LIGHTWEIGHT ALUMINA REFRACTORY AGGREGATE

Phase III: Full-Scale Demonstration

By
T. G. Swansiger
A. Pearson

July 16, 1996

Work Performed Under Contract No. DE-FC07-89ID12903

For
Idaho Operations Office
Idaho Falls, Idaho

By
Aluminum Company of America
Alcoa Center, PA

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Report No. 06-96-11

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Prepared by
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1996 July 16
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Lightweight Alumina Refractory Aggregate

Phase III - Full-Scale
Demonstration

Task 1 - Resolution of Technical Issues
Concerning Density, Intermediate
Strength, and Steel Slag Exposure
Performance

Contract No. DE-FC07-89ID12903

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ABSTRACT

This report summarizes experimental work performed at Alcoa Technical Center on Phase III/Task 1 of Department of Energy Contract No. DE-FC07-89ID12903 for development of a high alumina, lightweight refractory aggregate (LWA).

The technical problems related to: a) higher than target fired density, and b) poor intermediate strength after binder burnout but before sintering were addressed and solved. The solution involved the use of a large loading of CP-5 alumina (controlled pore, rehydratable), increased loading of one of the binders, and a steam aging step. The resistance of the LWA in a brick formulation to steel slag penetration was assessed in a preliminary test and found to be almost as good as that exhibited by T-64.

The pelletized process economic feasibility study was updated, based on production levels of 10,000 and 20,000 mt/year, the most up-to-date raw material costs, and the assumption of a retrofit into the Arkansas plant tabular production facility. For these assumptions: a) a 10,000 mt/yr production level, b) realistic process recycle and losses, and c) a \$0.66/lb selling price (35% more than T-64 selling price on a volume basis), the economics would be favorable (~18% R.O.I.C.). For these assumptions: a) a 20,000 mt/yr production level, b) realistic process recycle and losses, and c) a \$0.60/lb selling price (15% more than T-64 on a volume basis), the economics would be favorable (~17% R.O.I.C.). For the 10,000 mt/y production level, the required selling price of 35% more than the T-64 selling price exceeds the objective which is 25% or less.

The market survey will be the overriding factor in determining whether to continue with this development into the full scale demonstration that will produce at least 54.4 mt (120,000 lb) of the aggregate for incorporation into products, followed by end-user testing and evaluation.

SUMMARY

Phase III/Task 1 of the Alcoa/DOE contract was successfully executed consisting of pilot-scale experiments aimed at fine tuning the formulation to result in: a) attainment of the 2.5 g/cc maximum target fired density, and b) improvement in the intermediate strength (after binder burnout but before sintering) of the lightweight aggregate (LWA). In addition, a sample of LWA from Phase II work was incorporated into a separately funded Alcoa study to ascertain performance of LWA in brick upon exposure to molten steel slag.

The recommended pelletized formulation has been modified to consist of a blend of 60% A-13/40% CP-5 and two binders (Methocel F4M and Mogul 1607) at a combined loading of ~9 wt %. The CP-5 provides an inorganic binder whose bonding is effective well above the temperatures at which the organic binders are burned out. The CP-5 performs this function without adding impurities to the system. Patent protection for this use of CP-5 in the process is being sought. In addition to enhancing the intermediate strength of the aggregate before sintering, the CP-5 allows the use of additional water that reduces the density, while avoiding a paste consistency in the Eirich mixer.

The recommended formulation requires ~30 wt % moisture to attain the target fired density. A steam aging step after forming (before drying) is required to maximize the benefit of the CP-5 addition regarding increased intermediate strength. In the green state, this new formulation exhibits a density of 1.39 g/cc. Upon firing, the volumetric and linear shrinkage is ~51% and ~21%, respectively. The fired aggregate has a fired density of 2.5 g/cc or slightly less and a fired strength of ~41 MPa for -8 + 10 mesh, approximately equiaxed grains.

The pelletized process was subjected to an economic feasibility study based on production levels of 10,000 and 20,000 mt/year, the most up-to-date raw material costs, and the assumption of a retrofit into the Arkansas plant tabular production facility. For these assumptions: a) a 10,000 mt/yr production level, b) realistic process recycle and losses, and c) a \$0.66/lb selling price (35% more than T-64 selling price on a volume basis), the economics would be favorable (~18% R.O.I.C.). For these assumptions: a) a 20,000 mt/yr production level, b) realistic process recycle and losses, and c) a \$0.60/lb selling price (15% more than T-64 on a volume basis), the economics would be favorable (~17% R.O.I.C.). The economy of scale is evident for the two projections of a 10,000 or 20,000 mt/yr production level. For the 10,000 mt/y production level, the required LWA selling price exceeds the maximum level set forth in the project objectives.

As stated in prior reports, the formal market survey is the overriding factor that will determine whether to continue with this development into the full scale demonstration to produce at least 54.4 mt (120,000 lb) of the aggregate for incorporation into products, followed by end-user testing.

ACKNOWLEDGMENTS

The efforts of the following Alcoa personnel are recognized for their work during the execution of this contract phase:

Messrs. L. L. Lizik, R. R. Burr, and M. Cervone (Bidwell extern) are credited for the pilot-scale sample preparation and data generation involving density, shrinkage, and strength measurements. Mr. R. M. Dunlap performed the firing of the specimens in our pilot-scale gas-fired converters.

Mr. Alan Pearson is recognized as the Principal Investigator for this contract with responsibility for overall project direction and management, including planning of experiments, and guidance and consulting whenever needed.

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NOMENCLATURE

A-13	Alcoa calcined alumina (unground), designated A-13
A-13M	Alcoa calcined alumina (ground to -325 mesh), designated A-13M
ATC	Alcoa Technical Center
CP-5	Alcoa activated alumina (controlled-pore), 5 μm nominal size
C-30	Alcoa hydrated alumina, designated C-30
H-W	Harbison-Walker Refractory Company
LWA	Lightweight aggregate
R-M	Refractory manufacturer
Tabular TM	Alcoa Tabular alumina, designated T-64
CA-25	Alcoa calcium aluminate cement
MAP	Mono-aluminum phosphate

OBJECTIVE

The specific objective of this contract between Alcoa and the Department of Energy is to develop a lightweight, high alumina refractory aggregate with the following specification targets:

- Compared to Alcoa Tabular™ alumina, achieve a 30% reduction in particle density from approximately 3.6 to 2.5 g/cc.
- Compared to existing high alumina aggregate (Tabular™/Fused), retain ~50% of the crushing strength.
- Compared to Alcoa Tabular™ alumina, develop a lightweight aggregate product having a selling price not to exceed 25% more than the present selling price of Tabular™, on a product volume basis.

Secondary objectives that must also be met, some of which impact on the primary objectives, include developing an aggregate that: a) is 99+ % alumina, b) possesses thermal stability similar to Tabular™, and c) is process compatible with existing tabular production facilities.

Specific goals for this contract dealt with bench and pilot-scale laboratory work to demonstrate further the feasibility of producing lightweight aggregates. The term 'feasibility' includes both technical and economic aspects of the process. Prior to embarking on the full-scale demonstration wherein 190.5 mt (420,000 lb) of aggregate would be processed, the following three goals need to be attainable:

1. A process demonstrated at a pilot-scale and defined in sufficient detail to allow capital and operating cost projections for a full-scale process.
2. Convincing evidence that this type of aggregate would find a significant market (say >10,000 mt/yr) in insulating applications at the projected selling price to yield an adequate return on investment.
3. A belief by Alcoa that the desired material could be manufactured with the required quality and for a cost that would justify new capital expenditure.

INTRODUCTION

This contract was based on a proposal submitted by Alcoa in response to DOE Solicitation for Federal Assistance Application No. DE-PS07-88ID12782 for Refractory Materials Research and Development. This application was for cost-sharing research for the development of new refractory materials or improvements to existing refractory materials, with end-use applications directed toward those refractories used by the aluminum, glass, cement, and iron and steel industries. These new or improved refractory materials should have the potential to lead to a reduction of energy consumption in one or more of the above end-use industries of 0.01 quadrillion BTU's annually. If successful, these energy savings will enhance the competitive position of the domestic end-use industries.

A brief summary of the contract history through Phase II is given in Reference 1. Phase III, slated to commence after resolution and review of the remaining process and product technical issues, is outlined below.

Phase III: This phase will be a plant demonstration of the technology to prove the manufacturing process and to provide test market quantities for use by refractory manufacturers and evaluation by end-users. The quantity of lightweight refractory aggregate to be produced was determined by one key factor: a full-scale sintering campaign for a period of one week (including start-up, achievement of steady-state, production of fired shapes having the target specifications for a period of 3 days, and shut-down). The estimate planned for processing 190.5 mt (420,000 lb) of aluminous raw materials, resulting in at least 108.9 mt (240,000 lb) of on-specification, fired refractory shapes. After crushing to the desired aggregate sizes, it was assumed that a minimum of 54.4 mt (120,000 lb) would be available for fabrication into end use products by two refractory manufacturers with each refractory manufacturer (R-M) to receive 27.2 mt (60,000 lb) of aggregate sized to their specification. Each R-M will prepare at least two insulating products for testing by two or more end-users. Phase III will involve toll processing outside of Alcoa for the raw material mixing, extrusion, and drying. Alcoa's Arkansas plant would fire, crush, and size the refractory. Prior to the primary production run, pre-qualification of the toll processor using 7.26 mt (16,000 lb) of aluminous raw materials would be performed to assure satisfactory performance of equipment for the mixing, extrusion, and drying steps. Further documentation of the planning for Phase III is beyond the scope of this report.

EXPERIMENTAL PLAN FOR PHASE III - TASK 1

The objective of this phase of the program is to address two technical problems related to fired density and improvement in the intermediate strength of the LWA. Also prior to the demonstration campaign, assess the performance of this LWA in brick upon exposure to molten steel slag. The experimental plan would evolve around these issues.

1. Modify the formulation so that the target density of 2.5 g/cc is attained, not merely closely approached from the high side.
2. Modify the formulation so that the intermediate strength (after binder burnout, but before sintering) is improved.
3. Evaluate the performance of both LWA and T-64 (as a control) in a brick formulation upon exposure to molten steel slag.

EXPERIMENTAL

Phase II of this contract represented an optimization of the process from Phase I with further scale-up to allow production of aggregate in the required quantities for initial evaluation by refractory manufacturers. At the conclusion of Phase II, two technical problems remained, namely the approach to target fired density and the intermediate strength concern. Also, because the largest market target for this material was the steel industry, some information was desired on the resistance to penetration of steel slag for bricks made using this LWA.

The strategy involved focusing on the addition of an inorganic binder to improve the intermediate strength of the LWA shapes. Green strength was never a problem. It was only the strength after binder burnout, but before sintering, that was cause for concern. It was feared that the low strength would lead to break-down and dusting during the large-scale sintering process. CP-5 was targeted as a logical additive because the hydroxyl bonding remains at temperatures well above those at which the organic binders have burned off. In addition, this additive should allow the addition of more water to the formulation without forming a paste in the Eirich mixer. The first grouping of experiments was an experimental design (face centered cubic) with 3 variables at 3 levels (15 experiments + one replication of the center point). The variables examined were the wt % loadings of CP-5, Methocel, and Mogul. Thus, the total number of experiments was 16 for this portion of the experimental plan. A requirement to maximize the benefit of the CP-5 was that the specimens be steam aged after extrusion. Steam aging enhances the hydroxyl bonding that occurs. To quantify the benefit of steam aging, the specimens were split into two groups immediately after extrusion. One group received steam aging prior to air oven drying at 110°C, the other did not. This procedure would characterize any benefit of the steam aging for the exact same formulation.

In addition to trials with CP-5, inorganic bonding was attempted through the addition of calcium aluminate cement (CA-25) and mono-aluminum phosphate. These materials were used in addition to the organic binders normally present in the formulation. The intent was to provide for inorganic bonding to increase intermediate strength during sintering.

Steam Aging

The steam aging was accomplished in a 5 gallon metal container. This container with a rimmed lid (loosely fitted to avoid pressure build-up) was placed in an air oven at 110°C. Perforated metal baskets containing the specimens were placed in this container that contained an inch or two of preheated water in the bottom (the specimens did not contact the water). This resulted in exposure of the specimens to a wet steam atmosphere. The exposure period was 4 hours.

A second grouping of experiments involved the use of CA-25 cement as an additive to impart additional intermediate strength. Provided the loading of CA-25 was not too high, the Ca would not violate the target of 99+ % Al_2O_3 in the fired aggregate. Unlike CP-5 that could accept a higher loading of water without becoming a paste, it was uncertain whether the CA-25 addition would function to reduce the fired density to 2.5 g/cc. The experiments (17, 18, and 19) with CA-25 employed loadings of 3, 5, and 10 wt %.

A third grouping of experiments represented a final, fine tuning of the CP-5 formulations that performed best in the first grouping of experiments. At this point in time, the results of the first two groupings of experiments were available, with the CP-5 clearly outperforming the CA-25 additions with respect to density attainment and improved intermediate strength. Three additional experiments (20, 21, and 22) were the last ones to be performed.

Specimens from these 22 experiments (some machined to cylinders and some processed in the 'as extruded' form) were fired in a small gas-fired converter in 4 separate firings over the course of the experimental work. The converter used for these firings was dedicated solely to this project to eliminate any chance of contamination from other materials being processed.

In addition to the above, several experiments were attempted using mono-aluminum phosphate (MAP) in conjunction with the aluminas and binders normally employed. Loadings of MAP tested were 5, 10 and 20 wt %. All these formulations allowed satisfactory pelletization in the Eirich mixer. However, higher loadings of MAP failed to result in acceptable extrudate; the extrudate swelled significantly and had little adhesive strength. Even more problematic, upon drying at 110°C, about 50% of all the extruded pieces for the two highest MAP loadings developed severe longitudinal cracking. The same type of cracking developed for the specimens employing 5% MAP, but to a lesser extent (about 10% of the pieces were affected). There appeared to be an incompatibility of MAP with the other binders. Further work using MAP was not considered. Because of the cracking, these specimens were not characterized by the normal methods used throughout this project. These experiments will not be discussed further in this report.

RAW MATERIALS

The raw materials utilized included various alumina products, including Alcoa A-13 and CP (controlled pore) aluminas. In addition, binders and burnouts were added to impart plasticity and porosity upon drying and firing.

ALUMINAS

Aluminas used in this work for the high alumina matrix included the following:

A-13	Alcoa calcined alumina, unground
A-13M	Alcoa calcined alumina, ground to nominally -325 mesh
CP-5	Alcoa activated (rehydratable) alumina, 5 μ m particle size

BINDERS/BURNOUTS

In order to extrude a ceramic material, a binder or plasticizer must be added to the solids to impart fluid and yet plastic properties to the mixture. Based on the performance in Phases I and II, Methocel 20-214, manufactured by Dow Chemical, continued to be the binder of choice in the formulation.

Methocel 20-214

Methocel cellulose ethers are water-soluble polymers derived from cellulose. Methocel products are used as thickeners, binders, film formers, and water retention agents. A broad range of Methocel products are available. There are two different chemical types and each is available in different grades, physical forms, and viscosities. By choosing a specific Methocel product, it is possible to obtain the optimum degree of thickening, binding, moisture retention, and other properties desired in a given formulation. Methocel 20-214, designated Type F, is a hydroxypropyl methylcellulose product made using propylene oxide and methyl chloride. Methocel 20-214 will decompose at $\sim 225^{\circ}\text{C}$.

Manufacture of Methocel 20-214 has been discontinued by Dow. The recommended product substitute is Methocel F4M (a detailed product specification sheet is not available at this time). Methocel F4M was obtained and utilized in the Phase III experiments to be reported.

CA-25

Alcoa calcium aluminate cement is a high purity, hydraulically setting refractory cement. This product is designed for use as a binder in castable refractories and mortars with useful service range up to 1760°C . CA-25 cement is composed of $\sim 79\%$ alumina, 18% lime, and 1.5% water and minor impurities. The predominant hydraulic bonding phases are monocalcium aluminate and pentacalcium tri-aluminate.

MAP

Mono-aluminum phosphate solution used in this work was a product of Albright & Wilson Company. Mono-aluminum phosphate exhibits decreasing water solubility when heated. Free and bonded water is lost resulting in the conversion of the acid orthophosphate to insoluble aluminum pyrophosphate and/or aluminum meta-phosphate. When MAP is used as a refractory binder, the mix is blended and then heated slowly to eliminate the free water. Further heating results in a release of the chemically bound water. Finally, when heated to about 1650°C, decomposition will occur with volatilization of P_2O_5 .

Burnout is the term used to describe an additive that is organic in composition. Burnouts are used to occupy volume in a green refractory. Upon firing, porosity is created. Two burnouts were utilized while attempting to optimize the formulation.

Mogul 1607

Mogul 1607 is a heavyweight cereal binder made from precooked yellow corn. Based on information from the manufacturer, Mogul when decomposed will leave behind 0.5 wt % ash. The magnesium oxide in the ash is a concern because it can cause increased densification of alumina during sintering. For 5 wt % loading of Mogul in ceramic (with ash equal to 0.5% of Mogul and the ash containing 7 wt % Mg by ATC analysis), the ash will contribute 17.5 ppm Mg to the ceramic. Based on Thermal Gravimetric (TGA)/Differential Thermal Analysis (DTA) curves developed by ATC for this binder, Mogul will decompose at ~310°C. An advantage to using Mogul, in addition to its relatively low cost of \$0.23/lb, was that it reduced the stickiness of the extrudate imparted by the Methocel.

Water

Water can also be considered a burnout material. Water is required to impart fluidity to the ceramic binders during mixing and extrusion. Water is the lowest cost burnout available. However, there is a cost associated with evaporating it due to its latent heat of vaporization. The water loading must be optimized to provide good forming properties, both during mixing and extrusion.

MIXING PROCEDURE

For a pelletized mixture, the aluminas and all binders/burnouts were dry blended by the intense mixing action within the Eirich mixer.

EQUIPMENT

Experimental work at the beginning of Phase III of the contract utilized pilot-scale mixers and extruders for formulation modification development. The converters used for

firing small samples from any batch size were those described in the literature reference by MacZura⁽²⁾ and were those used during Phase II.

Eirich Mixers - Two sizes of mixers were available. Only the RV02 Eirich was used during Phase III (10 lb batch size).

RV02 - This model had a bowl capacity of 20.3 liters, with working capacities for mixing or pelletizing of 10 or 7 liters, respectively.

R-7 - This model had a bowl capacity of 175 liters, with working capacities for mixing or pelletizing of 73.6 or 56.6 liters, respectively. It was found that the pin rotor was not satisfactory for this formulation that approached a paste consistency. An optional star rotor performed markedly better, as determined in Phase II. Limited machine variables, such as rotor speed and direction and bowl speed, are controlled via switches on the control panel. Additional variation in rotor speed can be attained by switching pulleys and belts.

EXTRUDERS

3" Macquiceram

This extruder had a 7.62 cm (3 in.) auger (screw) and a 2 H.P. motor. The single hole die had a diameter of 1.778 cm (0.70 in.). A wire chopper with actuator was custom designed and purchased from Starkey Machines, Inc.

GAS FIRED CONVERTERS

For this experimental work, bench-scale, batch-operated, gas-fired converters were used. Two of these units were available, each having a 30 in. diameter shell and an 18 in. inside diameter. Actual sample chambers were 11.43 x 11.43 x 7.62 cm (4.5 x 4.5 x 3 in.) deep, formed from alumina bricks. Heat-up rate from ambient to 1830°C required ~3.5 hours. An over-night cool-down period was required before the samples could be retrieved. Temperature monitoring was through a sight port utilizing an optical pyrometer focused on a specimen.

PRODUCT CHARACTERIZATION

The product characterization methods for density, shrinkage, and strength employed during Phases I and II of this contract were carried into Phase III. With the splitting of the samples into an air oven (AO) and a steam aged (SA) portion, the number of samples from 22 experiments doubled to 44.

DENSITY

The density and other physical properties were calculated utilizing ASTM Method C20-80a, that gives standard test procedures for apparent porosity, water adsorption, apparent specific gravity, and bulk density of burned refractory brick and shapes by the boiling water method. Five specimens were tested and the results averaged.

SHRINKAGE

Both linear and volumetric shrinkages were calculated from size measurements taken before and after firing the machined, test specimens. Five specimens were tested and the results averaged.

CRUSHING STRENGTH

The diametral compression test was found to be a simple and practical method to measure the tensile strength of brittle materials. In order to test approximately spherical specimens of the same size, it was necessary to manually crush and sort the individual test specimens. Groups of at least 20 nearly-spherical samples were selected at one specimen size, -8+10 mesh. The only criterion applied to the final sample selection was that the grains had approximately equiaxed cross sections suitable for compression testing. The maximum test load at fracture and the average screen opening size were used to calculate the fracture stress.

MICROSTRUCTURE

Phases I and II of this contract focused on numerous formulations involving binders, burnouts, and aluminous species. Because of the narrow focus on formulations in Phase III, no samples were submitted for examination of the microstructure.

INTERMEDIATE STRENGTH

Based on preliminary tests in which lightweight aggregate precursor shapes were heated at 500°C to burnout the binders followed by crude assessment of remaining adhesion by rubbing the shapes between the fingers, a concern was raised that the extruded shapes would not survive passage through the commercial sintering process. The concern is that there will be a period of movement through the shaft furnace when the binder has decomposed (leaving a porous, weak structure) and sintering of the particles has not yet begun. During this period, the shapes would be susceptible to disintegration. It remains to be determined how critical this factor will be in dynamic sintering equipment. Variables that impact this factor include: a) the time in the shaft furnace (after binder burnout and before the start of sintering) that the specimens are in this fragile condition, b) the particle-to-particle abrasion as the shapes travel through the furnace, and c) the compressive load due to the height of the bed on specimens in the furnace. Further experimentation with the formulation was undertaken to improve this situation by employing inorganic binders, while maintaining the 99+% alumina purity specification. It is also strongly recommended that a pilot-scale dynamic sintering trial be performed during the pre-qualification trial of Phase III.

The abrasion test (samples from all 22 experiments) and stress test (samples from selected experiments) were employed for determination of intermediate strength, as discussed previously.

Abrasion test

The abrasion test consisted of subjecting dried extruded shapes (with and without steam aging) to controlled heat-up and holding at 500°C for 2 hours so as to burnout the organic binders. Approximately 80 g of shapes (~5 pieces) were then placed on a Ro-tap screen and shaken for 1 to 3 minutes in the Ro-tap shaker. The intent was to abrade alumina from the weakened shapes. The higher the weight loss (increased generation of fines), the poorer the intermediate strength. This is a screening test to differentiate between different formulations. The weight loss values are of value only when compared with other samples.

Stress test

The stress test consisted of cutting the dried, cylindrical extruded shapes (with and without steam aging) so their ends were parallel. The circumference was then machined on a lathe to a targeted diameter. Both the diameter and length of the cylinders were determined using a micrometer. These shapes were then subjected to controlled heat-up and holding at 500°C for 2 hours to burnout the organic binders. The specimens were then fractured (diametral stress test) using a Chatillon tester to determine a fracture stress. This is the same procedure used to determine the fracture stress of fired aggregate (-8 + 10 mesh size pieces approaching spheres). The higher the stress value, the better the intermediate strength. Because this procedure of machining the specimens was very laborious, only selected experiments were included for this test. The stress values from this screening test may be accurate enough to assess the strength performance of the material in the vertical shaft furnaces used for commercial firing.

RESISTANCE TO PENETRATION BY STEEL SLAG

Harbison-Walker performed 'cup slag tests' on the lightweight aggregate and on dense tabular T-64 as a control. These tests consisted of exposure of CA-25 bonded aggregate to molten steel slag (iron cupola slag from Eljer Plumbing) for a period of 5 hours at 2700°F. The CA-25 bonded aggregate was shaped into a cup form before firing. This cup depression was used to hold 100 grams of slag. After exposure, the cup was cooled and sectioned to reveal the depth of penetration of the slag into the formed ceramic container.

DENSITY/RAW MATERIAL COST MODEL

The raw material cost model, developed in Phase I and used extensively during Phase II for selection of the proper combination of binders, burnouts, and free moisture was again employed during Phase III. In addition to tracking the raw material weights and costs,

the model results were found to be accurate enough to be used for selection of variables to result in the target fired density, based on a calculated green density and known shrinkage values. The selection of the binder/burnout levels was critical because free water usage had to be minimized so that a paste was not formed in the Eirich mixer.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental data on Task 1 of Phase III were recorded in Alcoa Technical Center notebooks 25247-X - pages 39-100 and 25896X - pages 1-56.

The runs performed during Phase III of this project numbered 22 and consumed approximately 93 kg of aluminous raw materials and 7 kg of the two binders. Because of the splitting of samples into an 'air oven' and 'steam aged' groups, the number of sample groups doubled to 44 (recall that normally 5 specimens were processed for each characterization test). Steam aging is an important step in the processing of extrudates containing CP-5 if the intermediate strength is to be increased. As the results will show for samples containing no CP-5 and those containing CA-25 cement, steam aging could also have a detrimental impact on intermediate and fired strength.

