylvania Power and Light Co.(Montour Plant) fly ash. + Not prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -13 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 7-10-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	27.33 / 12.14
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	62.88 / 27.94
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	107.78 / 47.89
Min. Admix.	____ Class-C Fly Ash* ___	____ G-07 ____	11.55 / 5.13
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	15.54 / 6.90

Mixing Data: Mixing Date:_ 7-10-90_Mixer Used: Eirich Pan Mixing Time:_10:45 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.40 F/C=0.42

Pre-set Properties:

	Method
Slump_____1.25 in. _____	____ ASTM C 143___
Density___ 151.22 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.3 % _____	____ ASTM C 231___
Setting Time Initial:__ 5.50 hrs. __	____ ASTM C 403___
Final :__ 6.75 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-13-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-13-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-13-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-13-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-13-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate __

Testing Dates:(1d)July. 11, (3d)July. 13, (7d)July. 17, (14d)July. 24, (28d)Aug. 9-90

28-Day Compressive Strength: 50.45 MPa ($\sigma_{6\ Samples}$ = 1.90 MPa)

Notes: * Rockport fly ash. + Not prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -14* __ Originated by: __ R.I.A.MALEK _
Date: ____ 5-22-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	38.51 / 17.11
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	68.74 / 30.54
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	101.09 / 44.91
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____ /_____
Admixtures	Superplasticizer & Retarder	___ RD-1 _____	0.19** / 0.08
Water	_____	_____	16.56 / 7.36

Mixing Data: Mixing Date:_ 5-22-90_Mixer Used: Eirich Pan Mixing Time: 10:56 am__
Temp.: 23 ± 1.5°C W/C= 0.43

Pre-set Properties:

		Method
Slump	5.25 in.	____ ASTM C 143___
Density___	151.49 lb/cu ft ____	____ ASTM C 138___
Air Content_____	2.25 % _____	____ ASTM C 231___
Setting Time: Initial:__	5.50 hrs. __	____ ASTM C 403___
Final :__	7.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-14-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-14-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-14-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-14-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-14-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate __

Testing Dates:(1d)May. 23, (3d)May. 25, (7d)May. 29, (14d)June 5, (28d)June 19-90

28-Day Compressive Strength: 48.84 MPa ($\sigma_{6\ Samples}$ = 0.76 MPa)

Notes: * **AAA** Concrete Formulation for Bridge Decks (PADOT Specs. 408)_____
** 0.5% by weight of the cement. + Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 -15*** __ Originated by: __ **R.I.A.MALEK** _
Date: ____ 5-24-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	35.62 / 15.81
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	68.74 / 30.51
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	101.09 / 44.87
Min. Admix.	__ Micro Silica Fume** __	___ G-15 ____	2.89 / 1.28
	_____	_____	_____ /_____
Admixtures	Superplasticizer & Retarder	___ RD-1 _____	0.38+/ 0.17
Water	_____	_____	16.56 / 7.35

Mixing Data: Mixing Date:_ 5-24-90_Mixer Used: Eirich Pan Mixing Time: 11:02 am__
Temp.: 23 ± 1.5°C W/(C+S.F.)= 0.43

Pre-set Properties:

	Method
Slump_____6.25 in. _____	____ ASTM C 143___
Density___ 150.29 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 2.25 % _____	____ ASTM C 231___
Setting Time: Initial:__ 6.00 hrs. __	____ ASTM C 403___
Final :__ 7.50 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-15-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-15-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-15-$\emptyset_1$,$\emptyset_3$,$\emptyset_7$,$\emptyset_{14}$,$\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-15-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-15-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d)May. 25, (3d)May. 27, (7d)May. 31, (14d)June. 10, (28d)June 21-90

28-Day Compressive Strength: 55.58 MPa ($\sigma_{6\ Samples}$ = 3.62 MPa)

Notes: * **AAA** Concrete Formulation for Bridge Decks (PADOT Specs. 408)_____
** Elkem Chemicals. + 1.0% by weight of the cementitious. ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 -16*** __ Originated by: __ **R.I.A.MALEK** _
Date: ____ 6-12-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	23.11 / 10.27
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	68.74 / 30.54
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	101.09 / 44.91
Min. Admix.	____ Newcem Slag** ____	___ G-24 ____	15.40 / 6.84
	_____	_____	_____ /_____
Admixtures	Superplasticizer & Retarder	___ RD-1 _____	0.19+/ 0.08
Water	_____	_____	16.56 / 7.36

Mixing Data: Mixing Date:_ 6-12-90_Mixer Used: Eirich Pan Mixing Time: 11:25 am__
Temp.: 23 ± 1.5°C W/(C+S)= 0.43

Pre-set Properties:

	Method
Slump_____4.50 in. _____	____ ASTM C 143___
Density___ 151.49 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.50 % _____	____ ASTM C 231___
Setting Time: Initial:__ 6.00 hrs. __	____ ASTM C 403___
Final :__ 7.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-16-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-16-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-16-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-16-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-16-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d)June. 13, (3d)June. 15, (7d)June. 19, (14d)June. 26, (28d)July 10-90

28-Day Compressive Strength: 44.29 MPa ($\sigma_{6\ Samples}$ = 3.06 MPa)

Notes: * **AAA** Concrete Formulation for Bridge Decks (PADOT Specs. 408)_____
** Blue Circle Atlantic. + 0.5% by weight of the cementitious. ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -17* __ Originated by: __ R.I.A.MALEK _
Date: ____ 6-19-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-23 ____	28.08 / 12.65
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	63.99 / 28.82
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	101.09 / 45.53
Min. Admix.	___ Class-F Fly Ash** ___	___ B-92 ____	12.19 / 5.49
Admixtures	Superplasticizer & Retarder	___ RD-1 _____	0.19+/ 0.08
Water	_____	_____	16.51 / 7.44

Mixing Data: Mixing Date:_ 6-19-90_Mixer Used: Eirich Pan Mixing Time: 12:35 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.41 F/C=0.43

Pre-set Properties:

	Method
Slump_____6.50 in. _____	____ ASTM C 143___
Density___ 150.03 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 1.50 % ____	____ ASTM C 231___
Setting Time: Initial:__ 6.00 hrs. __	____ ASTM C 403___
Final :__ 8.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-17-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-17-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-17-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-17-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-17-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d)June. 20, (3d)June. 22, (7d)June. 26, (14d)July. 3, (28d)July 17-90

28-Day Compressive Strength: 40.58 MPa ($\sigma_{6\ Samples}$ = 2.20 MPa)

Notes: * **AAA** Concrete Formulation for Bridge Decks (PADOT Specs. 408)_____
** Pennsylvania Power and Light Co. (Montour Plant) fly ash.
+ 0.5% by weight of the cementitious. ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -18* __ Originated by: __ R.I.A.MALEK _
Date: ____ 6-26-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	26.97 / 11.96
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	68.58 / 30.42
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	101.09 / 44.84
Min. Admix.	___ Class-C Fly Ash** ___	___ G-07 ____	13.30 / 5.90
	_____	_____	_____ /_____
Admixtures	Superplasticizer & Retarder	___ RD-1 _____	0.19+/ 0.08
Water	_____	_____	15.30 / 6.79

Mixing Data: Mixing Date:_ 6-26-90_Mixer Used: Eirich Pan Mixing Time: 12:40 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.38 F/C=0.49

Pre-set Properties:

