Fly Ash in Concrete

An Overview of Benefits and Quantities Needed for Use in Portland Cement Concrete in North Carolina, South Carolina, and Virginia

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This report provides a brief summary of the technical and economic benefits of using fly ash in concrete and estimates of the quantities required in North Carolina, South Carolina, and Virginia, the primary market areas for fly ash produced by coal-fired power generation units in North Carolina.

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Executive Summary

Part 1 of this report describes the numerous benefits of incorporating fly ash into concrete, including significant improvements in durability to corrosion, alkali-silica reactivity (a significant problem in many areas of North Carolina, South Carolina, and Virginia) and sulfate related deterioration (both in both seawater and in soil), significant improvements in costs, and important improvements in sustainability and environmental protection. Part 1 also notes the lack of economically available alternates to fly ash in this region; fly ash would be imported from other regions if not available from local coal-fired power generation plants, many in North Carolina.

This report provides an estimate of future fly ash demand in the primary markets for fly ash produced in North Carolina. The projections of fly ash demand are based on recent market trends and projected population growth in North Carolina, South Carolina, and Virginia. A description of the methods used to develop that estimate are also provided. Statistical modeling was conducted using JMP Pro 10, SAS Institute, Inc.. Parameters used to estimate projected fly ash demand were all statistically significant at a 5% confidence level or better.

In 2014, fly ash use was estimated to be roughly 807,000 tons in North Carolina, 489,000 tons in South Carolina, 656,000 tons in Virginia, a total of over 1.9 million tons for all three states. Table 1, below, shows the projected estimates of fly ash demand in North Carolina, South Carolina, and Virginia given to the nearest thousand tons (US) from 2015 to 2030, inclusive, based on recent market trends.

Table 1
Projected Fly Ash Demand in North Carolina, South Carolina and Virginia
2015 to 2030 (in thousands of US tons)

Area	2015 - 2019	2020 - 2024	2025 - 2030	total 2015 - 2030
North Carolina	4,985	6,680	10,161	21,826
South Carolina	2,125	2,675	3,831	8,631
Virginia	4,028	4,943	7,044	16,014
total: NC, SC, VA	11,138	14,298	21,036	46,471

At current demand levels, a total of almost $46^{1}/_{2}$ million tons (US) of fly ash is projected to be needed in North Carolina, South Carolina and Virginia in the next 15 years. North Carolina alone is projected to need at least almost 5 million tons of fly ash between 2015 and 2020. The yearly average between 2015 and 2030 is estimated at well over 1.3 million tons in North Carolina, and just over 2.9 million tons for all three states combined. These are average demands based on current market conditions; those quantities will increase if market conditions strengthen. Demand for fly ash in North Carolina would likely rise from almost 5 million tons to well over 6 million tons in that period with only a slight increase in demand for concrete.

Part 1: Benefits of Fly Ash in Concrete

Fly ash, a by-product of coal combustion, is an important constituent of modern concrete. Fly ash is typically available in commercially useful quantities from coal-fired power plants after processing to ensure appropriate quality.

Fly ash and the hydrates of Portland cement combine to form the cementitious material of most of the commercially produced concrete in North Carolina. Fly ash is one of a handful of supplementary cementitious materials (SCM) discussed and regulated in the Building Code Requirements for Structural Concrete (ACI 318), which is referenced in all commercial concrete design and construction documents, and all local building codes in the US. SCM are also referred to as "mineral admixtures." Fly ash is one of the primary SCMs in use in concrete today. Fly ash contributes significantly and simultaneously to improved durability, sustainability, and economic benefits in ways that other SCM do not, even when locally available.

I. Durability:

Fly ash not only contributes to long-term strength gain but significantly improves durability of concrete in several key ways.

<u>Ia. Corrosion:</u> Corrosion is a major concern with infrastructure elements, not only along the many miles of coastline in North Carolina, South Carolina and Virginia but in many other parts of those states as well. North Carolina in particular has many miles of salt and brackish water exposure along the Outer Banks and Sounds.

Concrete provides corrosion protection for the reinforcing steel in concrete structures, but that protection can be compromised if chloride ions (such as from seawater or deicing salts) migrates into the concrete. The use of fly ash improves corrosion resistance of concrete by improving permeability and reducing ion migration into the concrete compared to Portland cement only based concretes with the same specified strength. While structures such as bridges over seawater or brackish water are exposed to salt spray or splash, bridges in the center and western parts of those states are also at risk since they are routinely exposed to deicing salt applications. Clearly the chloride ions in the salts can reduce the service life of bridge decks where the salt is applied, but chloride will also accumulate in the piers, bents and supports due to splashing of salt-laden slush or ice and snow melt sprayed by passing traffic. While there are other means to reduce permeability, the use of fly ash to replace a portion of the Portland cement is typically the most economical.

<u>Ib. Alkali-Silica Reactivity (ASR):</u> ASR remains a significant potential problem in most of North Carolina, and many parts of South Carolina and Virginia. Evidence of deleterious ASR can be found in structures in all parts of North Carolina, some severe.