MIXER/FORMULATIONS

As discussed in prior reports, during consideration of the equipment needed for a demonstration process in Phase III and based on contact with 11 vendors who were potential toll processors, it was found that most did not have the equipment to support a paste formulation. The potential tollers, particularly those willing to bid on the job, had Eirich or similar mixers that required a drier formulation (less water and more burnouts) to allow for pelletization. A rough estimate of the throughput and the capital equipment required for a commercial process also supported the use of a pelletized formulation. Because of the rapid throughput of Eirich machines and the elimination of separate dry blending equipment, Eirich mixers would be preferred because they minimize capital costs. Mixer/extruders in one machine were also considered even though they are expensive. A pelletized formulation containing about 28 wt % free moisture and several burnouts was developed during Phase II. To form porosity in a refractory, either water or burnout materials must be used to create void volume upon drying or firing.

During this experimental work in Phase III, the focus continued to be on a pelletized formulation. The goal was to modify the formulation by the addition of CP-5 (to partially or fully replace the A-13M material) and still produce a pelletized material with a closer approach to the target fired density and improved intermediate strength. In addition, a pelletized formulation was evaluated using a 3, 5 or 10 wt % loading of CA-25 cement.

EIRICH MIXER TRIALS (Pelletized Formulation)

Alcoa Technical Center had two sizes of Eirich mixers available: an RV02 and a R-7. The size and capacity of each machine were discussed previously.

Runs in RV02 Eirich

The small Eirich was utilized to establish a revised formulation using batch sizes composed of about 4.5 kg of aluminous and binder materials. Several Eirich machine variables were available to change if needed, including bowl speed and rotor direction and speed. In Phase II it was found that these variables contributed to success or failure of pelletized mixes because the addition of water required was borderline for a pelletized product. In Phase II work there was a strong tendency to form a paste in the Eirich. To compensate for this, the amount of water was reduced, but this caused an undesired increase in density. For this reason, further modifications of formulation and procedures were tested in Phase III.

Runs in R-7 Eirich

There were no runs made in the R-7 during this phase of the experimental program. With the addition of CP-5 to the formulation, there appears to be some leeway remaining for the addition of even more water, if necessary, to further reduce the density of the product. This leeway should be able to handle any scale-up differences between the RV02 and the R-7 Eirich machines.

OVERVIEW OF EXPERIMENTAL FORMULATIONS

Table 1 details the formulations tested with a focus on improving the intermediate strength and attaining a closer approach to the target fired density of 2.5 g/cc. In the balanced faced-centered cubic (FCC) experimental design (experiments 1-15 only, plus #16 that was a replicate of #9), the variables included loadings of CP-5 (0, 20, and 40 wt %), Methocel (1.0, 1.5, and 2.0 wt %), and Mogul (3, 5, and 7 wt %). It should be noted that the wt % basis was chosen such that the wt % for the aluminous species summed to 100%. When calculating actual weights of aluminous materials and binders, the percentages were normalized to 100%. Figure 1 is a schematic of the experimental design. Because of the balanced experimental design, the data may be statistically analyzed. Immediately after extrusion, each batch was split in two. One part received a steam aging prior to drying, while the other part did not. Table 1 also lists the target moisture content. This moisture level was calculated based on the volume that needed to be occupied by burnouts (water or binders) to attain the target fired density. Recall that there is a limit on the water content that can be used while still attaining pelletization (not paste) in the mixer. Of course, because of cost, the intent is to maximize the use of water while minimizing the use of binders. In cases where a low binder content is specified in the experimental plan, the moisture target may exceed that level to allow for pelletization. In these cases, the water addition was stopped short of that required. The overriding concern was to attain pelletization from the Eirich. If insufficient water was added, the fired density target would be expected to exceed target.

Experiments 17, 18, and 19 are evaluations of CA-25 cement in the formulations. Experiments 20, 21, and 22 represent a fine tuning of the best CP-5 formulations determined from inspection of the data from experiments 1 to 19.

Table 2 is an extension of Table 1 and details the actual weights of components added to a formulation. Note that the total of dry components added was a 4.536 kg (10 lb) batch. The column designated 'FACTOR' is the weight fraction of the dry components that remains after organic binder burnout. This value does not include the chemically combined water (~7 wt %) associated with the CP-5 addition.

Table 3 focuses on the total water in the formulations. The actual water added and the calculated moisture wt % is given. Measured percentage moistures on the SA and AO treated portions are also given. There has been continual difficulty in attaining a low enough fired density. For this reason, if a formulation would tolerate additional water, it was added until the point where a transition from pellets to paste in the Eirich was imminent. The last column in Table 3 lists a water deficit (if positive) or surplus (if negative), as calculated from target and actual free moisture levels attained. A water surplus is indicative of a formulation that can take more water than estimated to attain target density. From a process standpoint, this is a desired condition that provides some leeway in the process control requirement. For the experiments with CP-5, the measured free moistures often fall short of the calculated value based on the weight added. This may be due to the hydroxyl bonding that occurs with the CP-5 addition; these bonds are not broken during normal drying.

GREEN AND FIRED DENSITY

Table 4 summarizes averaged values for green and fired density data for the 22 experiments (44 values with AO and SA treatment options). The fired densities were marginally to significantly higher than target for all the experiments in the FCC experimental design and also for the 3 experiments utilizing CA-25 cement. Only the experiments to fine-tune the formulation (20 to 22) resulted in fired densities of 2.5 g/cc or less. Based on the fired density results, formulation 20, 21 or 22 would be satisfactory. More often than not, the affect of steam aging of the samples resulted in a lower fired density. Whether this density decrease is statistically significant has not been evaluated.

Supplemental data on green density for the 5 individual specimens tested (including averages and standard deviations) is given in Appendix A. These data are contained in 4 pages, one for each of the 4 firing campaigns.

Supplemental data on fired density, apparent porosity, water absorption, apparent specific gravity, and total porosity for the 5 individual specimens tested (including averages and standard deviations) are given in Appendix B. These data are contained on 4 pages, one for each of the 4 firing campaigns. Data on the 5 individual specimens tested for each experiment and treatment condition (including averages and standard deviations) are also given in Appendix B on 4 additional pages, one for each of the 4 firing campaigns.

SHRINKAGE

Table 5 summarizes averaged values for volumetric and linear shrinkage for the 22 experiments. There is good agreement between AO and SA treated samples for all three of the dimensional categories (volume, linear-thickness, and linear-diameter). For steam aged samples from runs 20, 21, and 22, the volumetric shrinkage was ~52%, while the linear shrinkage (thickness and diameter) was ~ 21%.

Supplemental data on shrinkage for the 5 individual specimens tested (including averages and standard deviations) is given in Appendix C. These data are contained in 4 pages, one for each of the 4 firing campaigns.

INTERMEDIATE STRENGTH OF EXTRUDED FORMS DURING SINTERING

Table 6 summarizes averaged values for characterization of intermediate strength as indicated by abrasion resistance and stress (for selected samples only). In the abrasion test, note the wide variation in the values indicating that the formulation is a key variable. Note also that for CP-5, the steam aged (SA) samples performed markedly better than the air oven (AO) samples. In the cases where no CP-5 was used, steam aging was sometimes detrimental to the abrasion resistance (higher value). The abrasion resistance test indicated that runs 4 and 22 (a fine-tuned composition based on #4) performed best. This finding is also supported by the stress measurement, where the steam aged samples for runs 4 and 22 exhibited 3.3 times the strength of the air oven (AO) samples. From these data it is evident that the CP-5 formulation improves the intermediate strength more so than any of the CA-25 cement formulations. The reverse performance for run 21 for the SA and AO samples in both the abrasion and stress tests cannot be explained. Of the runs meeting the fired density criterion, run 22 also exhibits the best improvement in intermediate strength.

Supplemental data on the abrasion resistance test, including RoTap time data for 1 and 2 minutes, are included in Appendix D-1 (5 pages). Supplemental data on the intermediate strength as characterized by the stress measurement are given in Appendix D-2 (3 pages). These tables include dimensional and strength measurements for samples (5) from selected experiments.

FIRED STRENGTH

Table 6 also summarizes the fired strength test data. While there is a wide range of values, this is to be expected because the fired densities also vary widely. Also, because of defects, strength of ceramic materials characteristically has a wide range of values. For run #22 that met the fired density target and showed improved intermediate strength via the use of CP-5 with steam aging, the fired strength value of 40.8 MPa is within the range of values characteristic of Phase II experimental work.

Supplemental data on the fired strength of samples from the 22 experiments are given in Appendix E (5 pages). The diametral compression test result is based on the average of 20 approximately spherical pieces crushed using the Chatillon tester.

ANOVA OF DATA FROM FCC EXPERIMENTAL DESIGN

Analysis of the data from the experimental design comprising experiments 1 through 16 was conducted. The report³ on the ANOVA results by the statistical consultant to this project is included in this report as Appendix F. The objective of the experimental design was to: a) determine which factors have the greatest influence on three responses: fired density, abrasion, and fired strength; and b) determine the combination of components and drying that optimizes the three responses with these added constraints: the fired density should approach 2.5 g/cc, the abrasion (% weight loss) should be minimized, and fired strength (MPa) should be maximized. It was also assumed that density and abrasion were of equal importance and were each twice as important as fired strength. Separate models for the air oven dried and for the steam aged, then air oven dried samples were developed.

The optimal component combinations and resulting predictions are:

	CP-5 %	Methocel %	Mogul %	Fired Density g/cc	Abrasion Wgt Loss %	Fired Strength MPa
Air Oven	0	0.75	5	2.50	76.7	58.7
Steam Age	40	2.25	6.48	2.51	27.1	26.9

Note that air oven and steam age drying options are optimized at opposite extremes of the CP-5/A-13M combinations and that steam aging will require additional Methocel and Mogul. Steam aging of formulations containing a high loading of CP-5 definitively increases the intermediate strength (lower abrasion weight loss). Additional details on this ANOVA and predictive models may be found in reference 3.

One short-coming of the optimization models is that they extrapolate outside the experimental variable range to attain the target density. Unfortunately, all of the experiments (1-16) resulted in higher than target fired density. Also, an element lacking in the model is the mix consistency required during Eirich and extruder machine processing. It is probable that the predicted air oven optimum conditions above are not satisfactory with respect to processing in either the Eirich mixer or extruder. Moisture content is also a factor that is not included in the models.

The steam age optimal results predicted above are somewhat more believable because the experimental fired densities were closer to target. Good agreement between predicted and actual abrasion results for experiment no. 22 may be viewed as a limited verification of the model for steam aged samples. However, based on experiment no. 22, the

predicted fired strength for steam aged samples appears to be lower than that actually attained.

Based on the above observations, the benefit of the models would be to give relative indication of the effect of composition on the key response variables. The absolute values of the predictions do not appear to be reliable due to the forced requirement of attaining the 2.5 g/cc fired density from data with densities above this target.

RESISTANCE TO PENETRATION BY MOLTEN STEEL SLAG

Cup slag tests were employed to assess the resistance to penetration of the LWA in brick upon exposure to molten steel slag. Dense tabular aggregate in brick was also tested for comparison. These tests were conducted by Harbison-Walker in a separate, Alcoa funded study.

The composition of the slag used in these cup slag tests was as follows:

SiO ₂	62.6 %
Al ₂ O ₃	10.2
TiO ₂	1.43
Fe ₂ O ₃	5.1
CaO	9.0
MgO	5.0
MnO	1.46
SO ₃	0.81
BaO	0.33
Na ₂ O	2.55
K ₂ O	0.96

The results of the exposure of the CA-25 bonded samples containing either light weight or dense tabular is summarized below.

Sample	Penetration depth * inches
LWA (Lot 36) - Fired 3000°F	7/8
Dense tabular T-64	3/4

* Thickness of discolored area at bottom of cup. These discolored zones appear to be a combination of erosion and penetration.

It should be noted that the LWA aggregate samples from lot 36 exhibit a fired density of 2.8 g/cc, which is higher than the targeted density for our new product. This sample was used because it was the only fired aggregate available in sufficient quantity for this test work. This comparison should be construed as only a preliminary indication of performance of the LWA material. In this test, the performance in the cup slag test was almost as good as the dense tabular T-64 aggregate having a fired density of 3.4 g/cc.

FEASIBILITY STUDY OVERVIEW

An economic feasibility study was updated for the lightweight aggregate process as a retrofit into the existing tabular production facilities within Alcoa. A schematic flowsheet for the LWA process is shown in Figure 2. Because this evaluation is primarily for Alcoa's information to decide on the economic feasibility of this proposed process, details of the assumptions comprising this study are considered to be beyond the scope of this report. In addition, many of the details are considered Alcoa proprietary information. Only a summary of these results are presented, see Table 7. The variables in this study included: a) two nominal LWA production levels, b) three LWA selling prices, referenced to the current selling price of Alcoa Tabular™ on a volume basis, and c) two process scenarios. The nominal production levels were 10,000 and 20,000 mt/yr. Selling prices were 15, 25, and 35% over the current price of Tabular™, on a volume basis. The process scenarios included worst and likely case assumptions. The LWA process will have a level of recycle of fines that will not be negligible. Recycle of these fines within the process consumes binders/burnouts and processing capacity. These scenarios deal with assumptions on how these fines are handled. The notes at the bottom of Table 7 list the scenario bases.

Assuming the 'likely' scenario represents a conservative but realistic view of the economics, and if a threshold R.O.I.C. of at least 15% is targeted, then at a nominal production level of 10,000 mt/yr a selling price of approximately 35% more than for T-64 on a volume basis is required. This translates to a required selling price for the LWA equal to \$0.66/lb, a value that exceeds the target maximum of 25% as per stated objectives.

Assuming the 'likely' scenario represents a conservative but realistic view of the economics, and if a threshold R.O.I.C. of at least 15% is targeted, then at a nominal production level of 20,000 mt/yr a selling price of approximately 15% more than for T-64 on a volume basis is required. This translates to a required selling price for the LWA equal to \$0.60/lb.

A market survey has been completed to determine whether the market and selling price will justify further development of this new aggregate process. Discussion of the marketing aspects of this LWA is beyond the scope of this report.

CONCLUSIONS

1. The altered formulation employing CP-5 has solved the technical issues related to target fired density and intermediate strength.
2. The resistance to slag penetration of brick samples made with LWA approached that exhibited by brick samples made using T-64.

RECOMMENDATIONS

1. Determine if the significant improvement in intermediate strength is sufficient to allow firing in Alcoa converters (vertical shaft kilns). This may include calculation of the minimum stress required to resist breakage as the pieces travel down the height of the converter until the point where sintering has provided additional strength.
2. Prior to a demonstration run wherein large tonnages of material are processed, conduct a pre-qualification test on a few tonnes of material to assess intermediate strength and fired properties.
3. Finalize the marketing results to determine whether Phase III should be pursued for full-scale demonstration of the process.

SAFETY

Safety is an important aspect of any experimental program. In this work high temperature firing and noxious vapors presented the most severe hazards. The material safety data sheets (MSDS) were considered to be an important aspect of safety awareness. These documents were reviewed for all materials used. Hoods over the converters and isolation of these units helped to minimize operator exposure to any fumes. Other working hazards that would become more threatening for large scale operation include dust problems, a concern both for the safety of the operator because of inhalation and also because of the explosion hazard for some of the organic dusts.

REFERENCES

1. Swansiger, T. G. and Pearson, A., "Lightweight Alumina Refractory Aggregate Phase II-Pilot-scale Development," DOE Energy Conservation - Topical Report, Contract No. FC07-89ID12903, November 1994.
2. MacZura, G., "Production Processes, Properties, and Applications for Tabular Alumina Refractory Aggregates," as published in Alumina Chemicals: Science and Technology Handbook, L. D. Hart, editor, Am. Ceramic Society, Westerville, Ohio, 109-170, 1990.
3. Goodman, J. H., "Analysis of Phase 3, DOE Lightweight Aggregate Optimization Experiment," Alcoa Data Letter to T. G. Swansiger, dated 1996 April 3. (Note: This reference is included in this report as Appendix F)

Table 1. Expt. Plan with CP-5 and CA-25 Cement- 4.536 KG (10 LB) BATCH SIZE

TEST	ALUMINOUS MATERIAL ADDED					BURNOUT	BINDER	STEAM AGE Y/N	TARGET
	A-13	A-13M	CP-5	C-30	CA-25	METHOCEL	MOGUL		MOISTURE
	WT%	WT%	WT%	WT%	wt%	WT%	WT%		WT%
1	60	0	40	0	0	1.0	7.0	Y&N	27.1
2	60	0	40	0	0	1.0	3.0	Y&N	31.6
3	60	0	40	0	0	2.0	3.0	Y&N	30.4
4	60	0	40	0	0	2.0	7.0	Y&N	25.8
5	60	40	0	0	0	2.0	3.0	Y&N	30.4
6	60	40	0	0	0	2.0	7.0	Y&N	25.8
7	60	40	0	0	0	1.0	7.0	Y&N	27.1
8	60	40	0	0	0	1.0	3.0	Y&N	31.6
9	60	20	20	0	0	1.5	5.0	Y&N	28.8
10	60	20	20	0	0	1.0	5.0	Y&N	29.4
11	60	20	20	0	0	2.0	5.0	Y&N	28.2
12	60	40	0	0	0	1.5	5.0	Y&N	28.8
13	60	0	40	0	0	1.5	5.0	Y&N	28.8
14	60	20	20	0	0	1.5	3.0	Y&N	31.0
15	60	20	20	0	0	1.5	7.0	Y&N	26.4
16	60	20	20	0	0	1.5	5.0	Y&N	28.8
17	60	37	0	0	3	2.0	7.0	Y&N	30.1
18	60	35	0	0	5	2.0	7.0	Y&N	30.1
19	60	30	0	0	10	2.0	7.0	Y&N	29.9
20	60	0	40	0	0	2.0	7.0	Y&N	30.3
21	60	0	40	0	0	1.5	5.0	Y&N	33.0
22	60	0	40	0	0	1.5	7.5	Y&N	29.6
NOTES:	1. Convention: aluminous materials sum to 100 wt%								
	2. Actual weights are determined by normalizing to 100 wt% the aluminous								
	species plus binders/burnouts								

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5/20/96

Table 3. Experimental Summary on Added Moisture Compared with Measured Values
Expt. Plan with CP-5 and CA-25 Cement- 4.536 KG (10 LB) BATCH SIZE

TEST	TOTAL WATER KG	TOTAL DRY COMP KG	PASS/FAIL PELLETS EX RV02 EIRICH	ACTUAL WATER ADDED KG	ACTUAL MOISTURE WT%	%_MOIST S.A. %	%_MOIST A.O. %	TARGET MOISTURE WT%	DEFICIT ON MOISTURE WT% (IF POSITIVE)
1	1.687	4.536	PASS	2.090	31.5	28.9	27.0	27.1	-4.4
2	2.096	4.536	PASS	2.096	31.6	28.0	27.3	31.6	0.0
3	1.977	4.536	PASS	1.977	30.4	26.3	26.3	30.4	0.0
4	1.574	4.536	PASS	1.924	29.8	26.1	26.5	25.8	-4.0
5	1.977	4.536	PASS	1.524	25.1	25.4	25.6	30.4	5.2
6	1.574	4.536	PASS	1.574	25.8	25.7	25.7	25.8	0.0
7	1.687	4.536	FAIL	1.687	27.1	27.2	27.1	27.1	0.0
8	2.096	4.536	PASS	1.610	26.2	26.2	26.2	31.6	5.4
9	1.832	4.536	PASS	1.832	28.8	26.8	26.4	28.8	0.0
10	1.892	4.536	PASS	1.892	29.4	21.7	33.4	29.4	0.0
11	1.778	4.536	PASS	1.776	28.1	26.8	27.3	28.2	0.0
12	1.832	4.536	PASS	1.560	25.6	26.4	26.1	28.8	3.2
13	1.832	4.536	PASS	1.932	29.9	26.1	27.2	28.8	-1.1
14	2.037	4.536	PASS	1.688	27.1	25.7	25.6	31.0	3.9
15	1.629	4.536	PASS	1.729	27.6	25.6	25.3	26.4	-1.2
16	1.832	4.536	PASS	1.832	28.8	27.6	19.9	28.8	0.0
17	1.950	4.536	FAIL	1.802	28.4	27.9	28.0	30.1	1.6
18	1.950	4.536	PASS	1.850	29.0	27.4	27.6	30.1	1.1
19	1.937	4.536	PASS	1.937	29.9	24.3	27.7	29.9	0.0
20	1.973	4.536	PASS	2.073	31.4	26.3	27.7	30.3	-1.1
21	2.232	4.536	PASS	2.182	32.5	26.7	25.5	33.0	0.5
22	1.905	4.536	PASS	2.105	31.7	25.2	25.1	29.6	-2.1
	41.279	99.790							

Table 4. Experimental Results - Green and Fired Density
Expt. Plan with CP-5 and CA-25 Cement- 4.536 KG (10 LB) BATCH SIZE

TEST	ALUMINOUS MATERIAL ADDED					BURNOUT	BINDER	AO	SA	AO	SA
	A-13	A-13M	CP-5	C-30	CA-25	METHOCEL	MOGUL	GR. DENSITY	GR. DENSITY	FIRE DENSITY	FIRE DENSITY
	WT%	WT%	WT%	WT%	wt%	WT%	WT%	G/CC	G/CC	G/CC	G/CC
1	60	0	40	0	0	1.0	7.0	1.42	1.40	2.582	2.565
2	60	0	40	0	0	1.0	3.0	1.38	1.31	2.574	2.551
3	60	0	40	0	0	2.0	3.0	1.46	1.46	2.631	2.560
4	60	0	40	0	0	2.0	7.0	1.45	1.40	2.589	2.597
5	60	40	0	0	0	2.0	3.0	1.49	1.46	2.792	2.774
6	60	40	0	0	0	2.0	7.0	1.57	1.52	2.821	2.840
7	60	40	0	0	0	1.0	7.0	1.44	1.42	2.673	2.628
8	60	40	0	0	0	1.0	3.0	1.55	1.37	2.626	2.589
9	60	20	20	0	0	1.5	5.0	1.48	1.43	2.582	2.603
10	60	20	20	0	0	1.0	5.0	1.38	1.37	2.583	2.537
11	60	20	20	0	0	2.0	5.0	1.37	1.46	2.593	2.609
12	60	40	0	0	0	1.5	5.0	1.49	1.45	2.780	2.711
13	60	0	40	0	0	1.5	5.0	1.41	1.39	2.619	2.620
14	60	20	20	0	0	1.5	3.0	1.49	1.46	2.712	2.685
15	60	20	20	0	0	1.5	7.0	1.52	1.51	2.699	2.644
16	60	20	20	0	0	1.5	5.0	1.38	1.41	2.578	2.591
17	60	37	0	0	3	2.0	7.0	1.40	1.33	2.614	2.524
18	60	35	0	0	5	2.0	7.0	1.50	1.40	2.716	2.651
19	60	30	0	0	10	2.0	7.0	1.45	1.39	2.693	2.615
20	60	0	40	0	0	2.0	7.0	1.39	1.36	2.422	2.401
21	60	0	40	0	0	1.5	5.0	1.43	1.30	2.448	2.420
22	60	0	40	0	0	1.5	7.5	1.45	1.39	2.497	2.495
NOTES:	1. Convention: aluminous materials sum to 100 wt%										
	2. Actual weights are determined by normalizing to 100 wt% the aluminous										
	species plus binders/burnouts										

Table 5. Experimental Results - Volume and Linear Shrinkage
Expt. Plan with CP-5 and CA-25 Cement- 4.536 KG (10 LB) BATCH SIZE

TEST	ALUMINOUS MATERIAL ADDED					BURNOUT	BINDER	AO	SA	AO	SA	AO	SA
	A-13	A-13M	CP-5	C-30	CA-25	METHOCEL	MOGUL	SHRINKAGE	SHRINKAGE	SHRINKAGE	SHRINKAGE	SHRINKAGE	SHRINKAGE
	WT%	WT%	WT%	WT%	wt%	WT%	WT%	VOL-%	VOL-%	LIN-THICK-%	LIN-THICK-%	LIN-DIAM-%	LIN-DIAM-%
1	60	0	40	0	0	1.0	7.0	52.2	52.6	21.5	21.7	21.9	22.2
2	60	0	40	0	0	1.0	3.0	52.9	54.1	22.2	22.6	22.2	23.1
3	60	0	40	0	0	2.0	3.0	50.0	50.6	21.0	21.1	20.5	20.9
4	60	0	40	0	0	2.0	7.0	51.6	54.4	21.4	22.8	21.6	23.1
5	60	40	0	0	0	2.0	3.0	49.6	50.0	20.2	20.4	20.6	20.7
6	60	40	0	0	0	2.0	7.0	49.6	49.9	19.8	20.6	20.7	20.6
7	60	40	0	0	0	1.0	7.0	50.2	49.7	20.6	20.4	20.8	20.5
8	60	40	0	0	0	1.0	3.0	48.5	48.5	19.1	19.1	20.3	20.2
9	60	20	20	0	0	1.5	5.0	50.0	50.6	20.3	20.7	20.8	21.1
10	60	20	20	0	0	1.0	5.0	51.6	51.1	20.8	20.8	21.9	21.4
11	60	20	20	0	0	2.0	5.0	50.3	50.5	20.8	20.4	20.8	21.1
12	60	40	0	0	0	1.5	5.0	49.9	49.7	20.3	20.2	20.7	20.6
13	60	0	40	0	0	1.5	5.0	52.3	54.0	22.0	22.6	21.8	22.9
14	60	20	20	0	0	1.5	3.0	50.0	50.3	20.4	20.5	20.8	20.9
15	60	20	20	0	0	1.5	7.0	48.5	50.2	20.0	21.4	19.8	20.4
16	60	20	20	0	0	1.5	5.0	51.3	51.2	20.5	20.8	21.7	21.5
17	60	37	0	0	3	2.0	7.0	49.4	49.2	20.1	19.9	20.4	20.4
18	60	35	0	0	5	2.0	7.0	49.6	49.7	20.0	19.8	20.6	20.8
19	60	30	0	0	10	2.0	7.0	50.7	51.0	20.6	20.8	21.2	21.3
20	60	0	40	0	0	2.0	7.0	49.7	51.9	19.7	20.5	20.9	22.2
21	60	0	40	0	0	1.5	5.0	49.6	52.5	19.8	21.1	20.7	22.4
22	60	0	40	0	0	1.5	7.5	48.9	51.2	19.7	21.0	20.2	21.4
NOTES:													
1. Convention: aluminous materials sum to 100 wt%													
2. Actual weights are determined by normalizing to 100 wt% the aluminous													
species plus binders/burnouts													