	Method
Slump_____5.25 in. _____	____ ASTM C 143___
Density___ 152.95 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.50 % _____	____ ASTM C 231___
Setting Time: Initial:__ 6.00 hrs. __	____ ASTM C 403___
Final :__ 8.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-18-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-18-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-18-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-18-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-18-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d)June. 27, (3d)June. 29, (7d)July. 3, (14d)July. 10, (28d)July 24-90

28-Day Compressive Strength: 51.46 MPa ($\sigma_{6\ Samples}$ = 4.90 MPa)

Notes: * **AAA** Concrete Formulation for Bridge Decks (PADOT Specs. 408)_____
** Rockport fly ash. + 0.5% by weight of the cementitious. ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -19 ___ Originated by: __ R.I.A.MALEK _
Date: ____ 7 - 5-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	8.58 / 12.95
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	13.87 / 20.94
Coarse Agg.	Crushed Limestone *(SSD)	_____	38.43 / 58.02
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	___ Superplasticizer __	__ Mighty 150 __	0.15**/ 0.23
Water	_____	_____	5.21 / 7.87

Mixing Data: Mixing Date:_ 7 - 5-90_Mixer Used: Eirich Pan Mixing Time: 1:35 pm__
Temp.: 23 ± 1.5°C W/C= 0.60

Pre-set Properties:

	Method
Slump_____ in§ ___	____ ASTM C 143___
Density_____ lb/ cu. ft§__	____ ASTM C 138___
Air Content_____ %§ ___	____ ASTM C 231___
Setting Time Initial:____ hrs.§ _	____ ASTM C 403___
Final :____ hrs.§__	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-19- C_{28} Compressive Strength ___ ASTM C 39 ____
B. S 90-19- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-19- $\emptyset_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-19-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-19-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate

Testing Date: August 2-90

28-Day Compressive Strength: 33.60 MPa ($\sigma_{6\ Samples}$ = 5.20 MPa)

Notes: *Graded Aggregate. **1.75 % by weight of the cement. §Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -20* __ Originated by: __ R.I.A.MALEK _
Date: ____ 7 -31-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-26 ____	45.96 / 19.76
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	60.19 / 25.88
Coarse Agg.	Crushed Limestone/ #57(SSD)	_____	110.06 / 47.32
Min. Admix.	_____	_____	____ / _____
Admixtures	__ Air Entraining Agent* _	___ MBVR ___	1.20(oz)/ ____
	___ Water REducer* ___	___ 122N ___	3.21(oz)/_____
	___ Accelerator ___	___ 122HE __	29.33(oz)/____
Water	_____	_____	16.38 / 7.04

Mixing Data: Mixing Date:_ 7-31-90_Mixer Used: Eirich Pan Mixing Time: 12:40 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.36

Pre-set Properties:

	Method
Slump_____2.50 in. _____	____ ASTM C 143___
Density___ 143.18 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 6.50 % _____	____ ASTM C 231___
Setting Time: Initial:__ 3.50 hrs. __	____ ASTM C 403___
Final :__ 5.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-20-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength _____

B. S 90-20-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard

C. S 90-20-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____

D. S 90-20-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___

E. S 90-20-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d))Aug.1, (3d)) Aug. 3, (7d)) Aug. 7, (14d) Aug. 14, (28d)Aug. 28-90

Notes: * **Rt. 322 [Seven Mountains] Patching (Type AA)** Concrete Foprmulation
(PADOT Specs. 408)
* Master Builders ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -21* __ Originated by: __ R.I.A.MALEK _
Date: ____ 8 -7-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-27 ____	34.84 / 19.76
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	64.06 / 25.88
Coarse Agg.	Crushed Limestone/ #57(SSD)	_____	114.73 / 47.32
Min. Admix.	_____	_____	____ / _____
	_____	_____	____ / _____
Admixtures	__ Air Entraining Agent* _	__ Micro Air __	0.50(oz)/ ____
	___ Retarder * ___	___ 100XE __	1.30(oz)/____
Water	_____	_____	15.70 / 7.04

Mixing Data: Mixing Date:_ 8-7-90_Mixer Used: Eirich Pan Mixing Time: 9:30 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.45

Pre-set Properties:

	Method
Slump_____2.00 in. _____	____ ASTM C 143___
Density___ 136.22 lb/cu ft ___	____ ASTM C 138___
Air Content_____ 6.50 % ____	____ ASTM C 231___
Setting Time: Initial:__ 6.50 hrs. __	____ ASTM C 403___
Final :__ 8.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-21-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength _____
B. S 90-21-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-21-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-21-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-21-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __
F._____

Testing Dates:(1d))Aug.8, (3d)) Aug.10, (7d)) Aug.14, (14d) Aug.21, (28d)Sept. 4-90

Notes: * **Interstate 80 Patching (Type AA)** Concrete Foprmulation (PADOT Specs. 408)
* Master Builders
++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -22* __ Originated by: __ R.I.A.MALEK _
Date: ____ 9-17-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-28 ____	10.89 / 14.01
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	27.06 / 34.81
Coarse Agg.	Crushed Limestone/ #57(SSD)	_____	34.76 / 44.71
Min. Admix.	_____	_____	____ / _____
	_____	_____	_____ /_____
Admixtures	__ Superplasticizer * __	_ Mighty-150 __	0.32(oz)/ _____
	___ Water REducer** ___	___ 122N ___	0.76(oz)/_____
Water	_____	_____	5.03 / 6.47

Mixing Data: Mixing Date:_ 9-17-90_Mixer Used: Eirich Pan Mixing Time: 10:20 am__
Temp.: 23 ± 1.5°C W/(C+F)= 0.46

Pre-set Properties:

	Method
Slump_____1.75 in. _____	____ ASTM C 143___
Density___ 148.34 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 2.00 % _____	____ ASTM C 231___
Setting Time: Initial:__ § hrs. __	____ ASTM C 403___
Final :__ § hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-22-C Compressive Strength § _____
B. S 90-22-K Perm.(a)Impulse§,(b)Chloride(28 d. only),(c)Standard§
C. S 90-22-Ø Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-22-M Microscopic Examination, (a) GMIC§, (b) MRL/PSU§ ___
E. S 90-22-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§ __

Testing Dates: October 15,1990.

Notes: * Faunce Bridge Pier Concrete Foprmulation (PADOT Specs. 408) without air entrainment and adjusting for the air by extra sand.
* Boremco Chemicals. ** Master Builders § Not Prepared/Measured.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 -23*** __ Originated by: __ **R.I.A.MALEK** _
Date: ____ 9-17-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-28 ____	28.31 / 14.79
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	59.66 / 31.17
Coarse Agg.	Crushed Limestone/ #57(SSD)	_____	90.37 / 47.21
Min. Admix.	_____	_____	____ / _____
Admixtures	__ Air Entraining Agent* _	___ MBVR ___	0.66(oz)/ _____
	___ Water REducer* ___	___ 122N ___	1.98(oz)/_____
Water	_____	_____	13.07 / 6.83

Mixing Data: Mixing Date:_ 9-17-90_Mixer Used: Eirich Pan Mixing Time: 12:40 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.46

Pre-set Properties:

	Method
Slump_____1.50 in. _____	____ ASTM C 143___
Density___ 140.54 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 6.50 % _____	____ ASTM C 231___
Setting Time: Initial:__ 5.00 hrs. __	____ ASTM C 403___
Final :__ 7.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-23-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 ____

B. S 90-23-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard

C. S 90-23-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____

D. S 90-23-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___

E. S 90-23-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d)Sept. 18, (3d) Sept. 20, (7d) Sept.24, (14d)Oct. 1, (28d)Oct. 15-90

28-Day Compressive Strength: 50.10 MPa ($\sigma_{6\ Samples}$ = 0.83 MPa)

Notes: * **Faunce Bridge Pier (Type A)** Concrete Foprmulation (PADOT Specs. 408)
* Master Builders ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -24* __ Originated by: __ R.I.A.MALEK _
Date: ____ 10-3-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-29____	28.31 / 15.23
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	54.50 / 29.32
Coarse Agg.	Crushed Limestone/ #57(SSD)	_____	90.42 / 48.64
Min. Admix.	_____	_____	____ / _____
dmixtures	__ Air Entraining Agent* _	___ MBVR ___	0.78(oz)/ _____
	___ Water Reducer* ___	___ 122N ___	1.50(oz)/_____
Water	_____	_____	12.65 / 6.81

Mixing Data: Mixing Date:_ 10-3-90_Mixer Used: Eirich Pan Mixing Time: 12:40 pm__
Temp.: 23 ± 1.5°C W/(C+F)= 0.45

Pre-set Properties:

	Method
Slump_____2.00 in. _____	____ ASTM C 143___
Density___ 143.31 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 6.50 % _____	____ ASTM C 231___
Setting Time: Initial:__ 5.00 hrs. __	____ ASTM C 403___
Final :__ 7.00 hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-24-C_1,C_3,C_7,C_{14}, and C_{28} Compressive Strength ___ ASTM C 39 _____
B. S 90-24-K_1,K_3,K_7,K_{14},and K_{28} Perm.(a)Impulse,(b)Chloride(28 d. only),(c)Standard
C. S 90-24-$Ø_1$,$Ø_3$,$Ø_7$,$Ø_{14}$,$Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-24-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU ___
E. S 90-24-I Interface, (a) Engineered without aggregate++,(b) Regular with aggregate __

Testing Dates:(1d))Oct. 4, (3d))Oct. 6, (7d))Oct. 10, (14d)Oct. 17, (28d)Oct. 31-90

28-Day Compressive Strength: 38.29 MPa ($\sigma_{6\ Samples}$ = 2.40 MPa)

Notes: * **Rt. 15 Patching (Type AA)** Concrete Foprmulation (PADOT Specs. 408)
* Master Builders ++ Not Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 -25*** ___ Originated by: __ **R.I.A.MALEK** _
Date: ____ 10- 3-90 ___

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 16.39
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	21.41 / 28.34
Coarse Agg.	Crushed Limestone/ # 67(SSD)	_____	35.93 / 47.56
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	_____	_____	_____/_____
	_____	_____	_____/_____
Water	_____	_____	5.82 / 7.70

Mixing Data: Mixing Date:_ 10- 3-90_Mixer Used: Eirich Pan Mixing Time:10:35 am__
Temp.: 23 ± 1.5°C W/C= 0.47

Pre-set Properties:

		Method
Slump_____	0.75 in ___	____ ASTM C 143___
Density_____	lb/ cu. ft§__	____ ASTM C 138___
Air Content_____	%§ ___	____ ASTM C 231___
Setting Time Initial:____	hrs.§ _	____ ASTM C 403___
Final :____	hrs.§__	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-25- C_{28} Compressive Strength§ _____
B. S 90-25- K_{28} Perm.(a)Impulse§,(b)**Chloride**,(c)Standard§
C. S 90-25- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-25-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-25-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G._____

Testing Date: October 31-90

Notes: * **For Chloride Permeability only.** §Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ **S 90 -26*** ____ Originated by: __ **R.I.A.MALEK** _
Date: ____ 10- 8-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	11.47 / 15.67
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	19.98 / 27.29
Coarse Agg.	Crushed Limestone/ # 67(SSD)	_____	35.93 / 49.08
Min. Admix.	____ Silica Fume** ____	___ G - 26 ____	0.93 / _____
	_____	_____	_____/_____
Admixtures	___ Superplasticizer + __	_ Mighty-150 __	0.06 /_____
	_____	_____	_____/_____
Water	_____	_____	5.83 / 7.96

Mixing Data: Mixing Date:_ 10- 8-90_Mixer Used: Eirich Pan Mixing Time:11:30 am__
Temp.: 23 ± 1.5°C W/(C+S) = 0.47

Pre-set Properties:

	Method
Slump_____ 2.00 in ___	____ ASTM C 143___
Density_____ lb/ cu. ft§__	____ ASTM C 138___
Air Content_____ %§ ___	____ ASTM C 231___
Setting Time Initial:____ hrs.§ _	____ ASTM C 403___
Final :____ hrs.§__	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-26- C_{28} Compressive Strength§ _____
B. S 90-26- K_{28} Perm.(a)Impulse§,(b)**Chloride**,(c)Standard§
C. S 90-26- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-26-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-26-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____

Testing Date: November 5-90

Notes: * **For Chloride Permeability only.** ** Elkem Chemicals.
+ Boremco Chemicals. § Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -27 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 8 - 30-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 16.54
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	21.00 / 28.05
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 47.89
Min. Admix.	_____	_____	_____/_____
	_____	_____	_____/_____
Admixtures	___ Superplasticizer* __	__ Mighty 150 _	1.0 (oz)/ _____
	_____	_____	_____/_____
Water	_____	_____	5.57 / 7.44

Mixing Data: Mixing Date:_ 8 - 30-90_Mixer Used: Eirich Pan Mixing Time: 9:25 am__
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

	Method
Slump_____2.00 in. _____	____ ASTM C 143___
Density___ 151.09 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 1.3% _____	____ ASTM C 231___
Setting Time Initial:_____ hrs. __	____ ASTM C 403___
Final :_____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-27- C_{28} Compressive Strength _____
B. S 90-27- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-27- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-27-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-27-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate
F._____
G _____

Testing Date: September 27-90

Notes: * Boremco Specialty Chemicals + Not prepared _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -28 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 8 - 30-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 17.58
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	16.54 / 23.49
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 51.02
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_ Air Entraining Agent * _	___ MBVR ___	0.33(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.91

Mixing Data: Mixing Date:_ 8 - 30-90_Mixer Used: Eirich Pan Mixing Time:11:25 am_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

		Method
Slump	1.75 in.	____ ASTM C 143___
Density	146.18 lb/cu ft	____ ASTM C 138___
Air Content	5.0%	____ ASTM C 231___
Setting Time Initial:	____ hrs. __	____ ASTM C 403___
Final :	____ hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-28- C_{28} Compressive Strength _____
B. S 90-28- K_{28} Perm.(a)Impulse,(b)Chloride,(c)Standard
C. S 90-28- $Ø_{28}$ Porosity. (a) MIP, (B) ASTM _____
D. S 90-28-M_{28} Microscopic Examination, (a) GMIC, (b) MRL/PSU
E. S 90-28-I Interface, (a) Engineered without aggregate+,(b) Regular with aggregate
F._____
G _____

Testing Date: September 27-90

Notes: * Master Builders Vinesol Resin. + Not prepared _____

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -29 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 11- 15-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 17.58
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	16.54 / 23.49
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 51.02
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_ Air Entraining Agent * _	___ MBVR ___	0.33(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.91