Table 6. Experimental Results - Intermediate and Fired Strength
Expt. Plan with CP-5 and CA-25 Cement- 4.536 KG (10 LB) BATCH SIZE

TEST	ALUMINOUS MATERIAL ADDED						BURNOUT		BINDER MOGUL WT%	AO-ABRASION		SA-ABRASION		AO-CRUSH		SA-CRUSH		AO		SA	
	A-13 WT%	A-13M WT%	CP-5 WT%	C-30 WT%	CA-25 wt%	METHOCEL WT%	WT%			INTER. STRENGTH % WGT LOSS	notes 1,3	INTER. STRENGTH % WGT LOSS	notes 1,3	INTER. STRENGTH MPa	notes 2,4	INTER. STRENGTH MPa	notes 2,4	FIRED STRENGTH MPa	note 2	FIRED STRENGTH MPa	note 2
1	60	0	40	0	0	1.0	7.0			75.20		56.40		---		---		33.8		26.4	
2	60	0	40	0	0	1.0	3.0			68.50		56.30		---		---		31.6		31.1	
3	60	0	40	0	0	2.0	3.0			58.30		40.60		0.043		0.051		31.3		29.7	
4	60	0	40	0	0	2.0	7.0			50.30		21.00		0.040		0.132		30.2		32.4	
5	60	40	0	0	0	2.0	3.0			87.70		74.80		0.036		0.029		56.4		69.2	
6	60	40	0	0	0	2.0	7.0			74.70		86.30		0.037		0.011		60.5		65.7	
7	60	40	0	0	0	1.0	7.0			77.20		88.10		---		---		57.1		52.2	
8	60	40	0	0	0	1.0	3.0			75.60		75.30		---		---		56.6		52.4	
9	60	20	20	0	0	1.5	5.0			93.50		71.60		---		---		51.5		47.6	
10	60	20	20	0	0	1.0	5.0			97.50		86.30		---		---		56.8		45.2	
11	60	20	20	0	0	2.0	5.0			97.40		67.70		0.009		0.022		47.9		46.8	
12	60	40	0	0	0	1.5	5.0			91.10		76.40		---		---		62.7		58.4	
13	60	0	40	0	0	1.5	5.0			51.60		28.30		0.053		0.097		37.3		34.6	
14	60	20	20	0	0	1.5	3.0			84.30		77.60		---		---		54.7		54.7	
15	60	20	20	0	0	1.5	7.0			91.40		72.50		---		---		56.5		53.6	
16	60	20	20	0	0	1.5	5.0			96.90		70.00		---		---		44.8		43.2	
17	60	37	0	0	3	2.0	7.0			71.00		85.40		0.030		0.012		59.4		39.4	
18	60	35	0	0	5	2.0	7.0			47.80		57.60		0.042		0.059		53.1		47.8	
19	60	30	0	0	10	2.0	7.0			39.10		38.30		0.098		0.033		58.9		53.6	
20	60	0	40	0	0	2.0	7.0			42.10		71.90		0.018		0.064		31.7		31.7	
21	60	0	40	0	0	1.5	5.0			65.70		42.50		0.072		0.038		33.2		33.6	
22	60	0	40	0	0	1.5	7.5			39.50		20.20		0.033		0.113		42.8		40.8	
										note 1- Values for 3 min. period on RoTap											
										note 2- Conversion: 1 MPa= 145 lb/in2											
										note 3- Higher value = poorer intermediate strength											
										note 4- Higher value = higher intermediate strength											
										note 5- Average of 5 specimens											
										note 6- Convention: aluminous materials sum to 100 wt%											
										note 7- Actual weights are determined by normalizing to 100 wt% the aluminous species plus binders/burnouts											

Table 7. Summary of Economic Simulations for the LWA Process

NOMINAL CAPACITY		LWA SELLING PRICE	LWA SELLING PRICE		LIKELY CASE SCENARIO ACTUAL PRODUCTION			WORST CASE SCENARIO ACTUAL PRODUCTION	
MT/YR	MILLION LB/YR	% (1,5)	\$/LB		MILLION LB/YR	R.O.I.C. % (4)		MILLION LB/YR	R.O.I.C. % (4)
20,000	44.1	15	\$0.600		34.8	17.1		34.8	10.3
20,000	44.1	25	\$0.652		34.8	24.8		34.8	18.0
20,000	44.1	(35)	\$0.705		34.8	32.7		34.8	25.9
10,000	22.1	15	\$0.600		17.5	4.6		17.5	-1.9
10,000	22.1	25	\$0.652		17.5	12.1		17.5	5.6
10,000	22.1	(35)	\$0.705		17.5	19.7		17.5	13.2

NOTES: (1) % INCREMENTAL COST INCREASE OVER T-64 ON A VOLUME BASIS (T-64 SELLING PRICE @ \$800/MT).

(2) R.O.I.C. CALCULATED AS NET PROFIT AFTER TAXES DIVIDED BY TOTAL CAPITAL INVESTMENT.

(3) ECONOMIC ANALYSIS SCENARIOS:

WORST CASE: PRODUCT FINES RECYCLED WITH NO CREDIT CLAIMED FOR ALUMINA VALUE.

LIKELY CASE: PRODUCT RECYCLE WITH CREDIT CLAIMED EQUAL TO RAW MATERIAL COST FOR A-13M.

(4) THE CASES BORDERED WITH DOUBLE-LINED BOXES ARE THOSE MEETING OR EXCEEDING THE 15% ROIC TARGET.

(5) CIRCLE INDICATES THAT PROJECT OBJECTIVE ON SELLING PRICE IS EXCEEDED.

(6) RECYCLE = $0.95 \times 0.85 \times 0.98 = 0.791$ OR RECYCLE = $100.0 - 79.1 = 20.9\%$

Figure 1

Experimental Design Schematic

FIGURE 2

**LIGHTWEIGHT TUBULAR PROCESS
USING
A-13/CP-5 FORMULATION**

Appendix A – Supplemental Data on Green Density

This table (comprised of 4 pages) contains a summary of the green density data for individual specimens. The green density data for the replicate samples (normally 5) were averaged and the standard deviation calculated. The average green density value was reported in Table 4 in the body of this report.

Sample Identification Code in this table: **XXXXXX-YY-Aa-ZZ**

where **XXXXXX** = ATC Research Notebook Number

YY = ATC Research Notebook Page Number

A = Replicate number for the specimens

a = Experiment Number in the series

ZZ = Special treatment (AO - air oven / SA - steam aged)

Appendix A - Supplemental Data on Green Density

SAMPLE ID.	GREEN DIAM.	GREEN THK.	GREEN WT.	GREEN VOL.	GREEN DENSITY
NO.	cm	cm	grams	cc	g/cc
25247-40-A1-AO	1.599	1.379	4.0082	2.769	1.45
25247-40-B1-AO	1.595	1.360	3.8375	2.717	1.41
25247-40-C1-AO	1.647	1.354	4.0255	2.885	1.40
25247-40-D1-AO	1.408	1.396	3.1160	2.174	1.43
25247-40-E1-AO	1.681	1.390	4.3724	3.085	1.42
Average					1.42
Std. Dev.					0.02
25247-40-A1-SA	1.576	1.380	3.7294	2.692	1.39
25247-40-B1-SA	1.517	1.378	3.4477	2.491	1.38
25247-40-C1-SA	1.582	1.434	4.0140	2.819	1.42
25247-40-D1-SA	1.575	1.298	3.5495	2.529	1.40
25247-40-E1-SA	1.497	1.483	3.6326	2.610	1.39
Average					1.40
Std. Dev.					0.02
25247-42-A2-AO	1.587	1.305	3.5616	2.581	1.38
25247-42-B2-AO	1.649	1.104	3.2191	2.358	1.37
25247-42-C2-AO	1.669	1.149	3.4676	2.514	1.38
25247-42-D2-AO	1.550	1.168	3.0587	2.204	1.39
25247-42-E2-AO	1.510	1.190	2.9285	2.131	1.37
Average					1.38
Std. Dev.					0.01
25247-42-A2-SA	1.674	1.214	3.4820	2.672	1.30
25247-42-B2-SA	1.670	1.240	3.5792	2.716	1.32
25247-42-C2-SA	1.666	1.146	3.2834	2.498	1.31
25247-42-D2-SA	1.589	1.220	3.1507	2.419	1.30
25247-42-E2-SA	1.632	1.094	2.9930	2.288	1.31
Average					1.31
Std. Dev.					0.01
25247-46-A3-AO	1.638	0.988	3.0465	2.082	1.46
25247-46-B3-AO	1.675	1.039	3.2727	2.289	1.43
25247-46-C3-AO	1.639	1.046	3.2009	2.207	1.45
25247-46-D3-AO	1.678	0.897	2.9187	1.984	1.47
25247-46-E3-AO	1.661	1.171	3.7838	2.537	1.49
Average					1.46
Std. Dev.					0.02
25247-46-A3-SA	1.680	1.341	4.3764	2.973	1.47
25247-46-B3-SA	1.683	1.523	4.8862	3.388	1.44
25247-46-C3-SA	1.684	1.393	4.4910	3.103	1.45
25247-46-D3-SA	1.683	1.584	5.1787	3.524	1.47
25247-46-E3-SA	1.682	1.571	5.0907	3.491	1.46
Average					1.46
Std. Dev.					0.01
25247-45-A4-AO	1.756	1.422	4.9403	3.444	1.43
25247-45-B4-AO	1.728	1.568	5.3402	3.677	1.45
25247-45-C4-AO	1.640	1.318	4.0082	2.784	1.44
25247-45-D4-AO	1.690	1.544	5.0534	3.463	1.46
25247-45-E4-AO	1.688	1.407	4.5862	3.149	1.46
Average					1.45
Std. Dev.					0.01
25247-45-A4-SA	1.497	1.424	3.5114	2.506	1.40
25247-45-B4-SA	1.682	1.514	4.7123	3.364	1.40
25247-45-C4-SA	1.723	1.501	4.9367	3.500	1.41
25247-45-D4-SA	1.685	1.448	4.5360	3.229	1.40
25247-45-E4-SA	1.580	1.435	3.9621	2.814	1.41
Average					1.40
Std. Dev.					0.01
25247-44-A13-AO	1.603	1.547	4.3711	3.122	1.40
25247-44-B13-AO	1.674	1.490	4.5624	3.279	1.39
25247-44-C13-AO	1.540	1.679	4.3700	3.127	1.40
25247-44-D13-AO	1.676	1.447	4.5556	3.192	1.43
25247-44-E13-AO	1.634	1.426	4.2142	2.990	1.41
Average					1.41
Std. Dev.					0.01
25247-44-A13-SA	1.623	1.564	4.5070	3.236	1.39
25247-44-B13-SA	1.644	1.410	4.1482	2.993	1.39
25247-44-C13-SA	1.546	1.589	4.1196	2.983	1.38
25247-44-D13-SA	1.656	1.380	4.1232	2.972	1.39
25247-44-E13-SA	1.557	1.615	4.3101	3.075	1.40
Average					1.39
Std. Dev.					0.01

Appendix A - Supplemental Data on Green Density

SAMPLE ID.	GREEN DIAM.	GREEN THK.	GREEN WT.	GREEN VOL.	GREEN DENSITY
NO.	cm	cm	grams	cc	g/cc
25247-43-A9-AO	1.621	1.300	3.8874	2.68	1.45
25247-43-B9-AO	1.659	1.521	4.9504	3.29	1.51
25247-43-C9-AO	1.709	1.241	4.2301	2.85	1.49
25247-43-D9-AO	1.546	1.321	3.6589	2.48	1.48
25247-43-E9-AO	1.532	1.387	3.8304	2.56	1.50
Average					1.48
Std. Dev.					0.02
25247-43-A9-SA	1.755	1.443	5.0564	3.49	1.45
25247-43-B9-SA	1.660	1.207	3.7497	2.61	1.44
25247-43-C9-SA	1.671	1.444	4.4888	3.17	1.42
25247-43-D9-SA	1.641	1.359	4.1457	2.87	1.44
25247-43-E9-SA	1.639	1.489	4.3763	3.14	1.39
Average					1.43
Std. Dev.					0.02
25247-52-A10-AO	1.680	1.484	4.5920	3.29	1.40
25247-52-B10-AO	1.566	1.400	3.7868	2.70	1.41
25247-52-C10-AO	1.672	1.384	4.0392	3.04	1.33
25247-52-D10-AO	1.537	1.383	3.5743	2.57	1.39
25247-52-E10-AO	1.590	1.295	3.4827	2.57	1.35
Average					1.38
Std. Dev.					0.03
25247-52-A10-SA	1.719	1.470	4.6282	3.41	1.36
25247-52-B10-SA	1.668	1.450	4.3058	3.17	1.36
25247-52-C10-SA	1.649	1.244	3.6686	2.66	1.38
25247-52-D10-SA	1.707	1.435	4.4801	3.28	1.36
25247-52-E10-SA	1.635	1.414	4.1243	2.97	1.39
Average					1.37
Std. Dev.					0.01
25247-53-A11-AO	1.674	1.503	4.6140	3.31	1.39
25247-53-B11-AO	1.743	1.382	4.7645	3.30	1.44
25247-53-C11-AO	1.744	1.408	4.5718	3.36	1.36
25247-53-D11-AO	1.595	1.414	4.0367	2.83	1.43
25247-53-E11-AO	1.734	1.415	4.0964	3.34	1.23
Average					1.37
Std. Dev.					0.09
25247-53-A11-SA	1.611	1.387	4.1364	2.83	1.46
25247-53-B11-SA	1.621	1.301	3.9087	2.68	1.46
25247-53-C11-SA	1.540	1.408	3.8102	2.62	1.45
25247-53-D11-SA	1.662	1.389	4.3597	3.01	1.45
25247-53-E11-SA	1.685	1.427	4.6716	3.18	1.47
Average					1.46
Std. Dev.					0.01
25247-51-A14-AO	1.574	1.473	4.2389	2.87	1.48
25247-51-B14-AO	1.676	1.536	5.0623	3.39	1.49
25247-51-C14-AO	1.554	1.370	3.8697	2.60	1.49
25247-51-D14-AO	1.667	1.418	4.6262	3.09	1.49
25247-51-E14-AO	1.658	1.535	5.0101	3.31	1.51
Average					1.49
Std. Dev.					0.01
25247-51-A14-SA	1.571	1.427	4.0324	2.77	1.46
25247-51-B14-SA	1.653	1.689	5.2836	3.62	1.46
25247-51-C14-SA	1.560	1.520	4.2573	2.91	1.47
25247-51-D14-SA	1.549	1.513	4.2140	2.85	1.48
25247-51-E14-SA	1.618	1.505	4.5350	3.09	1.47
Average					1.46
Std. Dev.					0.01
25247-47-A15-AO	1.620	1.439	4.5242	2.97	1.53
25247-47-B15-AO	1.618	1.335	4.2045	2.74	1.53
25247-47-C15-AO	1.693	1.373	4.6795	3.09	1.51
25247-47-D15-AO	1.702	1.376	4.7325	3.13	1.51
25247-47-E15-AO	1.706	1.345	4.6057	3.07	1.50
Average					1.52
Std. Dev.					0.01
25247-47-A15-SA	1.663	1.586	5.2220	3.44	1.52
25247-47-B15-SA	1.716	1.506	5.2493	3.48	1.51
25247-47-C15-SA	1.709	1.555	5.3929	3.57	1.51
25247-47-D15-SA	1.670	1.527	5.0581	3.34	1.51
25247-47-E15-SA	1.667	1.562	5.1904	3.41	1.52
Average					1.51
Std. Dev.					0.01
25247-54-A16-AO	1.712	1.459	4.6086	3.36	1.37
25247-54-B16-AO	1.612	1.393	3.8722	2.84	1.36
25247-54-C16-AO	1.683	1.473	4.6336	3.28	1.41
25247-54-D16-AO	1.794	1.405	4.8326	3.55	1.36
25247-54-E16-AO	1.744	1.493	4.8768	3.57	1.37
Average					1.38
Std. Dev.					0.02
25247-54-A16-SA	1.586	1.405	3.9490	2.78	1.42
25247-54-B16-SA	1.675	1.516	4.7160	3.34	1.41
25247-54-C16-SA	1.663	1.486	4.5286	3.23	1.40
25247-54-D16-SA	1.674	1.566	4.8824	3.45	1.42
25247-54-E16-SA	1.680	1.518	4.6853	3.36	1.39
Average					1.41
Std. Dev.					0.01

Appendix A - Supplemental Data on Green Density

SAMPLE		GREEN	GREEN	GREEN	GREEN
ID.	DIAM.	THK.	WT.	VOL.	DENSITY
NO.	cm	cm	grams	cc	g/cc
25247-43-A5-AO	1.610	1.632	4.950	3.3225	1.49
25247-43-B5-AO	1.624	1.523	4.737	3.1547	1.50
25247-43-C5-AO	1.598	1.540	4.588	3.0886	1.49
25247-43-D5-AO	1.625	1.554	4.713	3.2229	1.46
25247-43-E5-AO	1.583	1.553	4.543	3.0565	1.49
Average					1.49
Std. Dev.					0.01
25247-43-A5-SA	1.621	1.405	4.166	2.8996	1.44
25247-43-B5-SA	1.626	1.600	4.893	3.3224	1.47
25247-43-C5-SA	1.610	1.494	4.309	3.0415	1.42
25247-43-D5-SA	1.614	1.563	4.772	3.1978	1.49
25247-43-E5-SA	1.519	1.426	3.866	2.5842	1.50
Average					1.46
Std. Dev.					0.03
25247-52-A6-AO	1.644	1.503	4.929	3.1905	1.55
25247-52-B6-AO	1.661	1.429	4.827	3.0964	1.56
25247-52-C6-AO	1.654	1.508	5.029	3.2401	1.55
25247-52-D6-AO	1.688	1.555	5.547	3.4799	1.59
25247-52-E6-AO	1.647	1.448	4.892	3.0849	1.59
Average					1.57
Std. Dev.					0.02
25247-52-A6-SA	1.595	1.445	4.417	2.8872	1.53
25247-52-B6-SA	1.621	1.508	4.776	3.1121	1.53
25247-52-C6-SA	1.630	1.430	4.560	2.9840	1.53
25247-52-D6-SA	1.602	1.493	4.653	3.0094	1.55
25247-52-E6-SA	1.477	1.638	4.164	2.8065	1.48
Average					1.52
Std. Dev.					0.02
25247-53-A7-AO	1.632	1.552	4.728	3.2465	1.46
25247-53-B7-AO	1.616	1.549	4.665	3.1770	1.47
25247-53-C7-AO	1.601	1.553	4.384	3.1264	1.40
25247-53-D7-AO	1.743	1.548	5.345	3.6936	1.45
25247-53-E7-AO	1.645	1.572	4.703	3.3410	1.41
Average					1.44
Std. Dev.					0.03
25247-53-A7-SA	1.769	1.450	4.989	3.5638	1.40
25247-53-B7-SA	1.607	1.644	4.827	3.3344	1.45
25247-53-C7-SA	1.472	1.533	3.769	2.6088	1.44
25247-53-D7-SA	1.595	1.512	4.065	3.0211	1.35
25247-53-E7-SA	1.577	1.558	4.446	3.0431	1.46
Average					1.42
Std. Dev.					0.05
25247-51-A8-AO	1.584	1.611	4.513	3.1746	1.42
25247-51-B8-AO	1.666	1.468	4.530	3.2001	1.61
25247-51-C8-AO	1.665	1.364	4.229	2.9698	1.47
25247-51-D8-AO	1.618	1.562	4.568	3.2116	1.36
25247-51-E8-AO	1.669	1.553	4.811	3.3976	1.56
Average					1.55
Std. Dev.					0.10
25247-51-A8-SA	1.679	1.582	4.705	3.5027	1.34
25247-51-B8-SA	1.748	1.472	4.762	3.5325	1.35
25247-51-C8-SA	1.563	1.477	3.750	2.8339	1.32
25247-51-D8-SA	1.562	1.567	4.212	3.0028	1.40
25247-51-E8-SA	1.563	1.531	4.152	2.9375	1.41
Average					1.37
Std. Dev.					0.04
25247-47-A12-AO	1.642	1.551	4.947	3.2843	1.51
25247-47-B12-AO	1.683	1.481	4.922	3.2947	1.49
25247-47-C12-AO	1.687	1.386	4.603	3.0980	1.49
25247-47-D12-AO	1.689	1.454	4.788	3.2577	1.47
25247-47-E12-AO	1.653	1.457	4.706	3.1268	1.51
Average					1.49
Std. Dev.					0.02
25247-47-A12-SA	1.639	1.433	4.437	3.0234	1.47
25247-47-B12-SA	1.649	1.494	4.732	3.1907	1.48
25247-47-C12-S2	1.641	1.572	4.847	3.3248	1.46
25247-47-D12-SA	1.600	1.617	4.645	3.2512	1.43
25247-47-E12-SA	1.570	1.513	4.199	2.9291	1.43
Average					1.45
Std. Dev.					0.02

Appendix A - Supplemental Data on Green Density

SAMPLE ID.	GREEN DIAM.	GREEN THK.	GREEN WT.	GREEN VOL.	GREEN DENSITY
NO.	cm	cm	grams	cc	g/cc
25247-82-A17-AO	1.655	1.363	3.9129	2.932	1.33
25247-82-B17-AO	1.653	1.326	3.9703	2.846	1.40
25247-82-C17-AO	1.592	1.364	3.8454	2.715	1.42
25247-82-D17-AO	1.651	1.378	4.1741	2.950	1.41
25247-82-E17-AO	1.640	1.426	4.3069	3.012	1.43
Average					1.40
Std. Dev.					0.04
25247-82-A17-SA	1.736	1.328	4.1868	3.143	1.33
25247-82-B17-SA	1.664	1.436	4.2370	3.123	1.36
25247-82-C17-SA	1.611	1.446	3.9402	2.947	1.34
25247-82-D17-SA	1.648	1.320	3.7141	2.816	1.32
25247-82-E17-SA	1.647	1.357	3.8044	2.891	1.32
Average					1.33
Std. Dev.					0.02
25247-83-A18-AO	1.667	1.492	4.9137	3.256	1.51
25247-83-B18-AO	1.678	1.494	4.9524	3.304	1.50
25247-83-C18-AO	1.685	1.474	4.9595	3.287	1.51
25247-83-D18-AO	1.687	1.480	4.9588	3.308	1.50
25247-83-E18-AO	1.622	1.459	4.4756	3.015	1.48
Average					1.50
Std. Dev.					0.01
25247-83-A18-SA	1.551	1.413	3.7885	2.670	1.42
25247-83-B18-SA	1.652	1.435	4.2721	3.076	1.39
25247-83-C18-SA	1.663	1.328	3.9964	2.885	1.39
25247-83-D18-SA	1.606	1.350	3.7189	2.735	1.35
25247-83-E18-SA	1.637	1.416	4.2767	2.980	1.44
Average					1.40
Std. Dev.					0.03
25247-84-A19-AO	1.650	1.449	4.5476	3.098	1.47
25247-84-B19-AO	1.592	1.498	4.3884	2.982	1.47
25247-84-C19-AO	1.635	1.448	4.3209	3.040	1.42
25247-84-D19-AO	1.612	1.416	4.1829	2.890	1.45
25247-84-E19-AO	1.590	1.513	4.3896	3.004	1.46
Average					1.45
Std. Dev.					0.02
25247-84-A19-SA	1.455	1.457	3.3677	2.423	1.39
25247-84-B19-SA	1.590	1.431	3.9629	2.841	1.39
25247-84-C19-SA	1.589	1.524	4.2155	3.022	1.39
25247-84-D19-SA	1.592	1.506	4.1679	2.998	1.39
25247-84-E19-SA	1.593	1.507	4.1155	3.004	1.37
Average					1.38
Std. Dev.					0.01
25247-79-A20-AO	1.608	1.534	4.3516	3.115	1.40
25247-79-B20-AO	1.604	1.499	4.1724	3.029	1.38
25247-79-C20-AO	1.558	1.488	4.0340	2.837	1.42
25247-79-D20-AO	1.554	1.480	3.8737	2.807	1.38
25247-79-E20-AO	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN
Average					1.39
Std. Dev.					0.02
25247-79-A20-SA	1.609	1.506	4.1776	3.062	1.35
25247-79-B20-SA	1.606	1.462	4.0275	2.962	1.35
25247-79-C20-SA	1.606	1.531	4.1472	3.101	1.34
25247-79-D20-SA	1.606	1.536	4.3175	3.112	1.39
25247-79-E20-SA	1.619	1.498	4.1692	3.084	1.35
Average					1.36
Std. Dev.					0.02
25247-80-A21-AO	1.615	1.506	4.4577	3.085	1.44
25247-80-B21-AO	1.628	1.496	4.3510	3.114	1.40
25247-80-C21-AO	1.509	1.488	3.8636	2.661	1.45
25247-80-D21-AO	1.615	1.508	4.4228	3.089	1.43
25247-80-E21-AO	1.616	1.424	4.1823	2.921	1.43
Average					1.43
Std. Dev.					0.02
25247-80-A21-SA	1.606	1.415	3.6740	2.866	1.28
25247-80-B21-SA	1.607	1.492	3.8718	3.026	1.28
25247-80-C21-SA	1.610	1.532	4.1244	3.119	1.32
25247-80-D21-SA	1.607	1.438	3.7930	2.917	1.30
25247-80-E21-SA	1.610	1.460	3.9016	2.972	1.31
Average					1.30
Std. Dev.					0.02
25247-81-A22-AO	1.704	1.486	4.9525	3.389	1.46
25247-81-B22-AO	1.656	1.582	5.0219	3.407	1.47
25247-81-C22-AO	1.715	1.618	5.4059	3.738	1.45
25247-81-D22-AO	1.694	1.436	4.7331	3.236	1.46
25247-81-E22-AO	1.738	1.486	5.0134	3.525	1.42
Average					1.45
Std. Dev.					0.02
25247-81-A22-SA	1.699	1.484	4.7013	3.364	1.40
25247-81-B22-SA	1.649	1.540	4.5694	3.289	1.39
25247-81-C22-SA	1.699	1.485	4.6739	3.367	1.39
25247-81-D22-SA	1.644	1.437	4.1750	3.050	1.37
25247-81-E22-SA	1.698	1.498	4.7270	3.392	1.39
Average					1.39
Std. Dev.					0.01

Appendix B – Supplemental Data on Fired Density

The first series of tables (comprised of 4 pages) contains a summary of the fired density data for individual specimens. The fired density data for the replicate samples (normally 5) were averaged and the standard deviation calculated and reported in a separate table (subsequent 4 pages). The average fired density value was reported in Table 4 in the body of this report.

Sample Identification Code in this table: XXXXX-YY-Aa-ZZ

where XXXXX = ATC Research Notebook Number

YY = ATC Research Notebook Page Number

A = Replicate number for the specimens

a = Experiment Number in the series

ZZ = Special treatment (AO - air oven / SA - steam aged)

Appendix B - Supplemental Data on Fired Density

	DRY	SUS.	SAT.	BULK	APP.	H2O	APP.	TOTAL
I.D.	WEIGHT	WEIGHT	WEIGHT	DENSITY	POROSITY	ABS.	S.G.	POROSITY
NO.	(g)	(g)	(g)	(g/cc)	(%)	(%)	(g/cc)	(%)
25247-40-A1-AO	5.6895	4.2194	6.4330	2.56	33.59	13.11	3.86	35.61
25247-40-B1-AO	6.1928	4.5883	6.9851	2.58	33.06	12.83	3.85	35.28
25247-40-C1-AO	6.022	4.4525	6.7804	2.58	32.58	12.63	3.83	35.20
25247-40-D1-AO	5.9512	4.4167	6.6958	2.60	32.67	12.55	3.87	34.59
25247-40-E1-AO	5.8352	4.3197	6.569	2.59	32.62	12.61	3.84	35.01
25247-40-A1-SA	6.0372	4.4665	6.8113	2.57	33.01	12.86	3.83	35.50
25247-40-B1-SA	6.0095	4.4512	6.7467	2.61	32.12	12.30	3.84	34.42
25247-40-C1-SA	5.9789	4.4311	6.7452	2.58	33.11	12.86	3.85	35.28
25247-40-D1-SA	6.4781	4.8029	7.3344	2.55	33.83	13.26	3.86	35.90
25247-40-E1-SA	5.8431	4.3476	6.6581	2.52	35.27	13.99	3.90	36.65
25247-42-A2-AO	7.1582	5.285	8.1004	2.53	33.47	13.20	3.81	36.31
25247-42-B2-AO	5.1913	3.8259	5.8425	2.57	32.29	12.58	3.79	35.51
25247-42-C2-AO	7.2439	5.3396	8.1839	2.54	33.05	13.02	3.79	36.20
25247-42-D2-AO	5.5221	4.0766	6.1841	2.61	31.41	12.02	3.81	34.36
25247-42-E2-AO	6.4925	4.7886	7.2639	2.62	31.16	11.92	3.80	34.30
25247-42-A2-SA	5.8433	4.3245	6.6001	2.56	33.26	12.99	3.84	35.68
25247-42-B2-SA	5.833	4.3172	6.5955	2.55	33.47	13.11	3.84	35.87
25247-42-C2-SA	5.7632	4.2705	6.508	2.57	33.29	12.96	3.85	35.48
25247-42-D2-SA	5.5595	4.1065	6.2859	2.54	33.33	13.11	3.81	36.10
25247-42-E2-SA	6.3446	4.6835	7.1816	2.53	33.51	13.23	3.81	36.38
25247-46-A3-AO	7.0122	5.2015	7.9091	2.58	33.13	12.83	3.86	35.12
25247-46-B3-AO	7.3593	5.642	8.2822	2.78	34.96	12.58	4.27	30.17
25247-46-C3-AO	7.8278	5.8031	8.806	2.60	32.58	12.53	3.85	34.70
25247-46-D3-AO	6.2019	4.6016	6.9795	2.60	32.70	12.58	3.86	34.67
25247-46-E3-AO	7.483	5.5583	8.4325	2.60	33.04	12.73	3.88	34.78
25247-46-A3-SA	7.288	5.409	8.2469	2.56	33.79	13.20	3.87	35.67
25247-46-B3-SA	7.1383	5.2928	8.0595	2.57	33.30	12.94	3.86	35.37
25247-46-C3-SA	6.9636	5.1653	7.8644	2.57	33.37	12.97	3.86	35.37
25247-46-D3-SA	6.9593	5.1475	7.8697	2.55	33.44	13.12	3.83	35.96
25247-46-E3-SA	6.6725	4.9574	7.5707	2.55	34.37	13.50	3.88	36.04
25247-45-A4-AO	6.069	4.499	6.8363	2.59	32.83	12.68	3.85	34.95
25247-45-B4-AO	5.199	3.8541	5.8737	2.57	33.41	13.02	3.85	35.51
25247-45-C4-AO	5.6668	4.2107	6.3817	2.60	32.93	12.65	3.88	34.61
25247-45-D4-AO	6.1069	4.5315	6.8756	2.60	32.79	12.63	3.86	34.74
25247-45-E4-AO	6.2902	4.6675	7.0895	2.59	33.00	12.75	3.86	34.94
25247-45-A4-SA	6.5557	4.8588	7.3743	2.60	32.54	12.52	3.85	34.72
25247-45-B4-SA	6.2845	4.6689	7.0814	2.60	33.03	12.72	3.88	34.74
25247-45-C4-SA	4.9917	3.7051	5.622	2.60	32.88	12.66	3.87	34.77
25247-45-D4-SA	6.4575	4.7972	7.2862	2.59	33.29	12.87	3.88	35.01
25247-45-E4-SA	5.9987	4.4557	6.7501	2.61	32.75	12.56	3.88	34.51
25247-44-A13-AO	6.8215	5.0558	7.6359	2.64	31.56	11.97	3.85	33.77
25247-44-B13-AO	6.2508	4.6338	7.0233	2.61	32.33	12.40	3.85	34.47
25247-44-C13-AO	6.7153	4.9761	7.531	2.62	31.93	12.18	3.85	34.16
25247-44-D13-AO	6.2197	4.6176	6.9937	2.61	32.57	12.48	3.87	34.43
25247-44-E13-AO	6.6829	4.956	7.5007	2.62	32.14	12.27	3.86	34.21
25247-44-A13-SA	6.4494	4.7918	7.2433	2.62	32.38	12.35	3.88	34.10
25247-44-B13-SA	6.7836	5.0361	7.6304	2.61	32.64	12.52	3.87	34.50
25247-44-C13-SA	6.0895	4.5271	6.8426	2.62	32.52	12.40	3.89	34.12
25247-44-D13-SA	6.7454	5.0085	7.5751	2.62	32.33	12.34	3.87	34.16
25247-44-E13-SA	6.676	4.9575	7.49	2.63	32.14	12.23	3.87	33.96

Appendix B - Supplemental Data on Fired Density

SAMPLE	DRY	SUS.	SAT.	BULK	APP.	H2O	APP.	TOTAL
ID.	WEIGHT	WEIGHT	WEIGHT	DENSITY	POROSITY	ABS.	S.G.	POROSITY
NO.	(g)	(g)	(g)	(g/cc)	(%)	(%)	(g/cc)	(%)
25247-43-A9-AO	6.9112	5.1185	7.7311	2.64	31.38	11.90	3.84	33.73
25247-43-B9-AO	7.7695	5.7638	8.6768	2.66	31.15	11.71	3.86	33.19
25247-43-C9-AO	6.213	4.6006	6.921	2.67	30.51	11.43	3.84	32.93
25247-43-D9-AO	6.5153	4.8176	7.2728	2.65	30.85	11.66	3.83	33.52
25247-43-E9-AO	7.8405	5.8106	8.7547	2.66	31.05	11.70	3.85	33.29
25247-43-A9-SA	7.4548	5.5284	8.4317	2.56	33.65	13.14	3.86	35.68
25247-43-B9-SA	7.6961	5.7018	8.6372	2.61	32.06	12.27	3.85	34.32
25247-43-C9-SA	7.0124	5.2038	7.864	2.63	32.01	12.18	3.87	33.97
25247-43-D9-SA	6.9515	5.1466	7.8169	2.60	32.41	12.49	3.84	34.79
25247-43-E9-SA	6.3796	4.7266	7.1573	2.62	31.99	12.23	3.85	34.25
25247-52-A10-AO	8.943	6.6209	10.0452	2.60	32.19	12.36	3.84	34.58
25247-52-B10-AO	7.1883	5.3032	8.073	2.59	31.94	12.34	3.80	34.99
25247-52-C10-AO	9.7422	7.2015	10.9875	2.57	32.89	12.82	3.82	35.54
25247-52-D10-AO	10.6027	7.8453	11.9505	2.58	32.83	12.75	3.83	35.30
25247-52-E10-AO								
25247-52-A10-SA	6.8189	5.047	7.7663	2.50	34.84	13.94	3.84	37.18
25247-52-B10-SA	8.1749	6.0547	9.2381	2.56	33.40	13.04	3.84	35.67
25247-52-C10-SA	8.2136	6.085	9.3063	2.54	33.92	13.34	3.85	36.13
25247-52-D10-SA	8.0236	5.943	9.0689	2.56	33.44	13.07	3.84	35.70
25247-52-E10-SA	8.1572	6.038	9.2603	2.52	34.23	13.56	3.84	36.59
25247-53-A11-AO	7.6344	5.3283	8.0914	2.75	16.54	6.00	3.30	30.79
25247-53-B11-AO	7.2682	5.3954	8.2085	2.58	33.43	12.98	3.87	35.28
25247-53-C11-AO	6.7451	5.003	7.6734	2.52	34.76	13.80	3.86	36.73
25247-53-D11-AO	7.7597	5.7611	8.7942	2.55	34.11	13.37	3.87	35.91
25247-53-E11-AO	7.1727	5.3178	8.1035	2.57	33.41	13.02	3.86	35.50
25247-53-A11-SA	7.7365	5.7331	8.6972	2.60	32.41	12.46	3.85	34.62
25247-53-B11-SA	7.3591	5.461	8.2692	2.61	32.41	12.40	3.87	34.35
25247-53-C11-SA	8.5746	6.3568	9.6253	2.62	32.15	12.29	3.85	34.28
25247-53-D11-SA	7.3074	5.4207	8.2133	2.61	32.44	12.43	3.86	34.45
25247-53-E11-SA	7.5525	5.6039	8.4912	2.61	32.51	12.47	3.86	34.47
25247-51-A14-AO	7.5459	5.5871	8.3505	2.72	29.12	10.69	3.84	31.60
25247-51-B14-AO	8.5625	6.3433	9.4585	2.74	28.76	10.50	3.85	31.15
25247-51-C14-AO	7.3308	5.4374	8.14	2.70	29.94	11.07	3.86	32.05
25247-51-D14-AO	7.3385	5.4052	8.1545	2.66	29.68	11.15	3.78	33.14
25247-51-E14-AO	7.9767	5.9083	8.8185	2.73	28.93	10.58	3.84	31.34
25247-51-A14-SA	8.0553	5.9637	8.9549	2.68	30.07	11.20	3.84	32.54
25247-51-B14-SA	8.1088	6.0058	9.027	2.68	30.39	11.36	3.84	32.77
25247-51-C14-SA	8.6482	6.4178	9.6219	2.69	30.39	11.29	3.87	32.39
25247-51-D14-SA	8.6076	6.3818	9.5734	2.69	30.26	11.25	3.86	32.44
25247-51-E14-SA	8.383	6.2216	9.3339	2.69	30.55	11.38	3.87	32.53
25247-47-A15-AO	7.7347	5.7336	8.5683	2.72	29.41	10.81	3.85	31.65
25247-47-B15-AO	7.6374	5.6369	8.5049	2.65	30.25	11.39	3.81	33.29
25247-47-C15-AO	7.6159	5.6474	8.4571	2.70	29.94	11.08	3.86	32.10
25247-47-D15-AO	6.8467	5.0798	7.5913	2.72	29.65	10.91	3.86	31.71
25247-47-E15-AO	7.4188	5.5187	8.2572	2.70	30.62	11.34	3.89	32.14
25247-47-A15-SA	7.7522	5.4758	8.6335	2.45	27.91	11.40	3.40	38.50
25247-47-B15-SA	7.2705	5.4002	8.1126	2.67	31.05	11.62	3.88	32.85
25247-47-C15-SA	8.5974	6.3731	9.5448	2.70	29.87	11.05	3.85	32.10
25247-47-D15-SA	8.6921	6.4513	9.6528	2.71	30.01	11.09	3.87	31.99
25247-47-E15-SA	8.5265	6.3229	9.483	2.69	30.27	11.25	3.86	32.41
25247-54-A16-AO	9.7132	7.22	10.9949	2.57	33.95	13.24	3.88	35.54
25247-54-B16-AO	4.9833	3.697	5.6343	2.56	33.60	13.10	3.86	35.56
25247-54-C16-AO	8.266	6.1513	9.3668	2.56	34.23	13.36	3.90	35.60
25247-54-D16-AO	7.4989	5.5456	8.4163	2.60	31.96	12.27	3.83	34.56
25247-54-E16-AO	9.0422	6.7229	10.2017	2.59	33.33	12.86	3.89	34.89
25247-54-A16-SA	8.1442	6.0378	9.1753	2.59	32.86	12.70	3.85	34.98
25247-54-B16-SA	8.5552	6.3385	9.6188	2.60	32.42	12.47	3.85	34.67
25247-54-C16-SA	7.8308	5.8	8.8137	2.59	32.61	12.59	3.84	34.91
25247-54-D16-SA	7.5567	5.6014	8.5123	2.59	32.83	12.68	3.85	34.97
25247-54-E16-SA	10.0188	7.4458	11.302	2.59	33.28	12.85	3.88	34.92
NOTE:								
SAMPLES LOST OR DAMAGED IN CONVERTER.								

Appendix B - Supplemental Data on Fired Density

SAMPLE ID.	DRY WEIGHT	SUS. WEIGHT	SAT. WEIGHT	BULK DENSITY	APP. POROSITY	H2O ABS.	APP. S.G.	TOTAL POROSITY
NO.	(g)	(g)	(g)	(g/cc)	(%)	(%)	(g/cc)	(%)
25247-43-A5-AO	7.5465	5.5720	8.2727	2.79	26.89	9.65	3.81	30.00
25247-43-B5-AO	7.9823	5.8856	8.7430	2.79	26.62	9.56	3.80	30.02
25247-43-C5-AO	8.3954	6.2076	9.1908	2.81	26.66	9.50	3.83	29.50
25247-43-D5-AO	7.8491	5.8064	8.6033	2.80	26.97	9.64	3.83	29.70
25247-43-E5-AO	7.5981	5.6262	8.3461	2.79	27.50	9.87	3.84	30.02
25247-43-A5-SA	8.4011	6.2059	9.1994	2.80	26.67	9.53	3.82	29.70
25247-43-B5-SA	7.3383	5.4264	8.0831	2.75	28.03	10.18	3.83	30.81
25247-43-C5-SA	7.5440	5.5685	8.2731	2.78	26.96	9.69	3.81	30.13
25247-43-D5-SA	8.8905	6.5688	9.7495	2.79	27.01	9.69	3.82	29.98
25247-43-E5-SA	7.8763	5.8043	8.6577	2.75	27.38	9.95	3.79	30.85
25247-52-A6-AO	7.6324	5.6492	8.2939	2.88	25.01	8.69	3.84	27.71
25247-52-B6-AO	6.4137	4.7370	7.0151	2.81	26.40	9.41	3.81	29.47
25247-52-C6-AO	6.7105	4.9561	7.3645	2.78	27.15	9.78	3.81	30.20
25247-52-D6-AO	6.8349	5.0542	7.4957	2.79	27.07	9.70	3.83	29.87
25247-52-E6-AO	6.7275	4.9833	7.3335	2.85	25.79	9.03	3.85	28.29
25247-52-A6-SA	6.5845	4.8872	7.1822	2.86	26.04	9.10	3.87	28.13
25247-52-B6-SA	7.6864	5.6808	8.4103	2.81	26.52	9.45	3.82	29.46
25247-52-C6-SA	6.5868	4.8703	7.1585	2.87	24.98	8.71	3.83	27.89
25247-52-D6-SA	6.5332	4.8251	7.1124	2.85	25.32	8.89	3.81	28.45
25247-52-E6-SA	6.5472	4.8430	7.1611	2.82	26.48	9.40	3.83	29.25
25247-53-A7-AO	8.4582	6.2672	9.4609	2.64	31.40	11.89	3.85	33.66
25247-53-B7-AO	9.8570	7.2975	10.9501	2.69	29.93	11.12	3.84	32.40
25247-53-C7-AO	9.2779	6.8665	10.2808	2.71	29.37	10.84	3.84	31.93
25247-53-D7-AO	8.6099	6.3756	9.6555	2.62	31.88	12.18	3.84	34.24
25247-53-E7-AO	9.4958	7.0219	10.5211	2.71	29.30	10.83	3.83	32.02
25247-53-A7-SA	9.2973	6.8857	10.4717	2.58	32.75	12.67	3.84	35.05
25247-53-B7-SA	9.1599	6.7765	10.2091	2.66	30.57	11.49	3.83	33.15
25247-53-C7-SA	8.6655	6.4293	9.7392	2.61	32.44	12.43	3.86	34.42
25247-53-D7-SA	9.7845	7.2600	10.9514	2.64	31.61	11.96	3.86	33.60
25247-53-E7-SA	9.0937	6.7340	10.1651	2.64	31.23	11.82	3.84	33.61
25247-51-A8-AO	10.0236	7.4183	11.2393	2.62	31.82	12.16	3.84	34.29
25247-51-B8-AO	7.6948	5.7009	8.5594	2.68	30.25	11.27	3.85	32.57
25247-51-C8-AO	9.0567	6.7195	10.1912	2.60	32.68	12.56	3.86	34.65
25247-51-D8-AO	8.7741	6.4988	9.8257	2.63	31.61	12.02	3.84	33.93
25247-51-E8-AO	9.3745	6.9443	10.5388	2.60	32.39	12.46	3.85	34.67
25247-51-A8-SA	7.9822	5.9188	8.9976	2.58	32.98	12.76	3.86	35.05
25247-51-B8-SA	7.8042	5.7866	8.7425	2.63	31.74	12.06	3.86	33.86
25247-51-C8-SA	9.2111	6.8205	10.3807	2.58	32.85	12.74	3.84	35.19
25247-51-D8-SA	7.8460	5.8095	8.8615	2.56	33.27	12.98	3.84	35.60
25247-51-E8-SA	7.6595	5.6808	8.6344	2.59	33.01	12.77	3.86	35.04
25247-47-A12-AO	9.2513	6.8350	10.1896	2.75	27.97	10.17	3.82	30.92
25247-47-B12-AO	7.7065	5.6969	8.4461	2.79	26.90	9.63	3.82	29.78
25247-47-C12-AO	7.6566	5.6583	8.4029	2.78	27.19	9.78	3.82	30.12
25247-47-D12-AO	7.8798	5.8066	8.6055	2.81	25.93	9.24	3.79	29.48
25247-47-E12-AO	7.4865	5.5246	8.2194	2.77	27.20	9.82	3.80	30.41
25247-47-A12-SA	8.6052	6.3614	9.5586	2.68	29.82	11.11	3.82	32.58
25247-47-B12-SA	9.4277	6.9786	10.4582	2.70	29.62	10.96	3.84	32.13
25247-47-C12-S2	8.6486	6.3942	9.5330	2.75	28.18	10.26	3.82	30.98
25247-47-D12-SA	9.0757	6.7075	10.1027	2.67	30.25	11.35	3.82	33.04
25247-47-E12-SA	9.6848	7.1552	10.6564	2.76	27.75	10.06	3.82	30.71

Appendix B - Supplemental Data on Fired Density

SAMPLE ID. NO.	WEIGHT (g)	WEIGHT (g)	WEIGHT (g)	DENSITY (g/cc)	POROSITY (%)	ABS. (%)	S.G. (g/cc)	POROSITY (%)
25247-82-A17-AO	7.937	5.8778	8.8730	2.64	31.25	11.83	3.84	33.62
25247-82-B17-AO	8.4656	6.2317	9.4715	2.61	31.05	11.92	3.78	34.54
25247-82-C17-AO	8.2965	6.1072	9.2869	2.60	31.15	11.97	3.78	34.64
25247-82-D17-AO	7.398	5.4515	8.2596	2.63	30.68	11.68	3.79	34.00
25247-82-E17-AO	7.7768	5.727	8.7151	2.59	31.40	12.10	3.78	34.80
25247-82-A17-SA	7.4553	5.5181	8.4574	2.53	34.09	13.48	3.84	36.46
25247-82-B17-SA	8.1752	6.0329	9.2721	2.52	33.86	13.46	3.80	36.78
25247-82-C17-SA	8.2282	6.067	9.2975	2.54	33.10	13.03	3.80	36.20
25247-82-D17-SA	8.5973	6.3668	9.7909	2.50	34.86	13.93	3.84	37.10
25247-82-E17-SA	8.7746	6.4487	9.9022	2.53	32.65	12.89	3.76	36.35
25247-83-A18-AO	7.4845	5.5241	8.2363	2.75	27.72	10.07	3.81	30.87
25247-83-B18-AO	7.6804	5.5659	8.4313	2.67	26.21	9.81	3.62	32.86
25247-83-C18-AO	8.5915	6.3147	9.5065	2.68	28.67	10.68	3.76	32.57
25247-83-D18-AO	8.4656	6.25	9.3098	2.76	27.59	10.00	3.81	30.69
25247-83-E18-AO	7.9987	5.8865	8.826	2.71	28.14	10.37	3.78	31.84
25247-83-A18-SA	8.511	6.2476	9.4936	2.61	30.27	11.58	3.75	34.32
25247-83-B18-SA	8.1283	5.9833	9.0425	2.65	29.88	11.28	3.78	33.44
25247-83-C18-SA	7.502	5.5066	8.3139	2.66	28.92	10.86	3.75	33.06
25247-83-D18-SA	7.5925	5.5743	8.4258	2.65	29.22	11.01	3.75	33.30
25247-83-E18-SA	7.0322	5.1684	7.7907	2.67	28.92	10.82	3.76	32.82
25247-84-A19-AO	8.0646	5.9544	8.9374	2.70	29.26	10.86	3.81	32.28
25247-84-B19-AO	8.3801	6.1778	9.2872	2.69	29.17	10.86	3.79	32.49
25247-84-C19-AO	8.2945	6.1131	9.1742	2.70	28.74	10.64	3.79	32.12
25247-84-D19-AO	7.6807	5.6117	8.4588	2.69	27.33	10.16	3.70	32.42
25247-84-E19-AO	7.9727	5.8725	8.8265	2.69	28.90	10.74	3.78	32.39
25247-84-A19-SA	8.7605	6.4579	9.8377	2.58	31.87	12.33	3.79	35.07
25247-84-B19-SA	8.1886	6.0134	9.1198	2.63	29.98	11.41	3.75	33.97
25247-84-C19-SA	10.5088	7.7258	11.7282	2.62	30.47	11.64	3.76	34.23
25247-84-D19-SA	9.3986	6.9216	10.4737	2.64	30.27	11.47	3.78	33.72
25247-84-E19-SA	9.1985	6.7606	10.2771	2.61	30.67	11.76	3.76	34.47
25247-79-A20-AO	5.8378	4.324	6.7358	2.41	37.23	15.43	3.84	39.37
25247-79-B20-AO	6.0981	4.5193	7.0547	2.40	37.73	15.73	3.85	39.75
25247-79-C20-AO	6.3578	4.7081	7.3136	2.43	36.68	15.08	3.84	38.87
25247-79-D20-AO	6.3406	4.7003	7.3149	2.42	37.26	15.41	3.85	39.25
25247-79-E20-AO	6.7418	4.9856	7.7316	2.45	36.05	14.73	3.83	38.50
25247-79-A20-SA	7.5292	5.5849	8.7417	2.38	38.41	16.15	3.86	40.25
25247-79-B20-SA	7.7699	5.743	8.9469	2.42	36.74	15.19	3.82	39.25
25247-79-C20-SA	6.4567	4.7898	7.4574	2.41	37.51	15.55	3.86	39.37
25247-79-D20-SA	8.521	6.3119	9.8603	2.39	37.74	15.76	3.85	39.85
25247-79-E20-SA	6.8206	5.0517	7.8815	2.40	37.49	15.60	3.84	39.62
25247-80-A21-AO	6.756	5.0012	7.75	2.45	36.16	14.76	3.84	38.43
25247-80-B21-AO	7.4717	5.5377	8.5641	2.46	36.10	14.66	3.85	38.15
25247-80-C21-AO	6.5286	4.8271	7.4973	2.44	36.28	14.88	3.83	38.75
25247-80-D21-AO	8.2417	6.0927	9.4697	2.43	36.36	14.94	3.82	38.86
25247-80-E21-AO	7.0513	5.2154	8.077	2.46	35.84	14.59	3.83	38.27
25247-80-A21-SA	7.3632	5.4423	8.4601	2.43	36.35	14.94	3.82	38.88
25247-80-B21-SA	7.024	5.1915	8.119	2.39	37.40	15.64	3.82	39.90
25247-80-C21-SA	7.762	5.7359	8.9186	2.43	36.34	14.95	3.82	38.91
25247-80-D21-SA	6.7933	5.0201	7.8074	2.43	36.38	14.97	3.82	38.95
25247-80-E21-SA	7.4684	5.5204	8.6049	2.41	36.85	15.26	3.82	39.35
25247-81-A22-AO	6.5066	4.8306	7.4231	2.50	35.35	14.13	3.87	37.13
25247-81-B22-AO	7.301	5.3984	8.31	2.50	34.65	13.86	3.83	37.19
25247-81-C22-AO	5.9365	4.4071	6.7969	2.48	36.00	14.54	3.87	37.77
25247-81-D22-AO	7.536	5.585	8.5768	2.51	34.79	13.85	3.85	36.90
25247-81-E22-AO	6.6225	4.9014	7.5495	2.49	35.01	14.04	3.84	37.35
25247-81-A22-SA	7.3771	5.459	8.3935	2.51	34.64	13.82	3.83	37.03
25247-81-B22-SA	6.3296	4.6881	7.2143	2.50	35.02	14.02	3.84	37.23
25247-81-C22-SA	5.9357	4.3879	6.7533	2.50	34.56	13.82	3.82	37.14
25247-81-D22-SA	7.0655	5.234	8.0744	2.48	35.52	14.32	3.85	37.69
25247-81-E22-SA	7.3751	5.4569	8.412	2.49	35.09	14.10	3.83	37.48