Mixing Data: Mixing Date:_ 11- 15-90_Mixer Used: Eirich Pan Mixing Time:11:30 am_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

	Method
Slump_____2.375 in. _____	____ ASTM C 143___
Density___ 143.79 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 5.5%(P) _____	____ ASTM C 231___
Setting Time Initial:__ § hrs. __	____ ASTM C 403___
Final :__ § hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-29- C_{28} Compressive Strength§ _____
B. S 90-29- K_{28} Perm.(a)Impulse§,(b)Chloride§,(c)Standard§
C. S 90-29- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-29-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-29-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G _____

Notes: * Master Builders Vinesol Resin. § Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -30 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 8 - 30-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 17.58
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	16.54 / 23.49
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 51.02
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_____ Micro Air * ____	___ F-03 ___	0.17(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.91

Mixing Data: Mixing Date:_ 8 - 30-90_Mixer Used: Eirich Pan Mixing Time: 1:25 pm_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

		Method
Slump	1.50 in.	____ ASTM C 143___
Density	147.50 lb/cu ft	____ ASTM C 138___
Air Content	3.0%	____ ASTM C 231___
Setting Time Initial:	§ hrs.	____ ASTM C 403___
Final :	§ hrs.	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-30- C_{28} Compressive Strength _____
B. S 90-30- K_{28} Perm.(a)Impulse§,(b)Chloride,(c)Standard§
C. S 90-30- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-30-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-30-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G _____

Testing Date: September 27-90

Notes: * Master Builders. § Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -31 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 11- 15-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 17.58
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	16.54 / 23.49
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 51.02
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_____ Micro Air * ____	___ F-03 ___	0.42(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.91

Mixing Data: Mixing Date:_ 11- 15-90_Mixer Used: Eirich Pan Mixing Time: 9:30 am_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

	Method
Slump_____1.75 in. _____	____ ASTM C 143___
Density___ 146.29 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 4.2%(P)_____	____ ASTM C 231___
Setting Time Initial:__ § hrs. __	____ ASTM C 403___
Final :__ § hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-31- C_{28} Compressive Strength§ _____
B. S 90-31- K_{28} Perm.(a)Impulse§,(b)Chloride§,(c)Standard§
C. S 90-31- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-31-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-31-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G _____

Notes: * Master Builders. § Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -32 ____ Originated by: __ R.I.A.MALEK _
Date: ____ 11- 15-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 17.58
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	16.54 / 23.49
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 51.02
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_____ Micro Air * ____	___ F-03 ___	0.62(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.91

Mixing Data: Mixing Date:_ 11- 15-90_Mixer Used: Eirich Pan Mixing Time:11:00 am_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

	Method
Slump_____2.25 in. _____	____ ASTM C 143___
Density___ 137.83 lb/cu ft ____	____ ASTM C 138___
Air Content____ 8.00 %(P)_____	____ ASTM C 231___
Setting Time Initial:__ § hrs. __	____ ASTM C 403___
Final :__ § hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-32- C_{28} Compressive Strength§ _____
B. S 90-32- K_{28} Perm.(a)Impulse§,(b)Chloride§,(c)Standard§
C. S 90-32- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-32-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-32-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G _____

Notes: * Master Builders. § Not Determined/Prepared.

Mixing Data (SHRP)

Mix Identification No.: ____ S 90 -33* ___ Originated by: __ R.I.A.MALEK _
Date: ____ 11- 30-90 ____

Formulation:	Type/Size	Code	Wgt(lb)/%
Cement	_____Type - I _____	____ I-25 ____	12.38 / 16.78
Fine Aggregate	Lycoming Sand/ASTM C33(SSD)	_____	19.91 / 27.00
Coarse Agg.	Crushed Limestone/ #67(SSD)	_____	35.92 / 48.69
Min. Admix.	_____	_____	_____ /_____
	_____	_____	_____ /_____
Admixtures	_ Air Entraining Agent ** _	___ MBVR ___	0.60(oz)/ ____
	_____	_____	_____ /_____
Water	_____	_____	5.57 / 7.55

Mixing Data: Mixing Date:_ 11- 30-90_Mixer Used: Eirich Pan Mixing Time:10:30 am_
Temp.: 23 ± 1.5°C W/C= 0.45

Pre-set Properties:

	Method
Slump_____2.25 in. _____	____ ASTM C 143___
Density___ 138.91 lb/cu ft ____	____ ASTM C 138___
Air Content_____ 6.7%(P) _____	____ ASTM C 231___
Setting Time Initial:__ § hrs. __	____ ASTM C 403___
Final :__ § hrs. __	

Curing Conditions: Precure Time initl. 24 hrs. Temp. 23 ± 1.5°C Soln. in mold____
Curing Time after 24 hrs. Temp. 23 ± 1.5°C Soln.saturated lime

Samples Prepared/Tests Run/Disposition:

A. S 90-33- C_{28} Compressive Strength§ _____
B. S 90-33- K_{28} Perm.(a)Impulse§,(b)Chloride§,(c)Standard§
C. S 90-33- $Ø_{28}$ Porosity. (a) MIP§, (B) ASTM§ _____
D. S 90-33-M_{28} Microscopic Examination, (a) GMIC§, (b) MRL/PSU§
E. S 90-33-I Interface, (a) Engineered without aggregate§,(b) Regular with aggregate§
F._____
G _____

Notes: * S89-1 F0rmulation with reduced W/C ratio and added air entraining agent.
** Master Builders Vinesol Resin. § Not Determined/Prepared.

Appendix D
Modelling Rheological Behavior of Cement Pastes: A Review

MODELING THE RHEOLOGICAL BEHAVIOR OF CEMENT PASTES: A REVIEW

R. I. A. Malek and D. M. Roy

Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802

Abstract

The mechanical behavior of cement suspensions is complex. For decades research on the rheology of cement slurries has been dealing mainly with empirical equations such as the Bingham model, which is essentially descriptive. As a result of the work on micromechanics, theories evolved for the rheological behavior of dilute suspensions. Mathematical models have been developed to describe the direct dependency of the viscosity on particle packing. The thixotropic properties of cement slurries have been considered by developing time-dependent models. All of these models provide empirical descriptions of dispersions, in which the most elementary particle-particle interactions have not been well defined. Two recently developed models consider these types of interactions.

Introduction

Modeling the rheological behavior is necessary in order to predict the behavior of fresh concrete under different flow conditions and facilitate the development of formulations for optimum concrete specifications. A systematic approach to generate a rheological model for fresh concrete is to find an expression that enables calculating the mechanical properties of fresh concrete from the fundamental characteristics of the constituents and mix proportioning.

Fresh concrete can be represented by aggregate grains in a continuum of cement particles and water (paste). The aggregate amount and physical properties as well as the microstructure of the continuum will affect the rheological properties of fresh concrete. This signifies the importance of modeling the rheological behavior of cement pastes.

Due to the physical characteristics of cement particles, the particulate structure tends to coalesce and eventually encompass the whole sample in a global network of different size flocs or a gigantic floc. Depending on the forces present this flocculation has a considerable effect on the rheological behavior of fresh paste. The floc will have a structure that extends throughout the sample entailing a solid-like rigidity which is reflected in elastic behavior and in the appearance of a yield stress. Deformability under external forces could be a source of viscoelasticity. Finally, the structure can change reversibly under flow causing shear thinning and thixotropy. The mechanical behavior of the proposed floc structure is complex. This paper is a review of the most important work available which has dealt with the modelling of cement paste rheological behavior.