Appendix B - Supplemental Data on Fired Density

SAMPLE #		STATISTICAL SUMMARY				
		BULK	APP.	H2O	APP.	TOTAL
		DENSITY	POROSITY	ABS.	S.G.	POROSITY
		(g/cc)	(%)	(%)	(g/cc)	(%)
25247-40-1-AO	MEAN	2.582	32.903	12.747	3.847	35.138
	STD. DEV.	0.015	0.427	0.228	0.016	0.376
25247-40-1-SA	MEAN	2.565	33.468	13.054	3.856	35.549
	STD. DEV.	0.033	1.178	0.624	0.024	0.819
25247-42-2-AO	MEAN	2.574	32.276	12.548	3.800	35.337
	STD. DEV.	0.039	1.000	0.574	0.009	0.969
25247-42-2-SA	MEAN	2.551	33.370	13.080	3.829	35.899
	STD. DEV.	0.014	0.111	0.108	0.017	0.353
25247-46-3-AO	MEAN	2.631	33.279	12.649	3.946	33.889
	STD. DEV.	0.083	0.965	0.125	0.183	2.084
25247-46-3-SA	MEAN	2.560	33.655	13.148	3.858	35.681
	STD. DEV.	0.013	0.442	0.224	0.018	0.316
25247-45-4-AO	MEAN	2.589	32.992	12.744	3.864	34.952
	STD. DEV.	0.014	0.247	0.159	0.011	0.345
25247-45-4-SA	MEAN	2.597	32.900	12.669	3.870	34.749
	STD. DEV.	0.007	0.285	0.137	0.011	0.179
25247-44-13-AO	MEAN	2.619	32.106	12.262	3.857	34.208
	STD. DEV.	0.011	0.386	0.197	0.008	0.279
25247-44-13-SA	MEAN	2.620	32.404	12.368	3.876	34.169
	STD. DEV.	0.008	0.191	0.106	0.006	0.199
NOTES:						
1. SAMPLE # IS 25247 BOOK NO. - PAGE NO. - SAMPLE NO. - AO AIR DRIED, SA STEAM AGED.						
2. THE MEAN AND STANDARD DEVIATION IS OF FIVE SAMPLES.						
3. P3/F1 IS DOE PHASE 3 FIRING 1						

Appendix B - Supplemental Data on Fired Density

SAMPLE #		STATISTICAL SUMMARY				TOTAL
		BULK	APP.	H2O	APP.	
		DENSITY	POROSITY	ABS.	S.G.	
		(g/cc)	(%)	(%)	(g/cc)	
25247-43-9-AO	MEAN	2.582	30.989	11.680	3.845	33.332
	STD. DEV.	0.012	0.328	0.168	0.013	0.311
25247-43-9-SA	MEAN	2.603	32.425	12.461	3.852	34.602
	STD. DEV.	0.027	0.704	0.400	0.010	0.670
25247-52-10-AO	MEAN	2.583	32.463	12.569	3.825	35.102
	STD. DEV.	0.017	0.472	0.251	0.017	0.416
25247-52-10-SA	MEAN	2.537	33.966	13.391	3.842	36.254
	STD. DEV.	0.025	0.599	0.372	0.005	0.640
25247-53-11-AO	MEAN	2.593	33.927	13.292	3.751	34.841
	STD. DEV.	0.093	0.644	0.385	0.252	2.333
25247-53-11-SA	MEAN	2.609	32.383	12.410	3.859	34.436
	STD. DEV.	0.005	0.139	0.071	0.007	0.127
25247-51-14-AO	MEAN	2.712	29.285	10.800	3.835	31.854
	STD. DEV.	0.032	0.504	0.295	0.029	0.793
25247-51-14-SA	MEAN	2.685	30.334	11.297	3.854	32.532
	STD. DEV.	0.006	0.178	0.073	0.012	0.145
25247-47-15-AO	MEAN	2.699	29.971	11.105	3.855	32.177
	STD. DEV.	0.026	0.478	0.256	0.031	0.661
25247-47-15-SA	MEAN	2.644	29.820	11.282	3.770	33.570
	STD. DEV.	0.111	1.161	0.234	0.210	2.777
25247-54-16-AO	MEAN	2.578	33.416	12.966	3.872	35.232
	STD. DEV.	0.019	0.884	0.430	0.028	0.477
25247-54-16-SA	MEAN	2.591	32.801	12.658	3.856	34.888
	STD. DEV.	0.005	0.319	0.140	0.015	0.127
NOTES:						
1. SAMPLE # IS 25247 BOOK NO. - PAGE NO. - SAMPLE NO. - AO AIR DRIED, SA STEAM AGED.						
2. THE MEAN AND STANDARD DEVIATION IS OF FIVE SAMPLES.						
3. P3/F2 IS DOE PHASE 3 FIRING 2						

Appendix B - Supplemental Data on Fired Density

SAMPLE ID. NO.		STATISTICAL SUMMARY				
		BULK	APP.	H2O	APP.	TOTAL
		DENSITY	POROSITY	ABS.	S.G.	POROSITY
		(g/cc)	(%)	(%)	(g/cc)	(%)
25247-43-5-AO	MEAN	2.792	26.928	9.645	3.821	29.850
	STD. DEV.	0.009	0.352	0.142	0.018	0.237
25247-43-5-SA	MEAN	2.774	27.210	9.809	3.811	30.293
	STD. DEV.	0.020	0.527	0.256	0.014	0.514
25247-52-6-AO	MEAN	2.821	26.283	9.321	3.827	29.110
	STD. DEV.	0.042	0.901	0.456	0.014	1.066
25247-52-6-SA	MEAN	2.840	25.871	9.111	3.832	28.635
	STD. DEV.	0.027	0.692	0.321	0.021	0.689
25247-53-7-AO	MEAN	2.673	30.375	11.373	3.839	32.850
	STD. DEV.	0.041	1.190	0.624	0.008	1.040
25247-53-7-SA	MEAN	2.628	31.718	12.073	3.849	33.966
	STD. DEV.	0.030	0.890	0.475	0.014	0.759
25247-51-8-AO	MEAN	2.626	31.748	12.096	3.847	34.021
	STD. DEV.	0.035	0.943	0.511	0.010	0.867
25247-51-8-SA	MEAN	2.589	32.771	12.660	3.851	34.949
	STD. DEV.	0.026	0.595	0.351	0.009	0.649
25247-47-12-AO	MEAN	2.780	27.038	9.726	3.811	30.139
	STD. DEV.	0.022	0.736	0.339	0.014	0.558
25247-47-12-SA	MEAN	2.711	29.122	10.749	3.825	31.886
	STD. DEV.	0.040	1.093	0.560	0.008	1.010
NOTES:						
1. SAMPLE # IS 25247 BOOK NO. - PAGE NO. - SAMPLE NO. - AO AIR DRIED, SA STEAM AGED.						
2. THE MEAN AND STANDARD DEVIATION IS OF FIVE SAMPLES.						
3. P3/F3 IS DOE PHASE 3 FIRING 3						

Appendix B - Supplemental Data on Fired Density

SAMPLE ID. NO.		STATISTICAL SUMMARY				
		BULK	APP.	H2O	APP.	TOTAL
		DENSITY	POROSITY	ABS.	S.G.	POROSITY
		(g/cc)	(%)	(%)	(g/cc)	(%)
25247-82-17-AO	MEAN	2.614	31.106	11.901	3.794	34.322
	STD. DEV.	0.020	0.270	0.158	0.028	0.494
25247-82-17-SA	MEAN	2.524	33.713	13.358	3.808	36.578
	STD. DEV.	0.014	0.864	0.410	0.033	0.363
25247-83-18-AO	MEAN	2.716	27.665	10.188	3.755	31.765
	STD. DEV.	0.039	0.918	0.343	0.077	0.973
25247-83-18-SA	MEAN	2.651	29.445	11.109	3.758	33.388
	STD. DEV.	0.023	0.606	0.320	0.013	0.571
25247-84-19-AO	MEAN	2.693	28.681	10.650	3.776	32.340
	STD. DEV.	0.006	0.783	0.288	0.043	0.143
25247-84-19-SA	MEAN	2.615	30.651	11.722	3.771	34.291
	STD. DEV.	0.021	0.729	0.369	0.016	0.519
25247-85-20-AO	MEAN	2.422	36.991	15.276	3.844	39.148
	STD. DEV.	0.019	0.646	0.385	0.010	0.479
25247-85-20-SA	MEAN	2.401	37.579	15.652	3.847	39.668
	STD. DEV.	0.016	0.600	0.349	0.016	0.400
25247-86-21-AO	MEAN	2.448	36.148	14.768	3.834	38.495
	STD. DEV.	0.012	0.199	0.147	0.012	0.305
25247-86-21-SA	MEAN	2.420	36.664	15.152	3.821	39.195
	STD. DEV.	0.017	0.465	0.302	0.001	0.436
25247-87-22-AO	MEAN	2.497	35.161	14.084	3.851	37.268
	STD. DEV.	0.013	0.540	0.279	0.020	0.325
25247-87-22-SA	MEAN	2.495	34.966	14.016	3.836	37.314
	STD. DEV.	0.011	0.385	0.212	0.009	0.268
NOTES:						
1. SAMPLE # IS 25247 BOOK NO. - PAGE NO. - SAMPLE NO. - AO AIR DRIED, SA STEAM AGED.						
2. THE MEAN AND STANDARD DEVIATION IS OF FIVE SAMPLES.						
3. P3/F4 IS DOE PHASE 3 FIRING 4						

Appendix C - Supplemental Data on Shrinkage

This table (comprised of 4 pages) contains a summary of the shrinkage data for individual specimens. The shrinkage data for the replicate samples (normally 5) were averaged and the standard deviation calculated. The average shrinkage values were reported in Table 5 in the body of this report.

Sample Identification Code in this table: XXXXX-YY-Aa-ZZ

where XXXXX = ATC Research Notebook Number

YY = ATC Research Notebook Page Number

A = Replicate number for the specimens

a = Experiment Number in the series

ZZ = Special treatment (AO - air oven / SA - steam aged)

Appendix C - Supplemental Data on Shrinkage

								SHRINK.	SHRINK.
SAMPLE	GREEN	GREEN	FIRE	FIRE	GREEN	FIRE	SHRINK.	LINEAR	LINEAR
ID.	DIAM.	THK.	DIAM.	THICK.	VOLUME	VOLUME	VOLUME	THICK.	DIAM.
NO.	mm	mm	mm	mm	mm ^3	mm ^3	%	%	%
25247-40-A1-AO	15.99	13.79	12.53	10.82	2,769.18	1,334.19	51.82	21.54	21.64
25247-40-B1-AO	15.95	13.60	12.44	10.61	2,717.38	1,289.57	52.54	21.99	22.01
25247-40-C1-AO	16.47	13.54	12.83	10.64	2,884.66	1,375.58	52.31	21.42	22.10
25247-40-D1-AO	14.08	13.96	10.99	10.93	2,173.60	1,036.82	52.30	21.70	21.95
25247-40-E1-AO	16.81	13.90	13.12	10.97	3,084.89	1,483.08	51.92	21.08	21.95
Average							52.18	21.54	21.93
Std. Dev							0.30	0.34	0.17
25247-40-A1-SA	15.76	13.80	12.29	10.84	2,692.04	1,285.95	52.23	21.45	22.02
25247-40-B1-SA	15.17	13.78	11.81	10.80	2,490.63	1,183.08	52.50	21.63	22.15
25247-40-C1-SA	15.82	14.34	12.31	11.23	2,818.72	1,336.55	52.58	21.69	22.19
25247-40-D1-SA	15.75	12.98	12.20	10.24	2,528.86	1,197.04	52.66	21.11	22.54
25247-40-E1-SA	14.97	14.83	11.67	11.51	2,610.20	1,231.14	52.83	22.39	22.04
Average							52.56	21.65	22.19
Std. Dev							0.22	0.47	0.21
25247-42-A2-AO	15.87	13.05	12.21	10.25	2,581.39	1,200.18	53.51	21.46	23.06
25247-42-B2-AO	16.49	11.04	12.71	8.54	2,357.76	1,083.52	54.04	22.64	22.92
25247-42-C2-AO	16.69	11.49	13.13	9.02	2,513.75	1,221.31	51.41	21.50	21.33
25247-42-D2-AO	15.50	11.68	12.11	9.03	2,203.92	1,040.08	52.81	22.69	21.87
25247-42-E2-AO	15.10	11.90	11.81	9.21	2,131.03	1,008.90	52.66	22.61	21.79
Average							52.89	22.18	22.19
Std. Dev							0.99	0.64	0.76
25247-42-A2-SA	16.74	12.14	12.74	9.46	2,671.89	1,205.92	54.87	22.08	23.89
25247-42-B2-SA	16.70	12.40	12.79	9.69	2,716.09	1,244.96	54.16	21.85	23.41
25247-42-C2-SA	16.66	11.46	12.79	8.98	2,498.18	1,153.74	53.82	21.64	23.23
25247-42-D2-SA	15.89	12.20	12.31	9.30	2,419.34	1,106.85	54.25	23.77	22.53
25247-42-E2-SA	16.32	10.94	12.70	8.38	2,288.48	1,061.55	53.61	23.40	22.18
Average							54.14	22.55	23.05
Std. Dev							0.48	0.97	0.69
25247-46-A3-AO	16.38	9.88	13.07	7.69	2,081.97	1,031.73	50.44	22.17	20.21
25247-46-B3-AO	16.75	10.39	13.19	8.24	2,289.47	1,125.92	50.82	20.69	21.25
25247-46-C3-AO	16.39	10.46	13.05	8.20	2,206.88	1,096.79	50.30	21.61	20.38
25247-46-D3-AO	16.78	8.97	13.36	7.14	1,983.65	1,000.92	49.54	20.40	20.38
25247-46-E3-AO	16.61	11.71	13.24	9.38	2,537.38	1,291.42	49.10	19.90	20.29
Average							50.04	20.95	20.50
Std. Dev							0.70	0.92	0.43
25247-46-A3-SA	16.80	13.41	13.29	10.58	2,972.60	1,467.66	50.63	21.10	20.89
25247-46-B3-SA	16.83	15.23	13.25	12.03	3,388.11	1,658.77	51.04	21.01	21.27
25247-46-C3-SA	16.84	13.93	13.34	10.96	3,102.59	1,531.83	50.63	21.32	20.78
25247-46-D3-SA	16.83	15.84	13.30	12.58	3,523.81	1,747.73	50.40	20.58	20.97
25247-46-E3-SA	16.82	15.71	13.37	12.36	3,490.74	1,735.28	50.29	21.32	20.51
Average							50.60	21.07	20.89
Std. Dev							0.29	0.30	0.28
25247-45-A4-AO	17.56	14.22	13.74	11.16	3,443.80	1,654.73	51.95	21.52	21.75
25247-45-B4-AO	17.28	15.68	13.57	12.34	3,677.25	1,784.70	51.47	21.30	21.47
25247-45-C4-AO	16.40	13.18	12.83	10.37	2,784.15	1,340.67	51.85	21.32	21.77
25247-45-D4-AO	16.90	15.44	13.33	12.17	3,463.46	1,698.40	50.96	21.18	21.12
25247-45-E4-AO	16.88	14.07	13.20	11.05	3,148.68	1,512.17	51.97	21.46	21.80
Average							51.64	21.36	21.58
Std. Dev							0.43	0.14	0.29
25247-45-A4-SA	14.97	14.24	11.48	10.86	2,506.36	1,124.10	55.15	23.74	23.31
25247-45-B4-SA	16.82	15.14	12.97	11.72	3,364.09	1,548.45	53.97	22.59	22.89
25247-45-C4-SA	17.23	15.01	13.20	11.66	3,499.78	1,595.64	54.41	22.32	23.39
25247-45-D4-SA	16.85	14.48	12.95	11.17	3,228.92	1,471.24	54.44	22.86	23.15
25247-45-E4-SA	15.80	14.35	12.18	11.13	2,813.56	1,296.82	53.91	22.44	22.91
Average							54.37	22.79	23.13
Std. Dev							0.50	0.57	0.23
25247-44-A13-AO	16.03	15.47	12.53	12.14	3,122.10	1,496.96	52.05	21.53	21.83
25247-44-B13-AO	16.74	14.90	13.04	11.46	3,279.34	1,530.49	53.33	23.09	22.10
25247-44-C13-AO	15.40	16.79	12.02	13.07	3,127.39	1,483.11	52.58	22.16	21.95
25247-44-D13-AO	16.76	14.47	13.16	11.43	3,192.32	1,554.70	51.30	21.01	21.48
25247-44-E13-AO	16.34	14.26	12.80	11.07	2,990.29	1,424.48	52.36	22.37	21.66
Average							52.32	22.03	21.81
Std. Dev							0.74	0.80	0.24
25247-44-A13-SA	16.23	15.64	12.48	12.11	3,235.66	1,481.37	54.22	22.57	23.11
25247-44-B13-SA	16.44	14.10	12.72	10.87	2,993.04	1,381.32	53.85	22.91	22.63
25247-44-C13-SA	15.46	15.89	11.88	12.30	2,982.86	1,363.41	54.29	22.59	23.16
25247-44-D13-SA	16.56	13.80	12.77	10.70	2,972.28	1,370.42	53.89	22.46	22.89
25247-44-E13-SA	15.57	16.15	12.02	12.54	3,074.96	1,422.97	53.72	22.35	22.80
Average							54.00	22.58	22.92
Std. Dev							0.25	0.21	0.22

Appendix C - Supplemental Data on Shrinkage

SAMPLE	GREEN	GREEN	FIRE	FIRE	GREEN	FIRE	SHRINK.	SHRINK.	SHRINK.
ID.	DIAM.	THK.	DIAM.	THICK.	VOLUME	VOLUME	LINEAR	LINEAR	LINEAR
NO.	mm	mm	mm	mm	mm ³	mm ³	VOLUME	THICK.	DIAM.
25247-43-A9-AO	16.21	13.00	12.82	10.33	2682.87	1,333.42	50.30	20.54	20.91
25247-43-B9-AO	16.59	15.21	13.12	12.20	3287.85	1,649.37	49.83	19.79	20.92
25247-43-C9-AO	17.09	12.41			2846.72				
25247-43-D9-AO	15.46	13.21	12.22	10.53	2479.77	1,234.98	50.20	20.29	20.96
25247-43-E9-AO	15.32	13.87	12.17	11.04	2556.72	1,284.22	49.77	20.40	20.56
Average							50.03	20.25	20.84
Std. Dev							0.26	0.33	0.18
25247-43-A9-SA	17.55	14.43	13.92	11.44	3490.68	1,740.98	50.12	20.72	20.88
25247-43-B9-SA	16.60	12.07	13.07	9.65	2612.24	1,294.70	50.44	20.05	21.27
25247-43-C9-SA	16.71	14.44	13.10	11.40	3166.72	1,536.52	51.48	21.05	21.60
25247-43-D9-SA	16.41	13.59	12.95	10.75	2874.26	1,415.92	50.74	20.90	21.08
25247-43-E9-SA	16.39	14.89	12.98	11.77	3141.54	1,557.45	50.42	20.95	20.81
Average							50.64	20.73	21.09
Std. Dev							0.52	0.40	0.37
25247-52-A10-AO	16.80	14.84			3289.59				
25247-52-B10-AO	15.66	14.00	12.37	11.04	2696.50	1,328.78	50.80	21.14	21.01
25247-52-C10-AO	16.72	13.84	12.76	10.96	3038.77	1,401.53	53.88	20.81	23.68
25247-52-D10-AO	15.37	13.83	12.06	10.91	2566.02	1,246.26	51.43	21.11	21.54
25247-52-E10-AO	15.90	12.95	12.52	10.36	2571.30	1,275.43	50.40	20.00	21.26
Average							51.83	20.77	21.87
Std. Dev							1.56	0.53	1.23
25247-52-A10-SA	17.19	14.70	13.46	11.60	3411.60	1,650.58	51.62	21.09	21.70
25247-52-B10-SA	16.68	14.50	13.06	11.46	3168.47	1,535.18	51.55	20.97	21.70
25247-52-C10-SA	16.49	12.44	12.94	9.86	2656.75	1,296.69	51.19	20.74	21.53
25247-52-D10-SA	17.07	14.35	13.41	11.37	3284.04	1,605.86	51.10	20.77	21.44
25247-52-E10-SA	16.35	14.14	12.96	11.26	2968.76	1,485.38	49.97	20.37	20.73
Average							51.09	20.79	21.42
Std. Dev							0.66	0.27	0.40
25247-53-A11-AO	16.74	15.03	13.19	11.94	3307.95	1,631.49	50.68	20.56	21.21
25247-53-B11-AO	17.43	13.82	13.79	10.99	3297.56	1,641.40	50.22	20.48	20.88
25247-53-C11-AO	17.44	14.08	13.80	11.14	3363.45	1,666.22	50.46	20.88	20.87
25247-53-D11-AO	15.95	14.14	12.61	11.17	2825.27	1,395.00	50.62	21.00	20.94
25247-53-E11-AO	17.34	14.15	13.84	11.18	3341.52	1,681.91	49.67	20.99	20.18
Average							50.33	20.78	20.82
Std. Dev							0.41	0.25	0.38
25247-53-A11-SA	16.11	13.87			2827.20				
25247-53-B11-SA	16.21	13.01	12.80	10.37	2684.93	1,334.41	50.30	20.29	21.04
25247-53-C11-SA	15.40	14.08	12.18	11.21	2622.61	1,306.14	50.20	20.38	20.91
25247-53-D11-SA	16.62	13.89	13.13	11.00	3013.38	1,489.40	50.57	20.81	21.00
25247-53-E11-SA	16.85	14.27	13.22	11.38	3182.10	1,562.05	50.91	20.25	21.54
Average							50.50	20.43	21.12
Std. Dev							0.32	0.25	0.29
25247-51-A14-AO	15.74	14.73	12.48	11.67	2866.17	1,427.54	50.19	20.77	20.71
25247-51-B14-AO	16.76	15.36			3388.67				
25247-51-C14-AO	15.54	13.70	12.24	10.90	2598.44	1,282.56	50.64	20.44	21.24
25247-51-D14-AO	16.67	14.18	13.21	11.31	3094.83	1,550.09	49.91	20.24	20.78
25247-51-E14-AO	16.58	15.35	13.21	12.29	3314.11	1,684.41	49.17	19.93	20.33
Average							49.98	20.35	20.76
Std. Dev							0.62	0.35	0.37
25247-51-A14-SA	15.71	14.27	12.40	11.33	2766.09	1,368.24	50.54	20.60	21.07
25247-51-B14-SA	16.53	16.89	13.00	13.45	3624.64	1,785.25	50.75	20.37	21.36
25247-51-C14-SA	15.60	15.20	12.37	12.06	2905.24	1,449.36	50.11	20.66	20.71
25247-51-D14-SA	15.48	15.13	12.32	12.03	2851.22	1,434.09	49.70	20.48	20.46
25247-51-E14-SA	16.18	15.05	12.77	11.97	3094.45	1,533.08	50.46	20.47	21.08
Average							50.31	20.52	20.93
Std. Dev							0.41	0.12	0.35
25247-47-A15-AO	16.20	14.39	12.89	11.48	2966.06	1,498.09	49.49	20.22	20.43
25247-47-B15-AO	16.18	13.35	12.91	10.74	2744.91	1,405.87	48.78	19.55	20.21
25247-47-C15-AO	16.93	13.73	13.51	10.94	3090.82	1,568.26	49.26	20.32	20.20
25247-47-D15-AO	17.02	13.76	14.08	11.05	3130.60	1,720.51	45.04	19.69	17.27
25247-47-E15-AO	17.06	13.45	13.53	10.71	3074.47	1,539.84	49.92	20.37	20.69
Average							48.50	20.03	19.76
Std. Dev							1.98	0.38	1.41
25247-47-A15-SA	16.63	15.86	13.29	12.76	3444.90	1,770.07	48.62	19.55	20.08
25247-47-B15-SA	17.16	15.06	13.53	11.01	3482.96	1,582.97	54.55	26.89	21.15
25247-47-C15-SA	17.09	15.55	13.63	12.36	3567.01	1,803.43	49.44	20.51	20.25
25247-47-D15-SA	16.70	15.27	13.30	12.21	3344.73	1,696.32	49.28	20.04	20.36
25247-47-E15-SA	16.67	15.62	13.28	12.52	3409.12	1,734.16	49.13	19.85	20.34
Average							50.21	21.37	20.44
Std. Dev							2.45	3.11	0.42
25247-54-A16-AO	17.12	14.59	13.22	11.80	3358.55	1,619.70	51.77	19.12	22.78
25247-54-B16-AO	16.12	13.93	12.68	10.99	2842.96	1,387.80	51.18	21.11	21.34
25247-54-C16-AO	16.83	14.73	13.32	11.62	3276.88	1,619.21	50.59	21.11	20.86
25247-54-D16-AO	17.94	14.05			3551.49				
25247-54-E16-AO	17.44	14.93	13.61	11.82	3566.50	1,719.58	51.79	20.83	21.96
Average							51.33	20.54	21.73
Std. Dev							0.57	0.98	0.83
25247-54-A16-SA	15.86	14.05	12.48	11.09	2775.70	1,356.60	51.13	21.07	21.31
25247-54-B16-SA	16.75	15.16	13.19	11.98	3340.55	1,636.95	51.00	20.98	21.25
25247-54-C16-SA	16.63	14.86	13.11	11.81	3227.70	1,594.21	50.61	20.52	21.17
25247-54-D16-SA	16.74	15.66	13.21	12.43	3446.61	1,703.59	50.57	20.63	21.09
25247-54-E16-SA	16.80	15.18	13.00	12.00	3364.96	1,592.79	52.67	20.95	22.62
Average							51.19	20.83	21.49
Std. Dev							0.86	0.24	0.64

EMPTY CELL'S ARE FROM SAMPLES LOST OR DAMAGED IN CONVERTER.

Appendix C - Supplemental Data on Shrinkage

SAMPLE ID.	GREEN	GREEN	FIRE	FIRE	GREEN	FIRE	SHRINK.	SHRINK.	SHRINK.
NO.	DIAM.	THK.	DIAM.	THICK.	VOLUME	VOLUME	VOLUME	THICK.	DIAM.
	mm	mm	mm	mm	mm ^3	mm ^3	%	%	%
25247-43-A5-AO	16.10	16.32	12.80	13.05	3322.47	1679.27	49.46	20.04	20.50
25247-43-B5-AO	16.24	15.23	12.90	12.18	3154.72	1591.90	49.54	20.03	20.57
25247-43-C5-AO	15.98	15.40	12.65	12.29	3088.62	1544.62	49.99	20.19	20.84
25247-43-D5-AO	16.25	15.54	12.89	12.39	3222.90	1616.84	49.83	20.27	20.68
25247-43-E5-AO	15.83	15.53	12.64	12.37	3056.49	1552.22	49.22	20.35	20.15
Average							49.61	20.18	20.55
Std. Dev							00.31	00.14	00.26
25247-43-A5-SA	16.21	14.05	12.87	11.14	2899.56	1449.21	50.02	20.71	20.60
25247-43-B5-SA	16.26	16.00	12.85	12.75	3322.39	1653.51	50.23	20.31	20.97
25247-43-C5-SA	16.10	14.94	12.73	11.90	3041.53	1514.58	50.20	20.35	20.93
25247-43-D5-SA	16.14	15.63	12.83	12.45	3197.83	1609.58	49.67	20.35	20.51
25247-43-E5-SA	15.19	14.26	12.06	11.34	2584.19	1295.38	49.87	20.48	20.61
Average							50.00	20.44	20.72
Std. Dev							00.24	00.16	00.21
25247-52-A6-AO	16.44	15.03	13.00	11.93	3190.45	1583.49	50.37	20.63	20.92
25247-52-B6-AO	16.61	14.29	13.16	11.40	3096.43	1550.62	49.92	20.22	20.77
25247-52-C6-AO	16.54	15.08	13.10	12.26	3240.13	1652.43	49.00	18.70	20.80
25247-52-D6-AO	16.88	15.55	13.41	12.52	3479.88	1768.28	49.19	19.49	20.56
25247-52-E6-AO	16.47	14.48	13.09	11.56	3084.93	1555.70	49.57	20.17	20.52
Average							49.61	19.84	20.71
Std. Dev							00.55	00.76	00.17
25247-52-A6-SA	15.95	14.45	12.79	11.48	2887.21	1474.93	48.91	20.55	19.81
25247-52-B6-SA	16.21	15.08	12.83	12.00	3112.12	1551.40	50.15	20.42	20.85
25247-52-C6-SA	16.30	14.30	12.83	11.37	2984.01	1469.95	50.74	20.49	21.29
25247-52-D6-SA	16.02	14.93	12.72	11.90	3009.36	1512.21	49.75	20.29	20.60
25247-52-E6-SA	14.77	16.38	11.74	12.93	2806.50	1399.67	50.13	21.06	20.51
Average							49.94	20.56	20.61
Std. Dev							00.67	00.29	00.54
25247-53-A7-AO	16.32	15.52	12.93	12.32	3246.55	1617.70	50.17	20.62	20.77
25247-53-B7-AO	16.16	15.49	12.79	12.38	3177.05	1590.56	49.94	20.08	20.85
25247-53-C7-AO	16.01	15.53	12.68	12.33	3126.39	1557.01	50.20	20.61	20.80
25247-53-D7-AO	17.43	15.48	13.78	12.21	3693.65	1820.97	50.70	21.12	20.94
25247-53-E7-AO	16.45	15.72	13.04	12.51	3340.98	1670.71	49.99	20.42	20.73
Average							50.20	20.57	20.82
Std. Dev							00.30	00.38	00.08
25247-53-A7-SA	17.69	14.50	14.00	11.56	3563.80	1779.52	50.07	20.28	20.86
25247-53-B7-SA	16.07	16.44	12.74	13.05	3334.44	1663.56	50.11	20.62	20.72
25247-53-C7-SA	14.72	15.33	11.68	12.20	2608.84	1307.18	49.89	20.42	20.65
25247-53-D7-SA	15.95	15.12	12.70	12.05	3021.08	1526.45	49.47	20.30	20.38
25247-53-E7-SA	15.77	15.58	12.60	12.43	3043.13	1549.89	49.07	20.22	20.10
Average							49.72	20.37	20.54
Std. Dev							00.44	00.16	00.30
25247-51-A8-AO	15.84	16.11	12.63	13.05	3174.65	1634.96	48.50	18.99	20.27
25247-51-B8-AO	16.66	14.68	13.27	11.84	3200.11	1637.51	48.83	19.35	20.35
25247-51-C8-AO	16.65	13.64	13.30	11.05	2969.84	1535.17	48.31	18.99	20.12
25247-51-D8-AO	16.18	15.62	12.92	12.64	3211.65	1657.15	48.40	19.08	20.15
25247-51-E8-AO	16.69	15.53	13.29	12.60	3397.61	1747.87	48.56	18.87	20.37
Average							48.52	19.05	20.25
Std. Dev							00.20	00.18	00.11
25247-51-A8-SA	16.79	15.82	13.40	12.76	3502.66	1799.49	48.62	19.34	20.19
25247-51-B8-SA	17.48	14.72	13.90	11.92	3532.48	1808.82	48.79	19.02	20.48
25247-51-C8-SA	15.63	14.77	12.46	11.94	2833.92	1455.89	48.63	19.16	20.28
25247-51-D8-SA	15.62	15.67	12.47	12.70	3002.76	1551.05	48.35	18.95	20.17
25247-51-E8-SA	15.63	15.31	12.52	12.41	2937.53	1527.81	47.99	18.94	19.90
Average							48.48	19.08	20.20
Std. Dev							00.32	00.17	00.21
25247-47-A12-AO	16.42	15.51	13.04	12.35	3284.34	1649.35	49.78	20.37	20.58
25247-47-B12-AO	16.83	14.81	13.35	11.79	3294.68	1650.31	49.91	20.39	20.68
25247-47-C12-AO	16.87	13.86	13.37	11.03	3098.01	1548.56	50.01	20.42	20.75
25247-47-D12-AO	16.89	14.54	13.37	11.60	3257.72	1628.58	50.01	20.22	20.84
25247-47-E12-AO	16.53	14.57	13.13	11.61	3126.76	1572.00	49.72	20.32	20.57
Average							49.89	20.34	20.68
Std. Dev							00.13	00.08	00.11
25247-47-A12-SA	16.39	14.33	13.00	11.42	3023.39	1515.80	49.86	20.31	20.68
25247-47-B12-SA	16.49	14.94	13.10	11.94	3190.67	1609.30	49.56	20.08	20.56
25247-47-C12-S2	16.41	15.72	13.05	12.54	3324.75	1677.29	49.55	20.23	20.48
25247-47-D12-SA	16.00	16.17	12.67	12.88	3251.17	1623.90	50.05	20.35	20.81
25247-47-E12-SA	15.70	15.13	12.48	12.07	2929.06	1476.47	49.59	20.22	20.51
Average							49.72	20.24	20.61
Std. Dev							00.22	00.10	00.14

Appendix C - Supplemental Data on Shrinkage

SAMPLE	GREEN	GREEN	FIRE	FIRE	GREEN	FIRE	SHRINK.	SHRINK.	SHRINK.
ID.	DIAM.	THK.	DIAM.	THICK.	VOLUME	VOLUME	VOLUME	LINEAR	LINEAR
NO.	mm	mm	mm	mm	mm ³	mm ³	%	%	%
25247-82-A17-AO	16.55	13.63	13.15	10.91	2932.12	1481.72	49.47	19.95	20.54
25247-82-B17-AO	16.53	13.26	13.29	10.59	2845.63	1469.05	48.38	20.14	19.60
25247-82-C17-AO	15.92	13.64	12.62	10.91	2715.13	1364.69	49.74	20.01	20.73
25247-82-D17-AO	16.51	13.78	13.02	11.34	2950.07	1509.82	48.82	17.71	21.14
25247-82-E17-AO	16.40	14.26	13.12	11.04	3012.29	1492.54	50.45	22.58	20.00
Average							49.37	20.08	20.40
Std. Dev							0.81	1.73	0.61
25247-82-A17-SA	17.36	13.28	13.78	10.62	3143.31	1583.84	49.61	20.03	20.62
25247-82-B17-SA	16.64	14.36	13.26	11.52	3122.85	1590.85	49.06	19.78	20.31
25247-82-C17-SA	16.11	14.46	12.89	11.58	2947.47	1511.14	48.73	19.92	19.99
25247-82-D17-SA	16.48	13.20	13.04	10.61	2815.64	1416.97	49.68	19.62	20.87
25247-82-E17-SA	16.47	13.57	13.14	10.87	2891.06	1474.04	49.01	19.90	20.22
Average							49.22	19.85	20.40
Std. Dev							0.41	0.16	0.35
25247-83-A18-AO	16.67	14.92	13.27	11.92	3256.34	1648.57	49.37	20.11	20.40
25247-83-B18-AO	16.78	14.94	13.30	11.91	3303.88	1654.64	49.92	20.28	20.74
25247-83-C18-AO	16.85	14.74	13.39	11.75	3286.90	1654.58	49.66	20.28	20.53
25247-83-D18-AO	16.87	14.80	13.39	11.95	3308.12	1682.75	49.13	19.26	20.63
25247-83-E18-AO	16.22	14.59	12.86	11.68	3014.72	1517.10	49.68	19.95	20.72
Average							49.55	19.98	20.60
Std. Dev							0.30	0.43	0.14
25247-83-A18-SA	15.51	14.13	12.34	11.23	2669.66	1343.07	49.69	20.52	20.44
25247-83-B18-SA	16.52	14.35	13.09	11.44	3075.82	1539.55	49.95	20.28	20.76
25247-83-C18-SA	16.63	13.28	13.14	10.54	2884.51	1429.29	50.45	20.63	20.99
25247-83-D18-SA	16.06	13.50	12.73	10.81	2734.73	1375.85	49.69	19.93	20.73
25247-83-E18-SA	16.37	14.16	12.96	11.64	2980.23	1535.51	48.48	17.80	20.83
Average							49.65	19.83	20.75
Std. Dev							0.73	1.17	0.20
25247-84-A19-AO	16.50	14.49	13.09	11.53	3098.32	1551.67	49.92	20.43	20.67
25247-84-B19-AO	15.92	14.98	12.53	11.89	2981.86	1466.13	50.83	20.63	21.29
25247-84-C19-AO	16.35	14.48	12.88	11.46	3040.14	1493.16	50.89	20.88	21.22
25247-84-D19-AO	16.12	14.16	12.68	11.23	2889.90	1418.10	50.93	20.69	21.34
25247-84-E19-AO	15.90	15.13	12.47	12.03	3004.16	1469.22	51.09	20.49	21.57
Average							50.73	20.62	21.22
Std. Dev							0.46	0.17	0.34
25247-84-A19-SA	14.55	14.57	11.49	11.55	2422.56	1197.60	50.56	20.73	21.03
25247-84-B19-SA	15.90	14.31	12.53	11.31	2841.34	1394.61	50.92	20.96	21.19
25247-84-C19-SA	15.89	15.24	12.51	12.09	3022.19	1486.04	50.83	20.67	21.27
25247-84-D19-SA	15.92	15.06	12.50	11.93	2997.79	1464.03	51.16	20.78	21.48
25247-84-E19-SA	15.93	15.07	12.47	11.94	3003.55	1458.23	51.45	20.77	21.72
Average							50.98	20.78	21.34
Std. Dev							0.34	0.11	0.27
25247-79-A20-AO	16.08	15.34	12.65	12.28	3115.21	1543.37	50.46	19.95	21.33
25247-79-B20-AO	16.04	14.99	12.83	11.96	3029.00	1546.23	48.95	20.21	20.01
25247-79-C20-AO	15.58	14.88	12.29	12.07	2836.79	1431.86	49.53	18.88	21.12
25247-79-D20-AO	15.54	14.80	12.28	11.88	2807.07	1407.03	49.88	19.73	20.98
25247-79-E20-AO									
Average							49.70	19.69	20.66
Std. Dev							0.63	0.57	0.58
25247-79-A20-SA	16.09	15.06	12.43	11.91	3062.15	1445.25	52.80	20.92	22.75
25247-79-B20-SA	16.06	14.62	12.54	11.67	2961.61	1441.30	51.33	20.18	21.92
25247-79-C20-SA	16.06	15.31	12.49	12.10	3101.39	1482.52	52.20	20.97	22.23
25247-79-D20-SA	16.06	15.36	12.54	12.25	3111.51	1512.94	51.38	20.25	21.92
25247-79-E20-SA	16.19	14.98	12.59	11.94	3083.66	1486.43	51.80	20.29	22.24
Average							51.90	20.52	22.21
Std. Dev							0.61	0.39	0.34
25247-80-A21-AO	16.15	15.06	12.81	12.06	3085.03	1554.30	49.62	19.92	20.68
25247-80-B21-AO	16.28	14.96	12.85	11.91	3114.08	1544.57	50.40	20.39	21.07
25247-80-C21-AO	15.09	14.88	12.00	11.92	2661.16	1348.12	49.34	19.89	20.48
25247-80-D21-AO	16.15	15.08	12.77	12.13	3089.13	1553.57	49.71	19.56	20.93
25247-80-E21-AO	16.16	14.24	12.85	11.51	2920.67	1492.70	48.89	19.17	20.48
Average							49.59	19.79	20.73
Std. Dev							0.55	0.45	0.27
25247-80-A21-SA	16.06	14.15	12.42	11.15	2866.40	1350.85	52.87	21.20	22.67
25247-80-B21-SA	16.07	14.92	12.44	11.74	3026.15	1426.92	52.85	21.31	22.59
25247-80-C21-SA	16.10	15.32	12.49	12.14	3118.89	1487.42	52.31	20.76	22.42
25247-80-D21-SA	16.07	14.38	12.52	11.33	2916.62	1394.85	52.18	21.21	22.09
25247-80-E21-SA	16.10	14.60	12.54	11.50	2972.31	1420.31	52.22	21.23	22.11
Average							52.48	21.14	22.38
Std. Dev							0.35	0.22	0.27
25247-81-A22-AO	17.04	14.86	13.81	11.92	3388.81	1785.47	47.31	19.78	18.96
25247-81-B22-AO	16.56	15.82	13.14	12.79	3407.35	1734.41	49.10	19.15	20.65
25247-81-C22-AO	17.15	16.18	13.62	12.95	3737.63	1886.75	49.52	19.96	20.58
25247-81-D22-AO	16.94	14.36	13.57	11.48	3236.46	1660.32	48.70	20.06	19.89
25247-81-E22-AO	17.38	14.86	13.73	11.94	3525.40	1767.81	49.66	19.65	21.00
Average							48.90	19.72	20.22
Std. Dev							0.99	0.35	0.81
25247-81-A22-SA	16.99	14.84	13.19	11.70	3364.42	1598.69	52.48	21.16	22.37
25247-81-B22-SA	16.49	15.40	12.82	12.19	3288.91	1573.51	52.16	20.84	22.26
25247-81-C22-SA	16.99	14.85	13.35	11.75	3366.69	1644.71	51.15	20.88	21.42
25247-81-D22-SA	16.44	14.37	12.97	11.32	3050.35	1495.60	50.97	21.22	21.11
25247-81-E22-SA	16.98	14.98	13.58	11.89	3392.16	1722.15	49.23	20.83	20.02
Average							51.20	20.95	21.44
Std. Dev							1.27	0.24	0.95

Appendix D-1 - Supplemental Data on Abrasion Resistance

This table (comprised of 5 pages) contains a summary of the abrasion resistance data for specimens from individual experiments or tests. These data represent weight loss from the samples during shaking on the Ro-Tap machine. Note that data on weight loss were acquired after 1, 2, and 3 minutes. Only weight loss data after 3 minutes were reported in the body of this report in Table 6.

Appendix D1 - Supplemental Data on Abrasion Resistance

ABRASION TEST						
TEST #	TIME MIN.	SAMPLE INITIAL WT. gms.	ABOVE 8 MESH gms.	BELOW 8 MESH gms.	ABRASION LOSS %	AMT. CP-5 gms.
TEST 15 AO		166.62				
		79.95				830
TEST 15 AO	1		47.6	32.8	40.8	
TEST 15 AO	2		22	58.1	72.5	
TEST 15 AO	3		6.9	73.1	91.4	
		159.46				
TEST 15 SA		80.38				830
TEST 15 SA	1		61	20.1	24.8	
TEST 15 SA	2		41	39.6	49.1	
TEST 15 SA	3		22.1	58.2	72.5	
		168.29				
TEST 16 AO		79.97				848
TEST 16 AO	1		43	37.1	46.3	
TEST 16 AO	2		13.5	66.5	83.1	
TEST 16 AO	3		2.5	77.2	96.9	
		157.29				
TEST 16 SA		80.32				848
TEST 16 SA	1		57.5	23.2	28.7	
TEST 16 SA	2		38.7	42	52.0	
TEST 16 SA	3		24.2	56.5	70.0	
		131.88				
		80.01				1696
TEST 13 AO						
TEST 13 AO	1		65	14.9	18.6	
TEST 13 AO	2		51.8	28.2	35.3	
TEST 13 AO	3		38.8	41.4	51.6	
		131.24				
		80.38				1696
TEST 13 SA						
TEST 13 SA	1		73.3	6.8	8.5	
TEST 13 SA	2		65.7	15	18.6	
TEST 13 SA	3		57.9	22.9	28.3	
		160.04				
TEST 14 AO		80.49				866
TEST 14 AO	1		51.5	28.8	35.9	
TEST 14 AO	2		28.1	52.1	65.0	
TEST 14 AO	3		12.6	67.8	84.3	
		178.29				
TEST 14 SA		79.8				866
TEST 14 SA	1		54.1	25.5	32.0	
TEST 14 SA	2		33	46.9	58.7	
TEST 14 SA	3		17.9	62	77.6	

NOTES:

1. THE TIME ON THE RO-TAP WAS CONTROLLED BY STOP WATCH AND THE SWITCH TURNED ON AND OFF MANUALLY.
2. AO= AIR OVEN DRY OVERNIGHT
3. SA= STEAM AGE 4 HOURS. AIR OVEN DRY OVERNIGHT.
4. NOTEBOOK # 25247-X

Appendix D1 - Supplemental Data on Abrasion Resistance

ABRASION TEST

TEST #	TIME MIN.	SAMPLE INITIAL WT. gms.	ABOVE 8 MESH gms.	BELOW 8 MESH gms.	ABRASION LOSS %	AMT. CP-5 gms.
		159				
TEST 12 AO		80.78				0
TEST 12 AO	1		51	29.5	36.6	
TEST 12 AO	2		23.2	57.1	71.1	
TEST 12 AO	3		7.1	73	91.1	
TEST 12 SA		80.5				0
TEST 12 SA	1		55	26	32.1	
TEST 12 SA	2		34.2	45.9	57.3	
TEST 12 SA	3		18.9	61.1	76.4	
		140.02				
TEST 11 AO		80.09				844
TEST 11 AO	1		41.8	39.9	48.8	
TEST 11 AO	2		13	68.8	84.1	
TEST 11 AO	3		2.1	79.5	97.4	
		156.78				
TEST 11 SA		79.9				844
TEST 11 SA	1		58.9	20.6	25.9	
TEST 11 SA	2		40.8	39	48.9	
TEST 11 SA	3		25.8	54	67.7	
		165.44				
TEST 10 AO		80.5				853
TEST 10 AO	1		40.8	39.6	49.3	
TEST 10 AO	2		12.2	67.8	84.8	
TEST 10 AO	3		2	78	97.5	
		165.59				
TEST 10 SA		79.9				853
TEST 10 SA	1		54.1	25.5	32.0	
TEST 10 SA	2		26	53.5	67.3	
TEST 10 SA	3		10.9	68.8	86.3	
		132.16				
TEST 9 AO		80.46				848
TEST 9 AO	1		43.4	36.8	45.9	
TEST 9 AO	2		16.8	63.5	79.1	
TEST 9 AO	3		5.2	75	93.5	
		138.77				
TEST 9 SA		79.02				848
TEST 9 SA	1		57.1	21.9	27.7	
TEST 9 SA	2		37.9	41.1	52.0	
TEST 9 SA	3		22.5	56.6	71.6	

NOTES:

1. THE TIME ON THE RO-TAP WAS CONTROLLED BY STOP WATCH AND THE SWITCH TURNED ON AND OFF MANUALLY.
2. AO= AIR OVEN DRY OVERNIGHT
3. SA= STEAM AGE 4 HOURS. AIR OVEN DRY OVERNIGHT.
4. NOTEBOOK # 25247-X