Rheological Models

Bingham Model

The rheological literature deals mainly with empirical equations such as the Bingham model /1/ which is essentially descriptive. As a result of the work on micromechanics, theories evolved for dilute suspensions of axisymmetric particles in Newtonian fluids. These theories have been reviewed /2-5/ but they will be considered briefly in the present paper.

Packing Models

The direct dependency of the viscosity on particle packing has become an area in which mathematical models have been developed. This started with the initial work of Mooney /6/ in which it was attempted to calculate the shear dependency of viscosity from an estimate of the packing volume fraction of the solid [eqn. 1]:

$$\eta = e^{\alpha\phi/1-k\phi} \qquad [1]$$

where η = viscosity, ϕ = packing volume fraction, and α and k = constants.

Several other attempts have been made to express the packing volume fraction from the experimental determination of particle size distribution. Lee /7/ developed an analytical method to calculate the packing volume fraction of an idealized binary mixture of spheres as a function of diameter ratio and composition [eqn. 2]:

$$\phi = \sum_{j=1}^{j=n} \phi_{ij} \cdot x_j \qquad [2]$$

where ϕ_{ij} = packing volume fraction which is proportional to diameter ratio D_i/D_j, and x_j = volume fraction of component

$$j(\sum_{1}^{n} x_j = 1).$$

DeLarrad and coworkers /8,9/ extended Mooney's concept to calculate the packing density of a granular mixture, knowing particle distribution and the packing densities of the various elementary one-size classes of grains. Originally it was designed for spheres but later extended to cover other particle shapes. The principal equation of the model is as follows:

$$\rho_i = \alpha_i + (1-\alpha_i) \sum_{j=1}^{i-1} g(i,j)\phi_j + \sum_{j=i+1}^{n} f(i,j)\phi_j \qquad [3]$$

where ρ_i = packing density, α_i = constant (structural factor), g and f = crowding factors, and ϕj = fractional solid volume of component j.

Ball and Richmond /10/ theoretically accounted for the empirically derived formula /11/ [eqn. 4] for the effect of phase volume on viscosity,

$$\eta = (1 - \phi/\phi_{max})^{-3/2} \qquad [4]$$

where η = viscosity and ϕ_{max} = maximum packing fraction, i.e., the phase volume where the viscosity is infinite.

The packing models considered only the effect of solid phase volume on rheological properties of suspensions. At high solid loading (as in cement) the particle-particle interactions gradually dominate the volume effects and the packing volume fraction becomes shear dependent. This might induce difficulty in expressing the rheological behavior of slurries over a wide range of shear stresses.

Time-Independent Models

Several rheological expressions have been developed to fit shear rate-shear stress curves. In Table 1 a number of equations are listed which have been found to fit the viscometric data of several cement dispersions. Because the various model constants are mostly empirical, their physical meanings are not discussed here.

Table 1. Rheological models for cement pastes.

Model			Behavior
$\tau = \eta$	[5]		Newtonian
$\tau = \tau_o + \eta\gamma$	[6]	Bingham /1/	Binghamian
$\eta = \eta_o + k\gamma^n$	[7]		n > 1 Dilatant
	}	Herschel and Buckley /12/	
$\gamma = A\,(\tau - C)^B$	[8]		n < 1 Viscoplas.
$\eta = A\,(\gamma + C)^B$	[9]	Robertson and Stiff /13/	B > 1 Dilatant B < 1 Viscoplas.
$\tau = \tau_o + B\,\sinh^{-1}(\gamma/C)$	[10]	VomBerg /15/	Viscoplastic
$\tau = \sum_{i=1}^{n} A\,\sinh^{-1}(\gamma B_i)$	[11]		Pseudoplastic
	}	Eyring /16/	
$\tau = A\gamma + B\,\sinh^{-1}(\gamma/C)$	[12]		
$\gamma = K_1\tau + K_2\tau^n$	[13]	Ellis /17/	Pseudoplastic
$\tau^{1/2} = \tau_o^{1/2} + k_1\gamma^{1/2}$	[14]	Casson /18/	Viscoplastic

τ = shear stress
τ_o = yield stress
γ = shear rate
η = viscosity
A, B, C, k, k_1, k_2, α, β, δ = constants

While eqn. [5] describes a shear independent viscosity, eqn. [6] eventually describes a large part of the shear thickening zone in the rheogram. Equations [7] and [8] have been utilized by Jones and Taylor /14/. For cement dispersions, three specific cases emerged:

$C = 0$	$B = 1$	$; \gamma = A\tau$	Newtonian
	$B = 1$	$; \gamma = \tau_o + A\tau$	Bingham
$C = 0$		$; \gamma = A\tau^B$	Power Law

where the first two cases cannot describe the non-linear γ - τ relationships such as in cement slurries as does the third case.

Equation [10] describes the non-linear (parabolic) relationship between τ and γ at low shear rate. The yield stress has been defined as follows:

$$\tau_o = a_1 e^{b_1 C_v} S_{vB}^{b_2} \qquad [15]$$

where C_v = solid volume concentration, S_{vB} = specific surface area, and a_1, b_1 and b_2 = constants.

Equations [11] and [12] describe systems with non-Newtonian behavior (non-linear τ vs. γ) at low shear but tend to become Newtonian (linear τ vs. γ) with increasing shear rate. The equation constants depend on temperature, activation energy, and geometry. Atzeni and coworkers /19,20/ combined the linear part of Eyring's equation [12] and the von Berg equation [10] in one equation:

$$\tau = \tau_o + AD + \sinh^{-1}(\gamma/C) \qquad [16]$$

Equations [13] and [14] are generalizations from the Newtonian and Power Law relations.

All the above-mentioned models are time-independent models that can be used to describe parts of the rheograms. Cement pastes and concretes possess time-dependent rheological properties (thixotropy). Some models have been proposed to describe such properties.

Time-Dependent Models (Thixotropy)

The problem has been tackled by several investigators over two decades /21-29/. Their findings have been summarized by Atzeni et al. /30/ who forwarded the following equation to describe time-dependent properties (thixotropic model):

$$\tau = \tau_e + (\tau_m - \tau_e)\, e^{-B_\infty t} - B_\infty - \alpha\,(1-e^{-t/T}) \qquad [17]$$

where τ = shear stress; τ_e = shear stress (at $t = \infty$), equilibrium; τ_m = shear stress (at $t = 0$), initial; t = time; B_∞ and T = constants; and α = structural factor (dimensionless).

All the above-mentioned models [packing, time-independent, and time-dependent (thixotropic) models] describe, empirically, dispersions where the most elementary particle interactions have been poorly tackled. Even in those models where the points of contacts have been taken into consideration (thixotropic models), the interactions at points of contacts have not been well defined (i.e., repulsive, attractive, or balanced).

Particle-Particle Interactions Models

In cement systems where the repulsive interactions do not predominate completely over the attractive forces, particles may have a tendency to cluster forming flocs with a variety of types of structures depending upon other forces present (electrical charges, etc.). At the same time fluid will be immobilized between the particles and incorporated into the floc. With shear, flocs tend to

decrease in size releasing amounts of immobilized liquids, leading to shear thinning (thixotropic) behavior. Obviously, flocculation has considerable effects on rheological behavior. The size and shape of flocs will affect the interactions between them. Modeling of this behavior is complicated. The initial work attempted to calculate shear dependency of viscosity from crude estimates of floc size under shear /31,32/ followed by including time effects /33-35/ have been used essentially for more fitting purposes /31, 32, 33, 36/. Two recently developed models might deal with these types of interactions. The two theories are based on Smoluchowski's theory /37/ which accounts for the electrostatic drag on particles in motion, due to distortion of the ionic atmosphere (electrical double layer) around them. The Smoluchowski equation can be written as follows:

$$\eta=\eta_o\left[1+2.5\phi\left\{1+\frac{1}{\sigma\eta_o a^2}\left([\frac{\zeta\varepsilon}{2\pi}]\right)^2\right\}\right] \qquad [18]$$

where η = viscosity of the suspension, η_O = viscosity of the dispersion medium, ϕ = packing volume fraction, ε = dielectric constant, σ = specific conductivity of the electrolyte, a = radius of the solid particle, and ζ = electrokinetic potential.

The two theories predict some trends reasonably well based on the effect of particle size, volume concentration, and repulsive forces. The first theory (elastic floc model) developed by Hunter and collaborators /38-40/ expresses the repulsive forces in terms of the surface potential (ζ-potential) whereas the second theory developed by Hattori and Izumi /43/ expresses the repulsive forces in terms of the Debye radius. A summary of the basic equations of the two theories is presented in the following.

(a) Elastic Floc Model

Primary particles are linked in a three-dimensional array, trapping a significant volume of suspending medium. This array is destroyed by high shear rate so that floc volume ratio (C_{FP} =

ϕ_F/ϕ_P, where ϕ_F = volume of floc, and ϕ_P = volume of particles) tends to decrease. The rate by which the volume decrease depends on attraction forces between particles (ζ-potential)

$$\eta = \frac{n_F r}{5\gamma}\left[\frac{A}{12\, d_1^2} - B(d_1)\,\zeta^2\right] \qquad [19]$$

where η = viscosity, n_F = number of bonds, r = particle radius, γ = shear rate, A = constant, d_1 = distance of maximum attraction between particles, B = constant, and ζ = zeta potential.

(b) Friction and Viscosity Model

Viscosity depends on the number of friction points (junction points) of solid-solid, solid-liquid, and liquid-liquid contacts. For highly concentrated suspensions the first (solid-solid junction points) is the most significant.

$$\eta = B_3 . n_3^{2/3} \left\{ 1 - \frac{e^x G\, t^2}{(pt + e^x)\,(G\, t^2 1)} \right\} \qquad [20]$$

where η = viscosity, B = friction, n = number of particles, x is a value proportional to repulsive potential (ζ-potential), G = constant proportional to increasing shear rate, t = time, and P = constant proportional to Debye parameter.

The flow can induce or delay flocculation /41,42/. The effects produced by such a variation in structure of the flocs as well as the irreversible changes resulting from microstructure changes have to be taken into consideration to develop a completed model.

Conclusions

Several models have been introduced to express the rheological behavior of dense suspensions such as cement pastes. Packing models are only valid for low solid loading or at low shear

stresses. Time-independent as well as time dependent models have been forwarded for primarily curve-fitting purposes but they carry little physical significance. Elastic floc and friction models can describe the rheology of dense flocculated dispersions. Microstructural variations and irreversible changes need to be included to completely describe cement systems.

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This paper represents the views of the authors only, not necessarily reflective of the views of the National Research Council, the views of SHRP, or SHRP's sponsors. The results reported here are not necessarily in agreement with the results of other SHRP research activities. They are reported to stimulate review and discussion within the research community.

Nomenclature

C_v	solid volume concentration
d	distance of maximum attraction between particles
D	Particle diameter
g and f	crowding factors
n_F	number of bonds
n	number of particles
r	radius of the solid particle
S_{vB}	specific surface area
x_j	volume fraction of component j
t	time
γ	shear rate
ε	dielectric constant
η	viscosity
η_o	viscosity of the dispersion medium
ζ	electrokinetic (ζ) potential.
τ	shear stress

τ_o	yield stress
τ_e	shear stress (at t = ∞), equilibrium
τ_m	shear stress (at t = 0), initial
ϕ	packing volume fraction
ϕ_{max}	maximum packing fraction, i.e., the phase volume where the viscosity is infinite
ρ_i	packing density
ψ	friction
σ	specific conductivity of the electrolyte
$\alpha,\beta,\delta,a,b,A,B,C,k,T$	constants

Indeces

G	value proportional to increasing shear rate
P	value proportional to Debye parameter
x	value proportional to repulsive potential (ζ-potential)

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Appendix E
An Approach to Assess Concrete Thixotropy

Introduction

During the first few minutes and hours after mixing, the rheological properties of fresh concretes exhibit a wide range of behavior. The rate of build-up of load-bearing structure in concrete has a profound impact on the overall construction process. Extensive research has been dedicated to the assessment of chemical and physical changes in the non-sheared concretes during the early ages, but much less research has been directed towards the assessment of such properties under shear conditions. Sound tests and techniques are then required to understand and to quantify the physical changes in fresh concrete under shear that are related to structure build-up. Towards this end, the assessment of rheological properties of fresh concrete, done under the current research program may help in establishing the necessary information to initiate research work that can lead to an equipment that better describe concrete thixotropy than the traditional slump test. It may encompass the slump test; first, this is very familiar to the practitioners and secondly since it correlates with one of the two principal rheological constants for fresh concrete, namely the yield stress.

Thixotropy and Workability of Concrete

Workability of fresh concrete is too complex to be easily defined by a single term. Depending on the property measured and the technique adapted, several authors have proposed various definitions for workability. Perhaps the most exclusive definition is that recommended by ACI[1] as: "workability is that property of fresh concrete or mortar that determines the ease with which it can be mixed, transported, placed, compacted and finished. " Two constants, yield stress and plastic viscosity are often considered as sufficient to describe the workability and rheological behavior of fresh concrete. Assessment of the two constants requires shearing the concrete at higher rates. Under such circumstances the large deformation causes continuous breaking down the delicate structure which forms as the hydration reactions progress. This leads to shear thinning and the phenomenon is called thixotropy. The phenomenon is important since it is related to the rate of structure growth and strength development. It is also commercially important as its value provides a means to control the rate of structure build-up to meet the construction requirements.

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[1] ACI. "Cement and Concrete Terminology," Publication No. SP-19, The American Concrete Institute, Detroit, MI (1967).

Common Techniques for Measuring Workability

a. Slump Test. The most widely used type of test for measuring consistency is the slump test. Although it is sensitive to the conditions under which the test is made, its simplicity makes it suitable for field applications. The test has always been criticized; for instance, it does not cover all workability ranges. This is due to the fact that the test is entirely related to the plastic deformation of a concrete cone under forces exerted by its own weight. Shear or collapse in the test means that the concrete lacks plasticity and the test is not valid.