Appendix D1 - Supplemental Data on Abrasion Resistance

ABRASION TEST

TEST #	TIME MIN.	SAMPLE INITIAL WT. gms.	ABOVE 8 MESH gms.	BELOW 8 MESH gms.	ABRASION LOSS %	AMT. CP- 5 gms.
TEST 8 AO		153.23 79.71				0
TEST 8 AO	1		54.5	25.1	31.5	
TEST 8 AO	2		34.9	44.9	56.3	
TEST 8 AO	3		19.4	60.1	75.6	
TEST 8 SA		154.95 79.89				0
TEST 8 SA	1		55.2	24.8	31.0	
TEST 8 SA	2		35.4	44.6	55.8	
TEST 8 SA	3		19.7	60.2	75.3	
TEST 7 AO		165.44 80.3				0
TEST 7 AO	1		55	25.2	31.4	
TEST 7 AO	2		34	46.3	57.7	
TEST 7 AO	3		18.3	61.8	77.2	
TEST 7 SA		177.6 79.84				0
TEST 7 SA	1		46	33.5	42.1	
TEST 7 SA	2		22.6	57	71.6	
TEST 7 SA	3		9.5	70.1	88.1	
TEST 6 AO		118.33 79.71				0
TEST 6 AO	1		52.1	27.6	34.6	
TEST 6 AO	2		33.4	46	57.9	
TEST 6 AO	3		20.1	59.2	74.7	
TEST 6 SA		118.33 79.71				0
TEST 6 SA	1		47.6	32.3	40.4	
TEST 6 SA	2		23.9	55.8	70.0	
TEST 6 SA	3		10.9	68.4	86.3	
TEST 5 AO		160.48 80.69				0
TEST 5 AO	1		51	29.6	36.7	
TEST 5 AO	2		25.9	54.6	67.8	
TEST 5 AO	3		9.9	70.4	87.7	
TEST 5 SA		159.48 79.43				0
TEST 5 SA	1		57.1	21.9	27.7	
TEST 5 SA	2		36.2	42.7	54.1	
TEST 5 SA	3		19.9	59.1	74.8	

NOTES:

1. THE TIME ON THE RO-TAP WAS CONTROLLED BY STOP WATCH AND THE SWITCH TURNED ON AND OFF MANUALLY.
2. AO= AIR OVEN DRY OVERNIGHT
3. SA= STEAM AGE 4 HOURS, AIR OVEN DRY OVERNIGHT.
4. NOTEBOOK # 25247-X

Appendix D1 - Supplemental Data on Abrasion Resistance

ABRASION TEST

TEST #	TIME MIN.	INITIAL WT./SAMPLE WT. gms.	ABOVE 8 MESH gms.	BELOW 8 MESH gms.	ABRASION LOSS %	AMT. CP-5 gms.
TEST 4 AO		124.13				1651
TEST 4 AO	1	80.67	66.6	13.6	17.0	
TEST 4 AO	2		52	28.3	35.2	
TEST 4 AO	3		40	40.5	50.3	
TEST 4 SA		115.58				1651
TEST 4 SA	1	80.63	75.1	5.2	6.5	
TEST 4 SA	2		69.1	11.3	14.1	
TEST 4 SA	3		63.8	17	21.0	
TEST 3 AO		139.78				1724
TEST 3 AO	1	80.18	64.8	15.2	19.0	
TEST 3 AO	2		47.6	32.7	40.7	
TEST 3 AO	3		33.5	46.9	58.3	
TEST 3 SA		144.27				1724
TEST 3 SA	1	79.48	68.9	10.5	13.2	
TEST 3 SA	2		57.6	21.9	27.5	
TEST 3 SA	3		47.1	32.2	40.6	
TEST 2 AO		128.95				1742
TEST 2 AO	1	80.13	59.2	27	31.3	
TEST 2 AO	2		40.4	39.5	49.4	
TEST 2 AO	3		25.2	54.8	68.5	
TEST 2 SA		133.82				1742
TEST 2 SA	1	79.8	63.5	16	20.1	
TEST 2 SA	2		47.5	32.1	40.3	
TEST 2 SA	3		34.9	44.9	56.3	
TEST 1 AO		125.1				1669
TEST 1 AO	1	80.47	57.8	22.8	28.3	
TEST 1 AO	2		34.4	46	57.2	
TEST 1 AO	3		19.9	60.5	75.2	
TEST 1 SA		129.94				1669
TEST 1 SA	1	79.24	65.5	13.7	17.3	
TEST 1 SA	2		49.5	29.8	37.6	
TEST 1 SA	3		34.7	44.8	56.4	
STANDARD		110.59				
	1	79.8	79.8	0.1	0.1	
	2		79.8	0.1	0.1	
	3		79.8	0.1	0.1	

NOTES:

1. THE TIME ON THE RO-TAP WAS CONTROLLED BY STOP WATCH AND THE SWITCH TURNED ON AND OFF MANUALLY.
2. AO= AIR OVEN DRY OVERNIGHT
3. SA= STEAM AGE 4 HOURS. AIR OVEN DRY OVERNIGHT.
4. NOTEBOOK # 25247-X
5. ALL SA AND AO SAMPLES WERE RO-TAPPED TOGETHER FOR EACH TEST NUMBER.
6. STANDARD (TABULAR BALLS)- TOTAL WEIGHT LOSS 0.136 GMS.

ABRASION TEST		TIME MIN.	SAMPLE INITIAL WT. gms.	ABOVE MESH	8 gms.	BELOW 8 MESH gms.	8	ABRASION LOSS %
TEST #								
TEST 17 AO			81					
TEST 17 AO	1			56		25		30.9
TEST 17 AO	2			37.3		43.2		53.7
TEST 17 AO	3			23.2		57		71.1
TEST 17 SA			81					
TEST 17 SA	1			53		28		34.6
TEST 17 SA	2			27.8		53.2		65.7
TEST 17 SA	3			11.8		69		85.4
TEST 18 AO			79.9					
TEST 18 AO	1			63.8		15.8		19.8
TEST 18 AO	2			51.8		27.9		35.0
TEST 18 AO	3			41.5		38		47.8
TEST 18 SA			80					
TEST 18 SA	1			64		16		20.0
TEST 18 SA	2			47.5		32.2		40.4
TEST 18 SA	3			33.8		46		57.6
TEST 19 AO			79.8					
TEST 19 AO	1			67.3		12		15.1
TEST 19 AO	2			57.5		22.2		27.9
TEST 19 AO	3			48.5		31.1		39.1
TEST 19 SA			79.9					
TEST 19 SA	1			69		11		13.8
TEST 19 SA	2			57		21		26.9
TEST 19 SA	3			48		29.8		38.3
TEST 20 AO			80					
TEST 20 AO	1			68		11.7		14.7
TEST 20 AO	2			57		23.5		29.2
TEST 20 AO	3			46.5		33.8		42.1
TEST 20 SA			79.5					
TEST 20 SA	1			58.5		21.2		26.6
TEST 20 SA	2			38.8		41		51.4
TEST 20 SA	3			22.5		57.5		71.9
TEST 21 AO			80					
TEST 21 AO	1			61		19.7		24.4
TEST 21 AO	2			43		37.9		46.8
TEST 21 AO	3			27.7		53		65.7
TEST 21 SA			80					
TEST 21 SA	1			69		11		13.8
TEST 21 SA	2			57.1		23.8		29.4
TEST 21 SA	3			46		34		42.5
TEST 22 AO			80.6					
TEST 22 AO	1			69.5		11.1		13.8
TEST 22 AO	2			58.5		22		27.3
TEST 22 AO	3			48.9		31.9		39.5
TEST 22 SA			80.7					
TEST 22 SA	1			75.5		5.2		6.4
TEST 22 SA	2			69.6		10.9		13.5
TEST 22 SA	3			64.2		16.3		20.2

NOTES:

1. THE TIME ON THE RO-TAP WAS CONTROLLED BY STOP WATCH AND THE SWITCH TURNED ON AND OFF MANUALLY.
2. AO= AIR OVEN DRY OVERNIGHT
3. SA= STEAM AGE 4 HOURS. AIR OVEN DRY OVERNIGHT.
4. NOTEBOOK # 25247-X

Appendix D-2 - Supplemental Data on Intermediate Strength (stress)

This table (comprised of 3 pages) contains a summary of the intermediate strength data for individual specimens as determined by a stress measurement. The strength data for the replicate samples (normally 5) were averaged and the standard deviation calculated. The average strength values were reported in Table 6 in the body of this report. The weight before and after specimen firing at 500°C was determined for some of the specimens and reported here. The weight loss reflects binder burnout and possible water loss from the CP-5 added to the formulation. It was not deemed necessary to measure and record these weights for all specimens processed. If the work 'broken' is substituted for data in these tables, this means that the specimen was cracked or broken at some point before the stress determinations and could not be processed. Because of the labor intensive nature of this test (machining of the specimens), not all experiments were tested via this method. Only those formulations exhibiting promising characteristics, as indicated by other testing, were selected for this stress measurement.

Sample Identification Code in this table: **XXXXXX-YY-Aa-ZZ**

where **XXXXXX** = ATC Research Notebook Number
YY = ATC Research Notebook Page Number
A = Replicate number for the specimens
a = Experiment Number in the series
ZZ = Special treatment (AO - air oven / SA - steam aged)

Appendix D2 - Supplemental Data on Intermediate Strength (stress)

SAMPLE ID	DIAM. INCHES	LENGTH INCHES	C-PEAK LB	STRESS PSI	STRESS MPA	WEIGHT BEFORE	WEIGHT AFTER
5247-44-A13-A	0.6217	0.5016	2.64	5.4	0.0372	3.5780	N.D.
5247-44-B13-A	0.6177	0.5646	5.24	9.6	0.0660	3.9612	N.D.
5247-44-C13-A	0.6134	0.5965	3.68	6.4	0.0442	4.0151	N.D.
5247-44-D13-A	0.6189	0.5457	4.46	8.4	0.0580	3.9087	N.D.
5247-44-E13-A	0.6138	0.5441	4.58	8.7	0.0602	3.8159	N.D.
Average.			4.12	7.70	0.05		
Std Dev.			1.00	1.74	0.01		
5247-44-A13-S	0.6185	0.5791	7.66	13.6	0.0939	3.9890	N.D.
5247-44-B13-S	0.6209	0.5492	7.88	14.7	0.1015	3.7996	N.D.
5247-44-C13-S	0.6173	0.5256	7.74	15.2	0.1047	3.6395	N.D.
5247-44-D13-S	0.6209	0.6000	6.18	10.6	0.0728	4.1544	N.D.
5247-44-E13-S	0.6201	0.5870	9.26	16.2	0.1117	4.0899	N.D.
Average.			7.74	14.05	0.10		
Std Dev.			1.09	2.16	0.01		
5247-82-A17-A	0.0198	0.0204	BROKEN	BROKEN	BROKEN	BROKEN	N.D.
5247-82-B17-A	0.6240	0.5543	2.32	4.3	0.0294	3.6434	N.D.
5247-82-C17-A	0.6130	0.5512	2.30	4.3	0.0299	3.5650	N.D.
5247-82-D17-A	0.6264	0.5665	2.18	3.9	0.0270	4.0877	N.D.
5247-82-E17-A	0.6256	0.5232	2.42	4.7	0.0325	3.6102	N.D.
Average.			2.31	4.31	0.03		
Std Dev.			0.10	0.33	0.00		
5247-82-A17-S	0.6339	0.5449	1.20	2.2	0.0153	3.6103	N.D.
5247-82-B17-S	0.6138	0.5406	1.08	2.1	0.0143	4.4898	N.D.
5247-82-C17-S	0.6039	0.6043	0.84	1.5	0.0101	3.6912	N.D.
5247-82-D17-S	0.6118	0.5484	0.60	1.1	0.0079	3.5559	N.D.
5247-82-E17-S	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	N.D.
Average.			0.93	1.72	0.01		
Std Dev.			0.27	0.51	0.00		
5247-83-A18-A	0.6161	0.5417	4.16	7.9	0.0547	3.9381	N.D.
5247-83-B18-A	0.6472	0.5508	4.22	7.5	0.0520	4.3403	N.D.
5247-83-C18-A	0.6201	0.5646	3.70	6.7	0.0464	4.0761	N.D.
5247-83-D18-A	0.6016	0.5634	2.48	4.7	0.0321	3.7836	N.D.
5247-83-E18-A	0.6059	0.5449	1.98	3.8	0.0263	3.5584	N.D.
Average.			3.31	6.14	0.04		
Std Dev.			1.02	1.81	0.01		
5247-83-A18-S	0.6142	0.5634	BROKEN	BROKEN	BROKEN	BROKEN	N.D.
5247-83-B18-S	0.6055	0.6118	3.68	6.3	0.0436	4.1812	N.D.
5247-83-C18-S	0.6028	0.5650	3.18	5.9	0.0410	3.6992	N.D.
5247-83-D18-S	0.6094	0.5327	4.54	8.9	0.0614	3.6818	N.D.
5247-83-E18-S	0.5866	0.5642	6.68	12.8	0.0886	3.6341	N.D.
Average.			4.52	8.51	0.06		
Std Dev.			1.55	3.18	0.02		
5247-84-A19-A	0.6039	0.5768	8.46	15.5	0.1066	3.9488	N.D.
5247-84-B19-A	0.6106	0.5909	6.04	10.7	0.0735	4.0845	N.D.
5247-84-C19-A	0.6059	0.5449	6.12	11.8	0.0814	3.7422	N.D.
5247-84-D19-A	0.6047	0.5531	8.40	16.0	0.1103	3.8426	N.D.
5247-84-E19-A	0.6039	0.5087	8.34	17.3	0.1192	3.4550	N.D.
Average.			7.47	14.24	0.10		
Std Dev.			1.27	2.85	0.02		
5247-84-A19-S	0.6067	0.5685	3.28	6.1	0.0418	3.6365	N.D.
5247-84-B19-S	0.6303	0.5441	3.80	7.1	0.0486	3.7664	N.D.
5247-84-C19-S	0.6697	0.5906	2.02	3.3	0.0224	4.5256	N.D.
5247-84-D19-S	0.6846	0.5484	1.92	3.3	0.0225	4.3008	N.D.
5247-84-E19-S	0.6752	0.5449	2.48	4.3	0.0296	4.3277	N.D.
Average.			2.70	4.78	0.03		
Std Dev.			0.82	1.71	0.01		
N.D. = NOT DETERMINED							

Appendix D2 - Supplemental Data on Intermediate Strength (stress)

Sample Id.	LENGTH	DIAM.	C-PEAK	STRESS	STRESS	WEIGHT	WEIGHT
	INCHES	INCHES	LB	PSI	MPA	BEFORE	AFTER
25247-79-A20-AO	0.6622	0.6094	0.68	1.07	0.0074	4.7053	4.0459
25247-79-B20-AO	0.6787	0.6004	3.28	5.12	0.0353	4.8836	4.2205
25247-79-C20-AO	0.6772	0.6205	1.02	1.55	0.0107	4.9228	4.2683
25247-79-D20-AO	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN
25247-79-E20-AO	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN
Average			1.66	2.58	0.0178		
Std. Dev			1.41	2.22	0.0153		
25247-79-A20-SA	0.6008	0.5929	6.82	12.19	0.0841	3.7992	3.2310
25247-79-B20-SA	0.6134	0.6114	4.76	8.08	0.0557	3.9357	3.3605
25247-79-C20-SA	0.5772	0.5752	5.26	10.09	0.0696	3.4206	2.9056
25247-79-D20-SA	0.6000	0.5717	4.74	8.80	0.0607	3.6289	3.1004
25247-79-E20-SA	0.6012	0.6000	4.00	7.06	0.0487	3.6762	3.1561
Average			5.12	9.24	0.0637		
Std. Dev			1.05	1.98	0.0137		
25247-80-A21-AO	0.5988	0.5815	5.12	9.36	0.0646	3.4943	3.0762
25247-80-B21-AO	0.6091	0.5992	6.00	10.47	0.0722	3.7070	3.2483
25247-80-C21-AO	0.6063	0.6189	7.50	12.72	0.0878	3.8143	3.3555
25247-80-D21-AO	0.6079	0.5776	4.06	7.36	0.0508	3.5416	3.1143
25247-80-E21-AO	0.5992	0.5972	6.74	11.99	0.0827	3.5927	3.1668
Average			5.88	10.38	0.0716		
Std. Dev			1.35	2.14	0.0147		
25247-80-A21-SA	0.6075	0.6248	4.70	7.88	0.0544	4.2155	3.6242
25247-80-B21-SA	0.6138	0.6248	4.52	7.50	0.0517	4.2206	3.6459
25247-80-C21-SA	0.6098	0.5913	0.84	1.48	0.0102	3.9102	3.3928
25247-80-D21-SA	0.6114	0.5988	2.86	4.97	0.0343	4.0446	3.4736
25247-80-E21-SA	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN	BROKEN
Average			3.23	5.46	0.0377		
Std. Dev			1.80	2.95	0.0203		
25247-81-A22-AO	0.6000	0.6035	3.92	6.89	0.0475	4.0753	3.4933
25247-81-B22-AO	0.6039	0.6012	1.00	1.75	0.0121	3.9652	3.4223
25247-81-C22-AO	0.5984	0.4988	1.48	3.16	0.0218	BROKEN	BROKEN
25247-81-D22-AO	0.6055	0.6154	5.52	9.43	0.0650	4.1706	3.5834
25247-81-E22-AO	0.6201	0.5957	1.56	2.69	0.0185	4.1741	3.6037
Average			2.70	4.78	0.0330		
Std. Dev			1.94	3.25	0.0224		
25247-81-A22-SA	0.5965	0.5933	10.24	18.42	0.1270	3.8009	3.2871
25247-81-B22-SA	0.5988	0.5839	9.84	17.92	0.1236	3.7270	3.2279
25247-81-C22-SA	0.5941	0.5957	6.84	12.30	0.0849	3.7826	3.2664
25247-81-D22-SA	0.6020	0.6067	9.30	16.21	0.1118	3.8562	3.3275
25247-81-E22-SA	0.6028	0.5972	9.50	16.80	0.1159	3.7550	3.2453
Average			9.14	16.33	0.1126		
Std. Dev			1.34	2.42	0.0167		

SAMPLE ID	DIAM. INCHES	LENGTH INCHES	C-PEAK LB	STRESS PSI	STRESS MPA	WEIGHT BEFORE	WEIGHT AFTER
25247-46-A3-AO	0.6405	0.6031	4.08	6.72	0.0464	4.7573	4.1602
25247-46-B3-AO	0.6504	0.5811	4.02	6.77	0.0467	4.4712	3.9225
25247-46-C3-AO	0.6224	0.6130	3.52	5.87	0.0405	4.3427	3.8106
25247-46-D3-AO	0.6350	0.5846	4.56	7.82	0.0539	4.4593	3.9196
25247-46-E3-AO	0.6449	0.6114	2.65	4.28	0.0295	4.6988	4.1232
Average			3.77	6.29	0.04		
Std. Dev.			0.72	1.32	0.01		
25247-46-A3-SA	0.6220	0.6063	4.44	7.49	0.0517	4.4170	3.8764
25247-46-B3-SA	0.6236	0.5874	3.60	6.26	0.0431	4.3051	3.7851
25247-46-C3-SA	0.6256	0.6051	4.10	6.90	0.0476	4.3124	3.7974
25247-46-D3-SA	0.6201	0.6043	5.36	9.11	0.0628	4.4006	3.8676
25247-46-E3-SA	0.6417	0.5642	4.24	7.46	0.0514	4.2398	3.7336
Average			4.35	7.44	0.05		
Std. Dev.			0.65	1.06	0.01		
25247-45-A4-AO	0.6035	0.5750	1.50	2.75	0.0190	4.1039	3.3022
25247-45-B4-AO	0.6500	0.5915	6.02	9.97	0.0687	3.9628	3.9806
25247-45-C4-AO	0.6100	0.5965	5.20	9.10	0.0627	4.0132	3.5415
25247-45-D4-AO	0.6015	0.4950	2.68	5.73	0.0395	4.1075	2.9057
25247-45-E4-AO	0.6485	0.5895	1.02	1.70	0.0117	4.6142	3.9220
Average			3.28	5.85	0.04		
Std. Dev.			2.23	3.69	0.03		
25247-45-A4-SA	0.6585	0.6025	12.48	20.03	0.1381	3.5334	4.0963
25247-45-B4-SA	0.6510	0.5695	9.60	16.48	0.1137	3.3832	3.6845
25247-45-C4-SA	0.6605	0.5865	11.32	18.60	0.1283	3.5401	3.9853
25247-45-D4-SA	0.6575	0.5870	12.22	20.16	0.1390	4.2467	3.9574
25247-45-E4-SA	0.6240	0.5740	11.66	20.72	0.1429	3.4855	3.5197
Average			11.46	19.20	0.13		
Std. Dev.			1.13	1.71	0.01		
25247-43-A5-AO	0.6340	0.5905	3.20	5.44	0.0375	4.1724	4.2746
25247-43-B5-AO	0.6500	0.5620	2.56	4.46	0.0308	4.6253	4.2433
25247-43-C5-AO	0.6560	0.5635	3.78	6.51	0.0449	4.1320	4.4045
25247-43-D5-AO	0.6550	0.5565	2.48	4.33	0.0299	4.3593	4.3495
25247-43-E5-AO	0.6565	0.5755	2.96	4.99	0.0344	4.4630	4.4238
Average			3.00	5.15	0.04		
Std. Dev.			0.53	0.88	0.01		
25247-43-A5-SA	0.6122	0.6083		0.00	0.0000	4.2150	3.4262
25247-43-B5-SA	0.6200	0.5575	3.00	5.53	0.0381	4.1620	3.8005
25247-43-C5-SA	0.6210	0.5460	2.52	4.73	0.0326	3.9731	3.7356
25247-43-D5-SA	0.6085	0.5985	3.28	5.73	0.0395	4.2830	3.7377
25247-43-E5-SA	0.6305	0.5975	3.16	5.34	0.0368	4.6684	4.2675
Average			2.99	4.27	0.03		
Std. Dev.			0.33	2.41	0.02		
25247-52-A6-AO	0.6115	0.5365	3.18	6.17	0.0426	4.0859	3.6852
25247-52-B6-AO	0.6130	0.5910	1.20	2.11	0.0145	4.9089	3.9763
25247-52-C6-AO	0.6185	0.5475	3.58	6.73	0.0464	5.5199	3.7397
25247-52-D6-AO	0.6265	0.5395	3.56	6.71	0.0462	4.4475	3.8615
25247-52-E6-AO	0.6115	0.5740	2.82	5.11	0.0353	4.3870	3.8830
Average			2.87	5.37	0.04		
Std. Dev.			0.98	1.93	0.01		
25247-52-A6-SA	0.6614	0.5811		0.00	0.0000	4.8670	
25247-52-B6-SA	0.5970	0.5285	1.32	2.66	0.0184	4.9769	3.4968
25247-52-C6-SA	0.6200	0.5560	1.64	3.03	0.0209	4.0276	3.8053
25247-52-D6-SA	0.6299	0.5665		0.00	0.0000	4.3776	
25247-52-E6-SA	0.6175	0.5305	1.08	2.10	0.0145	4.1117	3.6533
Average			1.35	1.56	0.01		
Std. Dev.			0.28	1.46	0.01		
25247-53-A11-AO	0.5972	0.5862	0.38	0.69	0.0048	3.6247	N.D.
25247-53-B11-AO	0.5988	0.5787	1.38	2.54	0.0175	3.8499	N.D.
25247-53-C11-AO	0.6008	0.6028	0.90	1.58	0.0109	3.7107	N.D.
25247-53-D11-AO	0.6106	0.5988	0.20	0.35	0.0024	4.1719	N.D.
25247-53-E11-AO	0.6118	0.5819	BROKEN	BROKEN	BROKEN	4.0084	N.D.
Average			0.72	1.29	0.01		
Std. Dev.			0.53	0.98	0.01		
25247-53-A11-SA	0.6161	0.6059	2.00	3.41	0.0235	4.2693	N.D.
25247-53-B11-SA	0.6024	0.5657	1.38	2.58	0.0178	3.8171	N.D.
25247-53-C11-SA	0.6031	0.5579	1.04	1.97	0.0136	3.8660	N.D.
25247-53-D11-SA	0.6059	0.5807	1.32	2.39	0.0165	3.9336	N.D.
25247-53-E11-SA	0.6035	0.5547	2.80	5.32	0.0367	3.7973	N.D.
Average			1.71	3.13	0.02		
Std. Dev.			0.70	1.33	0.01		

Appendix E - Supplemental Data on Fired Strength (stress)

This table (comprised of 5 pages) contains a summary of the fired strength data for specimens from individual experiments or tests. These data represent crush strength measurements for 20 samples from each experiment. These tables also summarize the mean or average, standard deviation, coefficient of variation, minimum, maximum, and range for the data. Only the average values for the fired strength data were reported in the body of this report in Table 6.