Another frequent objection to the slump test is that the results fluctuate widely and the reproducibility is poor. This might be a reflection of the sensitivity of the slump test to materials variance. The slump values have been found to vary inversely with the yield stress values. Due to the small shear forces involved, the slump test is not suitable to assess thixotropy.

b. The Drop Table. A previously standardized test (ASTM C124-71) that has been discontinued; its use in the field would be cumbersome compared to the slump test. The reproducibility of the results, however, is much better than the slump. Dimond and Bloomer[2] found that the initial spread area of the DIN flow table (which corresponds roughly to the slump value) to be more sensitive to differences between mixes than the area after jigging the table.

c. Vebe Test. Similar in principle to the drop table, this test, however, is done under vibration. It is expressed as the time elapsed for a cone of concrete to reshape to a cylindrical configuration. It is, however, liable to the same difficulties as the drop table.

d. Penetration Tests and Consistometers. These tests measure the extent of penetration of a specified solid probe or body into fresh concrete. The deeper the penetration, the softer the consistency. The Kelly Ball test has been standardized (ASTM C360-63) for concrete. The performance of these tests is usually simple and quick and thus suitable for field use. The shortcomings of the test are that its reliability decreases with increasing size of aggregate and the entire result might be controlled by the composition of the top layer rather than by the bulk concrete. The low shear stresses involved makes the test invalid for thixotropic evaluation.

e. Tube, Orifice Flaw. Several test methods with various designs ranging from vertical tube, tilted tube to funnel hopper, etc., have been designed to assess the consistency

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[2] C.R. Dimond and S.J. Bloomer, "A Consideration of the DIN Flow Table," Concrete (London), Vol. 11, No. 12, pp. 29-30 (1977). Cited in "The Rheology of Fresh Concrete," by G.H. Tattersall and P.F.G. Baufill, Pitman Publishing Co. (1983).

of concrete. The time elapsed for a certain quantity of concrete to pass through an orifice is a measure for consistency of concrete. Difficulties include the dependency of the result on the orifice diameter relative to the aggregate size. Other difficulties include the very limited applicability in the field due to the need for highly skilled personnel and the use of vibration.

f. Shearing Rheometers. Tattersall and co-workers designed a shearing rheometer for determining the two rheological constants of fresh concrete, namely the yield stress and plastic viscosity. The test includes the measurement of torque values at variable shear rates. The limits of the equipment used in this laboratory are between 0.33 and 1.33 revolutions per second. When the results are plotted with the torque represented on the abscissa and the shear rate on the ordinate, an approximately straight line is obtained whose intersection with the abscissa gives the yield value and the reciprocal of its shear rate to torque gradient gives the plastic viscosity. The equipment is based on the idea that fresh concrete approximates a Bingham body in this range of shear stresses. The yield stresses were found to correlate inversely with the results of slump test.

The most important difficulties in using this equipment are its high sensitivity, the need for highly skilled personnel and the fact that it is a cumbersome procedure. The oil pressure system used for measuring torque limits the upper speed to ~1.5 revolutions per second and assessment of thixotropic properties might require much high shear stresses.

Conclusions

More than a single test of technique is needed to assess the thixotropic properties of fresh concrete. Quantification of the thixotropic properties is of economic and technical value to the construction industry especially in the highway environment. The slump test may have been under-estimated by several investigators in favor of more complicated procedures, yet with limited field applicability of the test equipment. Its simplicity and direct correlation with yield stress, makes slump favorable for field usage. The low shear forces involved in the test makes it necessary to find other equipment to assess high shear properties such as viscosity and thixotropy.