Appendix E - Supplemental Data on Fired Strength (stress)

DATE TESTED	95/07/06	95/07/06	95/07/06	95/07/06	95/07/06	95/07/06	95/07/06	95/07/06	95/07/19	95/07/19
SAMPLE IDENTIFICATION	25247-40	25247-40	25247-42	25247-42	25247-46	25247-46	25247-45	25247-45	25247-43	25247-43
EXPERIMENT NUMBER (RUN NO.)	1-AO	1-SA	2-AO	2-SA	3-AO	3-SA	4-AO	4-SA	5-AO	5-SA
SAMPLE SHAPE	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN
BATCH NO.										
SAMPLE SIZE (MESH)	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10
SAMPLE SIZE (mm)	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
SAMPLE SIZE (INCHES)	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
TEST INSTRUMENT	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON
CROSS-HEAD SPEED SETTING	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
CROSS-HEAD SPEED (mm/MIN)	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
PAD (MANILA FOLDER) Y OR N	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TEST SAMPLE ORIENTATION	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL
DATA:	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS	FRAC STRESS
UNITS:	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA
DATA TYPE:	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED
	27.3	21.1	20.4	56.1	16.5	34.5	33.1	35.9	44.0	67.2
	29.9	30.8	30.1	34.1	28.0	30.1	28.3	50.5	62.3	47.3
	49.1	34.8	38.7	34.3	24.3	32.4	29.0	31.1	47.0	78.1
	36.8	28.3	28.7	30.6	21.1	23.4	39.4	35.9	63.3	81.6
	40.6	17.8	39.9	20.9	29.9	39.9	29.4	21.6	63.7	84.8
	31.7	27.8	32.2	28.0	31.3	19.5	30.8	25.3	41.7	56.5
	38.5	26.9	38.7	35.0	28.0	19.0	19.2	22.2	44.5	113.8
	18.5	42.4	28.3	34.8	24.6	23.4	33.4	29.7	43.8	55.8
	34.5	25.7	18.8	35.0	29.4	25.5	21.1	26.6	73.5	71.8
	32.7	36.6	26.0	33.6	30.1	27.6	36.6	39.6	51.0	45.7
	36.6	30.1	15.5	46.6	63.7	29.7	26.4	44.7	46.6	65.6
	28.3	18.5	24.6	24.6	17.8	27.1	34.5	38.9	64.9	97.6
	57.0	21.8	33.6	19.5	22.2	22.5	23.2	47.7	45.7	54.2
	45.7	27.1	26.6	31.3	21.1	26.9	50.3	15.8	52.4	54.0
	45.0	18.1	36.6	18.8	34.8	42.2	35.9	44.7	92.7	44.7
	18.1	16.7	25.0	17.4	35.5	27.1	18.8	26.2	39.4	88.5
	24.3	13.4	33.1	41.5	58.2	38.2	30.4	29.9	44.5	47.5
	28.0	10.0	57.0	28.3	47.3	38.7	24.3	25.3	53.5	79.0
	29.4	57.9	33.1	20.6	35.5	35.5	27.8	35.0	68.1	70.0
	22.9	21.3	45.0	30.4	27.3	31.7	32.0	20.6	85.0	77.9
MEAN	33.8	26.4	31.6	31.1	31.3	29.7	30.2	32.4	56.4	69.2
ST. DEVIATION	10.1	10.9	9.6	9.7	12.4	6.8	7.4	9.8	14.9	19.3
COEFF. OF VARIATION =STDE	0.301	0.415	0.303	0.313	0.395	0.228	0.246	0.302	0.265	0.280
MIN	18.1	10.0	15.5	17.4	16.5	19.0	18.8	15.8	39.4	44.7
MAX	57.0	57.9	57.0	56.1	63.7	42.2	50.3	50.5	92.7	113.8
RANGE	38.9	48.0	41.5	38.7	47.3	23.2	31.5	34.8	53.3	69.1

Appendix E - Supplemental Data on Fired Strength (stress)

DATE TESTED	95/07/19	95/07/19	95/07/19	95/07/19	95/07/19	95/07/19	95/07/18	95/07/18	95/07/18	95/07/18
SAMPLE IDENTIFICATION	25247-52	25247-52	25247-53	25247-53	25247-51	25247-51	25247-43	25247-43	25247-52	25247-52
EXPERIMENT NUMBER (RUN NO.)	6AO	6SA	7AO	7SA	8AO	8SA	9AO	9SA	10AO	10SA
SAMPLE SHAPE	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN
BATCH NO.										
SAMPLE SIZE (MESH)	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10
SAMPLE SIZE (mm)	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
SAMPLE SIZE (INCHES)	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
TEST INSTRUMENT	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON
CROSS-HEAD SPEED SETTING	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
CROSS-HEAD SPEED (mm/MIN)	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
PAD (MANILA FOLDER) Y OR N	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TEST SAMPLE ORIENTATION	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL
DATA:	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS
UNITS:	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA
DATA TYPE:	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED
	36.4	54.7	75.1	64.7	69.8	87.6	39.4	47.7	38.9	37.8
	80.9	109.6	33.4	55.4	42.4	57.9	67.0	48.0	42.2	58.4
	51.0	49.1	48.2	60.5	61.9	38.5	37.5	50.1	50.1	42.6
	68.1	44.7	40.6	49.1	57.9	75.1	51.9	43.3	65.3	38.9
	75.5	66.7	89.2	48.9	46.8	49.6	62.8	48.4	66.0	48.0
	70.2	66.0	54.7	53.8	54.7	56.1	45.4	45.4	58.6	45.2
	42.2	62.8	72.8	40.8	53.1	64.7	43.6	30.6	90.6	48.0
	60.3	45.9	77.6	48.0	63.7	41.7	64.9	80.6	34.3	57.9
	41.9	55.8	21.1	33.1	47.5	100.8	32.2	46.6	64.0	46.1
	48.0	58.9	63.5	56.3	46.1	43.3	58.4	31.1	67.4	56.8
	63.0	68.4	80.4	50.8	51.0	25.5	56.3	54.2	59.6	32.2
	102.0	76.5	43.3	35.9	41.2	40.8	48.2	62.6	29.9	28.0
	49.8	74.2	49.6	38.9	85.7	49.1	64.2	40.8	96.9	35.5
	55.4	59.1	47.5	74.2	54.5	69.8	38.7	69.5	33.1	61.6
	57.0	58.2	49.6	28.0	38.9	50.3	37.1	36.6	49.8	57.2
	65.6	51.9	83.0	70.9	77.6	61.2	57.7	59.6	50.3	38.0
	50.5	48.4	59.1	76.5	64.9	36.6	46.1	37.1	56.8	44.7
	99.6	112.9	57.0	29.7	56.1	19.2	81.3	43.8	36.8	50.8
	49.8	52.4	45.9	90.8	64.7	41.2	50.3	30.1	104.3	40.8
	42.2	98.5	49.6	38.0	53.5	39.9	46.6	45.9	41.0	35.9
MEAN	60.5	65.7	57.1	52.2	56.6	52.4	51.5	47.6	56.8	45.2
ST. DEVIATION	18.2	20.0	17.9	16.9	12.1	20.0	12.5	12.9	21.1	9.6
COEFF. OF VARIATION =STDEV/	0.301	0.304	0.313	0.324	0.214	0.381	0.242	0.272	0.371	0.212
MIN	36.4	44.7	21.1	28.0	38.9	19.2	32.2	30.1	29.9	28.0
MAX	102.0	112.9	89.2	90.8	85.7	100.8	81.3	80.6	104.3	61.6
RANGE	65.6	68.1	68.1	62.8	46.8	81.6	49.1	50.5	74.4	33.6

Appendix E - Supplemental Data on Fired Strength (stress)

DATE TESTED	95/07/18	95/07/18	95/07/19	95/07/19	95/07/06	95/07/06	95/07/18	95/07/18	95/07/18	95/07/18
SAMPLE IDENTIFICATION	25247-53	25247-53	25247-47	25247-47	25247-44	25247-44	25247-51	25247-51	25247-47	25247-47
EXPERIMENT NUMBER (RUN NO.)	11AO	11SA	12AO	12SA	13-AO	13-SA	14AO	14SA	15AO	16SA
SAMPLE SHAPE	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN
BATCH NO.										
SAMPLE SIZE (MESH)	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10
SAMPLE SIZE (mm)	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
SAMPLE SIZE (INCHES)	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
TEST INSTRUMENT	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON
CROSS-HEAD SPEED SETTING	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
CROSS-HEAD SPEED (mm/MIN)	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
PAD (MANILA FOLDER) Y OR N	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TEST SAMPLE ORIENTATION	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL
DATA:	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS
UNITS:	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA
DATA TYPE:	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED
	43.1	49.1	52.4	70.7	36.2	36.8	98.0	36.4	82.3	51.0
	33.4	74.4	51.2	63.3	60.9	42.4	57.7	52.4	79.0	57.5
	69.8	36.4	45.4	79.0	21.8	37.3	50.8	73.9	49.1	40.6
	63.0	41.2	45.0	58.2	45.0	28.3	52.1	39.4	60.9	67.4
	28.5	42.4	46.1	46.1	32.2	27.6	64.7	64.0	65.8	71.6
	58.4	48.0	110.1	86.4	49.4	33.4	37.5	39.2	25.3	48.4
	43.1	63.5	59.8	46.3	19.9	31.1	46.8	56.3	46.1	46.1
	60.9	66.0	56.5	53.5	62.6	31.5	62.3	75.3	60.9	41.0
	61.4	40.1	67.4	75.5	38.7	33.8	64.2	38.5	45.9	52.6
	35.5	37.1	59.6	27.6	27.3	39.6	53.3	41.2	70.0	44.5
	40.8	24.6	38.0	82.5	48.9	44.7	59.3	60.0	60.9	50.8
	83.0	39.9	70.2	48.7	26.9	42.2	52.8	41.5	83.0	57.5
	54.7	49.8	95.0	81.1	26.0	41.7	54.2	56.8	26.4	39.6
	41.0	44.5	73.9	26.6	48.2	45.4	30.4	76.2	39.4	64.0
	27.1	30.8	38.5	85.5	23.6	28.5	82.0	52.1	25.3	48.2
	52.8	30.8	60.0	38.0	41.0	30.8	60.9	72.8	81.6	54.0
	40.3	66.7	82.3	47.5	45.9	28.3	34.1	58.6	68.6	47.5
	34.8	70.0	41.9	66.7	41.7	40.1	51.0	46.1	38.2	55.4
	46.6	43.8	90.1	38.7	20.2	22.5	38.9	33.8	42.9	49.4
	39.6	37.1	70.4	46.8	29.7	26.6	43.8	79.9	79.0	82.7
MEAN	47.9	46.8	62.7	58.4	37.3	34.6	54.7	54.7	56.5	53.6
ST. DEVIATION	14.7	14.2	19.9	19.2	13.0	6.8	15.8	15.1	19.8	11.3
COEFF. OF VARIATION =STDEV	0.306	0.303	0.317	0.329	0.348	0.196	0.288	0.275	0.350	0.210
MIN	27.1	24.6	38.0	26.6	19.9	22.5	30.4	33.8	25.3	39.6
MAX	83.0	74.4	110.1	86.4	62.6	45.4	98.0	79.9	83.0	82.7
RANGE	55.8	49.8	72.1	59.8	42.6	22.9	67.7	46.1	57.7	43.1

Appendix E - Supplemental Data on Fired Strength (stress)

DATE TESTED	95/07/18	95/07/18	95/07/24	95/07/24	95/07/24	95/07/24	95/07/24	95/07/24	95/07/24	95/07/24
SAMPLE IDENTIFICATION	25247-54	25247-54	25247-82	25247-82	25247-83	25247-83	25247-84	25247-84	25247-79	25247-79
EXPERIMENT NUMBER (RUN NO.)	16AO	16SA	17AO	17SA	18AO	18SA	19AO	19SA	20AO	20SA
SAMPLE SHAPE	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN	GRAIN
BATCH NO.										
SAMPLE SIZE (MESH)	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10	-8+10
SAMPLE SIZE (mm)	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.85
SAMPLE SIZE (INCHES)	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073
TEST INSTRUMENT	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON	CHATILLON
CROSS-HEAD SPEED SETTING.	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
CROSS-HEAD SPEED (mm/MIN)	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
PAD (MANILA FOLDER) Y OR N	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TEST SAMPLE ORIENTATION	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL
DATA:	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS
UNITS:	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA	MPA
DATA TYPE:	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED	CONVERTED
	55.6	51.2	56.5	47.5	76.9	47.7	50.8	50.3	31.7	20.4
	37.1	35.0	44.3	39.4	38.2	38.7	49.8	67.9	28.7	38.2
	47.5	50.3	65.8	36.6	34.8	52.1	51.7	59.8	27.1	40.3
	52.4	42.4	51.9	36.2	74.9	55.2	85.7	43.1	39.4	31.1
	41.7	69.8	78.1	45.7	29.0	57.0	38.0	43.8	33.8	34.5
	34.1	44.0	43.6	43.8	51.7	42.4	45.2	50.3	39.9	33.4
	40.8	44.3	52.8	56.8	56.3	31.1	84.6	58.4	21.3	39.4
	66.7	38.7	86.4	35.9	44.7	36.2	52.6	51.9	32.4	46.1
	35.5	38.0	35.5	31.7	59.1	58.4	73.5	44.5	32.4	40.3
	41.7	33.8	49.6	38.0	39.2	38.9	43.8	56.5	42.2	25.0
	48.7	38.2	54.5	22.2	54.9	77.2	80.6	68.1	40.8	19.0
	43.1	30.1	47.3	48.9	51.4	41.7	67.9	56.5	39.2	25.7
	59.3	20.9	76.7	29.4	47.5	51.0	61.4	56.1	31.5	14.1
	40.8	43.8	31.5	26.4	46.3	29.7	65.1	58.9	29.0	37.8
	32.9	52.1	32.4	70.4	41.2	73.5	51.4	38.9	23.9	29.4
	40.1	70.0	81.3	35.9	101.7	37.8	70.0	54.5	28.0	28.7
	66.7	28.5	50.1	32.2	47.3	34.8	60.3	36.4	23.2	32.0
	49.1	31.1	126.5	50.3	61.9	39.4	39.6	85.5	22.0	42.4
	28.0	57.2	64.7	32.4	69.5	44.5	50.5	40.1	33.8	25.7
	33.6	53.1	57.7	27.8	36.4	69.5	54.7	49.6	33.8	30.6
MEAN	44.8	43.2	59.4	39.4	53.1	47.8	58.9	53.6	31.7	31.7
ST. DEVIATION	10.9	13.1	22.3	11.5	17.4	13.8	14.4	11.6	6.4	8.4
COEFF. OF VARIATION =STDEV/	0.244	0.304	0.376	0.291	0.327	0.288	0.244	0.217	0.201	0.266
MN	28.0	20.9	31.5	22.2	29.0	29.7	38.0	36.4	21.3	14.1
MAX	66.7	70.0	126.5	70.4	101.7	77.2	85.7	85.5	42.2	46.1
RANGE	38.7	49.1	95.0	48.2	72.8	47.5	47.7	49.1	20.9	32.0

Appendix E - Supplemental Data on Fired Strength (stress)

DATE TESTED	95/07/24	95/07/24	95/07/24	95/07/24
SAMPLE IDENTIFICATION	25247-80	25247-80	25247-81	25247-81
EXPERIMENT NUMBER (RUN NO.):	21AO	21SA	22AO	22SA
SAMPLE SHAPE	GRAIN	GRAIN	GRAIN	GRAIN
BATCH NO.				
SAMPLE SIZE (MESH)	-8+10	-8+10	-8+10	-8+10
SAMPLE SIZE (mm)	1.85	1.85	1.85	1.85
SAMPLE SIZE (INCHES)	0.073	0.073	0.073	0.073
TEST INSTRUMENT	CHATILLON	CHATILLON	CHATILLON	CHATILLON
CROSS-HEAD SPEED SETTING	3.0	3.0	3.0	3.0
CROSS-HEAD SPEED (mm/MIN)	15.2	15.2	15.2	15.2
PAD (MANILA FOLDER) Y OR N	NO	NO	NO	NO
TEST SAMPLE ORIENTATION	DIAMETRAL	DIAMETRAL	DIAMETRAL	DIAMETRAL
DATA:	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS	FRAC. STRESS
UNITS:	MPA	MPA	MPA	MPA
DATA TYPE:	CONVERTED	CONVERTED	CONVERTED	CONVERTED
	28.3	32.4	41.9	33.6
	31.5	19.7	48.4	38.9
	17.8	30.4	28.5	44.0
	62.6	21.1	35.5	38.2
	35.7	30.8	44.5	38.0
	42.4	30.6	49.6	45.0
	27.1	41.5	23.2	27.6
	26.4	41.7	40.1	29.7
	27.3	30.1	45.0	38.2
	33.8	46.6	24.6	54.2
	39.6	26.6	52.1	43.6
	30.8	48.7	31.7	40.1
	40.1	32.4	38.2	38.0
	38.2	32.4	64.9	57.0
	23.4	31.5	41.0	29.2
	30.4	29.9	73.5	34.8
	16.7	28.3	30.8	33.6
	33.1	51.9	45.0	56.3
	36.2	37.1	61.4	50.5
	42.6	27.6	36.4	45.7
MEAN	33.2	33.6	42.8	40.8
ST. DEVIATION	10.1	8.6	13.1	8.7
COEFF. OF VARIATION =STDEV/	0.303	0.255	0.306	0.214
MIN	16.7	19.7	23.2	27.6
MAX	62.6	51.9	73.5	57.0
RANGE	45.9	32.2	50.3	29.4

Appendix F - Report on ANOVA of Experimental Design

This report by the statistical consultant to this project on the ANOVA of the experimental design is included in this appendix.

FROM

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TO

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1996-APRIL-3

RE: ANALYSIS OF PHASE 3, DOE LIGHTWEIGHT AGGREGATE OPTIMIZATION
EXPERIMENT

Background

The captioned experiment consisted of ceramic samples produced at 15 combinations of three components: CP-5, Methocel and Mogul. The specific experimental combinations are listed in Attachment 1 and depicted in Attachment 2. Additionally, CP-5 and another component A-13M (alumina with + 325 mesh screened out) sum to 40% of the mix. That is, when CP-5 is 0%, A-13M is 40%, etc. The balance of the mix is A-13, alumina including <325 mesh.

Each experimental combination was then split into two subsamples that were then either dried in an air oven or were steam aged. The resulting design structure is known as a "split-plot" or "split-unit" experiment. The main consequence of splitting samples for drying is that the experiment should be analyzed separately for the two types of drying because the experimental error introduced in preparing a new mix of components is not the same as that introduced by splitting a mix for drying. Stated more simply, the experimental error introduced by making 15 mixes and splitting them will be different from the error introduced by making 30 samples, two at each combination of components, and assigning complete samples to two drying methods.

The objective of the experiment was to 1) determine what factors have the greatest influence on three responses: fired density, abrasion and fired strength; and 2) to determine the combination of components and drying that optimizes those three responses in the sense that fired density should be close to 2.5 g/cc, abrasion (% weight loss) should be minimized, and fired strength (MPa) should be maximized. Furthermore, we assumed that density and abrasion were of equal importance and were each twice as important as strength. The responses are plotted versus the experimental combinations in Attachments 3-5.

Summary of Main Results

The optimal component combinations and resulting predictions are:

	CP-5 %	Methocel %	Mogul %	Fired Density g/cc	Abrasion % wgt. loss	Fired Strength MPa
Air Oven	0	0.75	5	2.50	76.72	58.66
Steam Age	40	2.25	6.48	2.51	27.09	26.93

Note that air oven and steam age are optimized at opposite extremes of the CP-5/A-13M combinations and that steam aging will require additional Methocel and Mogul. The net result is a 65% decrease in abrasion and corresponding 54% decrease in strength introduced by steam aging.

Description of Data Analyses

The following modeling approach was used:

- 1) Code each component (-1, 0, +1) for low, medium, high respectively.
- 2) Plot the data and fit a full second-order response surface model to each of the six responses (density, abrasion and strength, for both air oven and steam age).
- 3) Eliminate statistically insignificant terms to arrive at the most parsimonious model.
- 4) Re-fit the resulting model in terms of the original uncoded variables.
- 5) Examine residual plots.

The full models, data plots, Normal and Pareto analyses, reduced models and residual plots are provided in the appendices.

The coefficients of the resulting models (in the original scale, weight %) are provided in Attachment 6. Some observations include:

- 1) Mogul does not affect fired strength.
- 2) Drying does not affect fired density (although we have not modeled drying explicitly the coefficients in the two columns are quite similar. Also, a model of the differences in density (between air oven steam age) yields no significant terms.
- 3) Drying and Methocel together affect abrasion and fired strength. (Note the differences in the coefficients.)

Once we fit the models we can use the equations to optimize the responses. Attachments 7 and 8 contain pictures of the fitted response surfaces. To optimize we use a methodology called "Desirability Profiling" in the JMP® statistical package. (The method is based on Derringer, D. and Suich, R. (1980) "Simultaneous optimization of Several Response Variables," *Journal of Quality Technology*, 12:4, 214-219.)

We first create "desirability functions" that express how we would like the response to behave. [Note: this is easier to explain while looking at an interactive computer.] For our responses we have:

Fired Density:

Close to 2.5 g/cc is better. We make a triangular desirability function with desirability 1 at 2.5 falling off to desirability 0 as we move away from 2.5.

Abrasion:

Smaller is better. We make a linear desirability function with desirability 1 at low values and desirability 0 at high values.

Fired Strength:

Larger is better. We make a linear desirability function with desirability 0 at low values and desirability 1 at high values.

(To weight density and abrasion as twice as important as strength we actually include two copies of density and two copies of abrasion in our optimization.)

The desirability functions and the results of "integrating" these functions with the fitted response functions are given in Attachments 9-10.

Experimental Design Layout
(Face-Centered Cubic with 2 Centerpoints) × Drying

Test	Type	CP5 Methocel	Methocel	Mogul [wgt %]		Drying
1	Factorial	40	1.0	7.0	Air Oven	Steam Age
2	Factorial	40	1.0	3.0	Air Oven	Steam Age
3	Factorial	40	2.0	3.0	Air Oven	Steam Age
4	Factorial	40	2.0	7.0	Air Oven	Steam Age
5	Factorial	0	1.0	3.0	Air Oven	Steam Age
6	Factorial	0	1.0	7.0	Air Oven	Steam Age
7	Factorial	0	2.0	7.0	Air Oven	Steam Age
8	Factorial	0	2.0	3.0	Air Oven	Steam Age
9	Center	20	1.5	5.0	Air Oven	Steam Age
9R	Center	20	1.5	5.0	Air Oven	Steam Age
10	Axial	20	1.0	5.0	Air Oven	Steam Age
11	Axial	20	2.0	5.0	Air Oven	Steam Age
12	Axial	0	1.5	5.0	Air Oven	Steam Age
13	Axial	40	1.5	5.0	Air Oven	Steam Age
14	Axial	20	1.5	3.0	Air Oven	Steam Age
15	Axial	20	1.5	7.0	Air Oven	Steam Age

Experimental Design Schematic

Fired Density versus CP-5, Methocel and Mogul and Coded by Drying Method

F-5

design points:	2-level factorial points								center	axial (face-centered)						
CP5 [wgt %]	0	0	0	0	40	40	40	40	- 20 -	0	40	20	20	20	20	20
Methocel [wgt %]	1	1	2	2	1	1	2	2	- 1.5 -	1.5	1.5	1	2	1.5	1.5	1.5
Mogul [wgt %]	3	7	3	7	3	7	3	7	- 5 -	5	5	5	5	3	7	7

Abrasion versus CP-5, Methocel and Mogul and Coded by Drying Method

design points:	2-level factorial points								center	axial (face-centered)						
CP5 [wgt %]	0	0	0	0	40	40	40	40	- 20 -	0	40	20	20	20	20	20
Methocel [wgt %]	1	1	2	2	1	1	2	2	- 1.5 -	1.5	1.5	1	2	1.5	1.5	1.5
Mogul [wgt %]	3	7	3	7	3	7	3	7	- 5 -	5	5	5	5	3	7	7

Fired Strength versus CP-5, Methocel and Mogul and Coded by Drying Method

design points:	2-level factorial points								center	axial (face-centered)						
CP5 [wgt %]	0	0	0	0	40	40	40	40	- 20 -	0	40	20	20	20	20	20
Methocel [wgt %]	1	1	2	2	1	1	2	2	- 1.5 -	1.5	1.5	1	2	1.5	1.5	1.5
Mogul [wgt %]	3	7	3	7	3	7	3	7	- 5 -	5	5	5	5	3	7	7

Table of Coefficients for Fitted Models						
Response:	Fired Density [g/cc]		Abrasion [% wgt loss]		Fired Strength [MPa]	
Drying:	Air Oven	Steam Age	Air Oven	Steam Age	Air Oven	Steam Age
Intercept	2.2991	2.1632	72.1775	129.783	58.6600	10.3058
CP-5	-0.0036	-0.0005	2.5741	2.3422	-0.0172	-0.2366
(CP-5) ²	0.0001	0.0001	-0.0562	-0.0433	-0.0157	-----
Methocel	0.8982	0.8316	6.0550	-89.8818	-----	56.6050
Methocel ²	-0.2527	-0.2135	-----	29.2273	-----	-14.2933
Mogul	-0.1344	-0.0896	-----	2.7225	-----	-----
Mogul ²	0.0136	0.0095	-----	-----	-----	-----
(CP-5)•Methocel	-0.0031	-0.0045	-0.5588	-0.6100	-----	-0.3213
(CP-5)•Mogul	-----	-----	-----	-0.1369	-----	-----
Methocel•Mogul	-----	-----	-----	-----	-----	-----

Predicted Surfaces of Fired Density, Abrasion and Fired Strength
Air Oven

Predicted Surfaces of Fired Density, Abrasion and Fired Strength
Steam Age

Optimized Prediction Profile for Air Oven

Optimized Prediction Profile for Steam Age