Appendix F
Computer Code for Hydration Model

```
list
10 REM*********************************
20 REM CEMHYD
30 REM ****************
40 REM HYDRATION MODEL
50 REM PORTLAND CEMENT
60 REM *****************
70 REM B. OSBAEK , SEPT.-NOV.1988
80 REM RETTET VJ, GMIC 19. NOV 88
90 REM ***********************
95 COLOR 14,9,9
100 A$="                                                ANY KEY TO CONTINUE"
110 DIM N(15),N$(150),M(15),D(15),C(15),B(15),G(15),H(15,10)
120 DIM T(10),A(5,10),V(10),U(10),P(10),W(10),E(10),Q(10),R(10),L(10)
130 REM ****************************
140 REM COMPOUNDS * DATABASE
150 REM ************************
160 PRINT
170 PRINT
180 PRINT "***DATA BASE***"
190 B$= "***DATA BASE***"
200 PRINT
210 PRINT "No.  Compound        M           d        -dHf   "
220 C$= "No.  Compound        M           d        -dHf   "
230 PRINT
240 PRINT "                  (g/mole)     (g/cm3)    (kcal/mole)"
250 D$= "                  (g/mole)     (g/cm3)    (kcal/mole)"
260 PRINT
270 FOR I=1 TO 13
280 READ N(I),N$(I),M(I),D(I),C(I)
290 PRINT USING"##   ";N(I);
300 PRINT N$(I);:PRINT USING"   ####.##    ";M(I);D(I);C(I)
310 NEXT I
320 FOR J=1 TO 3
330 PRINT
340 NEXT J
350 REM No,  Name,  Molar weight,   Density,  Heat of formation (-)
360 DATA 1,"C3S     ",228.33,3.2,688.1
370 DATA 2,"C2S     ",172.25,3.28,538
380 DATA 3,"C3A     ",270.2,3.03,861
390 DATA 4,"C4AF    ",242.99,3.77,720
400 DATA 5,"C(free) ",56.08,3.32,151.9
410 DATA 6,"CaH2    ",172.178,2.32,483.06
420 DATA 7,"H       ",18.016,1,68.317
430 DATA 8,"CxSHy   ",221.882,2,754
440 DATA 9,"CH      ",74.096,2.24,235.8
450 DATA 10,"AFt     ",1255.15,1.76,4193
460 DATA 11,"AFm     ",622.538,1.95,2100
470 DATA 12,"C4AH19  ",668.584,1.8,2409
480 DATA 13,"C2AH8   ",358.248,1.97,1291
490 PRINT "*** CEMENT COMPOSITION AND WATER AMOUNT (grammes) ***"
500 E$= "*** CEMENT COMPOSITION AND WATER AMOUNT (grammes) ***"
510 PRINT
520 FOR I=1 TO 7
530 K1=(I-1)*10+1
540 K2=K1+9
550 PRINT N$(I)+" =",
560 INPUT B(I)
570 G(I)=B(I)/M(I)
580 NEXT I
```

```
590 PRINT"DO YOU WANT TO CORRECT? (Y/N)":INPUT I$
600 IF I$="Y"OR I$="y" THEN 520
610 REM **************
620 REM KINETIC DATA
630 REM **************
640 PRINT:PRINT:PRINT
650 PRINT "***KINETIC DATA (Time(d) and d.h.o. (%))***"
660 F$= "***KINETIC DATA (Time(d) and d.h.o. (%))***"
670 PRINT
680 U$="  T     C3S     C2S     C3A     C4AF     C"
690 PRINT U$
700 N1=0
710 FOR I=1 TO 6
720 READ T(I),A(1,I),A(2,I),A(3,I),A(4,I),A(5,I)
730 IF T(I)<0 THEN 920
740 N1=N1+1
750 PRINT  USING"###     ";T(I),A(1,I),A(2,I),A(3,I),A(4,I),A(5,I)
760 FOR J=1 TO 5
770 A(J,I)=A(J,I)/100
780 NEXT J
790 NEXT I
800 PRINT A$
810 IF INKEY$="" THEN 810
820 DATA 0,0,0,0,0,0
830 DATA 1,45,5,25,10,100
840 DATA 3,60,10,50,25,100
850 DATA 7,75,20,75,35,100
860 DATA 28,80,30,80,40,100
870 DATA 999,100,100,100,100,100
880 CLS
890 PRINT:PRINT:PRINT:PRINT
900 PRINT:PRINT"           WORKING"
910 REM **********************
920 REM PASTE COMPOSITION AT TIME T(I)840
930 REM ******************************
940 FOR I=1 TO N1
950 REM ANHYDRATES
960 FOR J=1 TO 5
970 H(J,I)=(1-A(J,I))*G(J)
980 NEXT J
990 REM ::::CxSHy AND CH
1000 X=1.6
1010 Y=4
1020 M(8)=X*56.08+Y*18.016+60.09
1030 H(8,I)=A(1,I)*G(1)+A(2,I)*G(2)
1040 H(9,I)=A(5,I)*G(5)+(3-X)*A(1,I)*G(1)+(2-X)*A(2,I)*G(2)
1050 REM::::: AFt,AFm,C4AH11,C2AH8
1060 REM ::::: HYDRATES (ZERO SETTING)
1070 FOR J= 10 TO 13
1080 H(J,I)=0
1090 NEXT J
1100 C3=A(3,I)*G(3)
1110 C2=A(4,I)*G(4)
1120 IF H(9,I)>0 THEN 1140
1130 GOTO 1220
1140 IF H(9,I)<C2 THEN 1190
1150 C3=C3+C2
1160 H(9 I)=H(9,I)-C2
1170 C2=0
1180 GOTO 1220
```

```
1190 C3=C3+H(9,I)
1200 C2=C2-H(9,I)
1210 H(9,I)=0
1220 IF C3=0 THEN 1360
1230 F=G(6)/C3
1240 IF F<3 THEN 1280
1250 H(10,I)=C3
1260 C3 =0
1270 GOTO 1350
1280 IF F<1 THEN 1330
1290 H(10,I)=(F-1)/2*C3
1300 H(11,I)=(3-F)/2*C3
1310 C3=0
1320 GOTO 1350
1330 H(11,I)=G(6)
1340 C3=C3-H(11,I)
1350 IF H(9,I)>0 THEN 1390
1360 H(12,I)=.5*C3
1370 H(13,I)=.5*C3+C2
1380 GOTO 1460
1390 IF H(9,I)>C3 THEN 1440
1400 H(12,I)=H(9,I)+.5*(C3-H(9,I))
1410 H(13,I)=.5*(C3-H(9,I))
1420 H(9,I)=0
1430 GOTO 1460
1440 H(12,I)=C3
1450 H(9,I)=H(9,I)-C3
1460 H(6,I)=G(6)-3*H(10,I)-H(11,I)
1470 H2=32*H(10,I)+12*H(11,I)+19*H(12,I)+8*H(13,I)
1480 H(7,I)=G(7)+2*(G(6)-H(6,I))-Y*H(8,I)-H(9,I)-H2
1490 V(I)=0
1500 W(I)=0
1510 E(I)=0
1520 FOR J=1 TO 13
1530 V(I)=V(I)+H(J,I)*M(J)/D(J)
1540 E(I)=E(I)+H(J,I)*C(J)
1550 NEXT J
1560 FOR J=1 TO 5
1570 W(I)=W(I)+H(J,I)*M(J)
1580 NEXT J
1590 U(I)=V(I)-H(7,I)*M(7)/D(7)
1600 P(I)=(V(1)-U(I))/V(1)
1610 Q(I)=(E(I)-E(1))/(W(1)+B(6))*1000
1620 R(I)=(1-W(I)/W(1))*100
1630 L(I)=((H(7,1)-H(7,I))*M(7)+H(6,I)*M(6)*.20927)/(W(1)+B(6))*100
1640 NEXT I
1650 REM ******************
1660 REM OUTPUT
1670 REM ******************
1680 CLS
1690 FOR I=1 TO 4
1700 PRINT
1710 NEXT I
1720 PRINT "PASTE COMPOSITION (millimoles) "
1730 G$= "PASTE COMPOSITION (millimoles) "
1740 PRINT
1750 PRINT "T"
1760 H$="T"
1770 PRINT
1780 PRINT "      C3S       C2S       C3A       C4AF      C       CaH2      H"
```

```
1790 K$= "       C3S        C2S       C3A       C4AF      C       CaH2      H"
1800 PRINT "     CxSHy     CH        AFt       AFm     C4AH19    C2AH8      "
1810 L$= "     CxSHy     CH        AFt       AFm     C4AH19    C2AH8      "
1820 FOR I=1 TO N1
1830 PRINT T(I)
1840 FOR J=1 TO 7
1850 PRINT USING" #######.##";H(J,I)*1000,
1860 NEXT J
1870 PRINT
1880 FOR J=8 TO 13
1890 PRINT USING" #######.##";H(J,I)*1000,
1900 NEXT J
1910 PRINT
1920 NEXT I
1930 PRINT A$
1940 IF INKEY$="" GOTO 1940
1950 FOR I=1 TO 4
1960 PRINT
1970 NEXT I
1980 PRINT "*** PASTE COMPOSITION (Volume pct.)***"
1990 M$= "*** PASTE COMPOSITION (Volume pct.)***"
2000 PRINT
2010 PRINT "T"
2020 PRINT "      C3S         C2S       C3A       C4AF      C       CaH2      H"
2030 PRINT "     CxSHy        CH        AFt       AFm     C4AH19    C2AH8     X"
2040 FOR I=1 TO N1
2050 PRINT
2060 PRINT T(I)
2070 FOR J=1 TO 7
2080 PRINT USING" #######.##";H(J,I)*M(J)/D(J)/V(1)*100,
2090 NEXT J
2100 PRINT:FOR J=8 TO 13
2110 PRINT USING" #######.##";H(J,I)*M(J)/D(J)/V(1)*100,
2120 NEXT J
2130 PRINT USING"#######.##";((V(1)-V(I))/V(1)*100),
2140 NEXT I
2150 PRINT A$
2160 IF INKEY$="" GOTO 2160
2170 FOR I=1 TO 4
2180 PRINT
2190 NEXT I
2200 CLS
2210 PRINT "*** TOTAL VOLUME, SOLID VOLUME & POROSITY ***"
2220 O$= "*** TOTAL VOLUME, SOLID VOLUME & POROSITY ***"
2230 PRINT
2240 PRINT "   T     V         dV        Va      dVa         P"
2250 P$= "   T     V         dV        Va      dVa         P"
2260 PRINT
2270 PRINT "  (d)  (cm3)    (cm3)     (cm3)    (cm3)"
2280 R$= "  (d)  (cm3)    (cm3)     (cm3)    (cm3)"
2290 PRINT
2300 FOR I=1 TO N1
2310 PRINT USING"###.###  ";T(I),V(I),(V(I)-V(1)),U(I),(U(I)-U(1)),P(I)
2320 NEXT I
2330 PRINT A$
2340 IF INKEY$="" GOTO 2340
2350 FOR I=1 TO 4
2360 PRINT
2370 NEXT I
2380 CLS
```

```
2390 PRINT "*** DEGREE OF HYDR., BOUND WATER, HEAT OF HYDR. ***"
2400 S$= "*** DEGREE OF HYDR., BOUND WATER, HEAT OF HYDR. ***"
2410 PRINT
2420 PRINT "    T       a       w       Q"
2430 PRINT
2440 PRINT "   (d)     (%)     (%)   (cal/g)"
2450 T$= "   (d)     (%)     (%)   (cal/g)"
2460 PRINT
2470 FOR I=1 TO N1
2480 PRINT USING"###.#   ";T(I),R(I),L(I),Q(I)
2490 NEXT I
2500 END
Ok
```

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