About 2/3 of concrete is composed of aggregate, that is, sand and stone. Alkalies in the cement will react with certain types of silica-based aggregates to form an expansive silica gel that causes cracking and can contribute to significant reductions in service life of affected structures. Except for limited amounts of stone mined from the coastal region of North Carolina, for example, most of the aggregates used in concrete in North Carolina are metamorphic and igneous and at least moderately reactive in the presence of alkalies.

In some areas the stone can be very reactive. Aggregates from the Carolina Slate Belt and the Eastern Slate Belt, for example, are known to be deleteriously reactive. Significant igneous and metamorphic belts extend from South Carolina through North Carolina into Virginia so deleterious reactivity is a potential problem in all three states.

Much of the Portland cement used in North and South Carolina before the '70s was produced using the very low alkali cement from South Carolina (produced from a limestone deposit with some of the lowest alkali contents in the world) and deleterious ASR was not particularly widespread in the Carolinas, although dams in western NC built in the late 20s exhibit ASR deterioration. With increased demand resulting in greater imports of higher alkali Portland cements, deleterious ASR has became much more widespread in North Carolina.

The most effective and economical way to control deleterious ASR is to use a supplementary cementitious material with a significant amount of amorphous silica. The fly ash produced in North Carolina is about 70% silica. The finely divided, amorphous silica in the fly ash acts as a "sacrificial silica" binding the alkalies before they can react with the aggregate. There are other SCM, such as silica fume (also called micro-silica) and ground granulated blast furnace slag, and liquid admixtures such as lithium compounds, that can also mitigate ASR, but these are either much more expensive or not commercially available in North Carolina. Blast furnace slag, for example, was used years ago in NC but has not been available commercially here for almost 20 years.

<u>Ic. Sulfate Attack:</u> Sulfate attack can occur with the intrusion of external sulfates from seawater or from soluble sulfates in the soil, or by internal hydrate conversion if the concrete reaches too high a temperature in the first few days after placement.

The use of fly ash produces a concrete with improved permeability that reduces the intrusion of sulfate ions, similar to the reduction in chloride ion penetration noted above, thereby improving the durability of concrete exposed to seawater or higher sulfate contents in runoff or groundwater.

The use of fly ash also reduces the amount of aluminates in the mixture. Aluminates are a "problem" constituent of all commercially available Portland cements and play a key role in sulfate related deterioration. Fly ash replaces a part of the Portland cement used to attain a specified strength thereby diluting the aluminate content in the concrete. Fly ash also ties up hydrates necessary for sulfate deterioration reactions.

Further, the use of fly ash can also improve what has been called "internal sulfate" attack associated with higher concrete temperatures in the first day or two after placement. Since the fly ash replaces a portion of the Portland cement, the temperature rise in the concrete related to heat of hydration of the Portland cement is reduced.

II. Economic:

Fly ash affects the cost of concrete to the contractor, and therefore the owner, in two ways. It reduces the cost of a cubic yard of concrete by replacing a portion of the more expensive Portland cement and it extends the limited supply of Portland cement available in periods with strong economic growth.

<u>IIa. Purchase Price:</u> The cost of a ton of fly ash is approximately 1/3 the cost of a ton of Portland cement. Replacement ratios of approximately 1.2 to 1.3 pounds of fly ash per

pound of Portland cement are required to provide the same specified compressive strength with typical percentages of fly ash used in practice, although the ratio can vary up to 1.4 to 1.5 in some situations. Concrete mixtures with fly ash are about 80% to 95% of the cost to the contractor compared to Portland cement only mixtures with the same specified strength. Compressive strength at later ages of mixtures containing fly ash is typically higher than in otherwise comparable Portland cement only mixtures although specifications normally require a given strength at 28 days.

There are several other commercially available supplementary cementitious materials in the US. Silica fume, or microsilica, is very expensive and its use requires additional materials, such as high range water reducers, a "chemical admixture." Silica fume is rarely used unless very high strengths are required or the environment is particularly aggressive. Concrete containing silica fume will be much more expensive than a typical concrete mixture. Blast furnace slag, a by-product of iron production, is about the same price as Portland cement and is an effective SCM but is not commercially available in most if not all of North Carolina. Market demand exceeds supply and available production is typically consumed relatively close to the source (the blast furnace). Metakaolin and rice husk ash are other supplementary cementitious materials that have positive effects on permeability and ASR. Metakaolin is also very expensive compared to fly ash; rice husk ash is not commercially available in many parts of the eastern US.

<u>IIb. Portland Cement Availability:</u> Portland cement suppliers had difficulty meeting demand during the strong economic market about ten years ago. The worldwide demand was very high, in part due to the strong economic growth in the US, but also to the high demand for Portland cement internationally, particularly in China and India. During that time there were routine instances of projects in North Carolina in which delivery of ready mixed concrete could not be assured even on a day to day and sometimes on an hour to hour basis. If fly ash had not been available to replace part of the Portland cement, both the prices of ready mixed concrete and construction labor costs would have increased. The increased demand for and limited availability of Portland cement would have increased material costs; increases in labor costs could be expected due to lost productivity associated with irregularities or the inability to deliver concrete in a predictable or timely manner.

III. Other Benefits:

The use of fly ash in concrete also contributes positively in other ways. Its use reduces the energy and emissions required to produce a volume of concrete and provides beneficial use of a product that would otherwise be a waste material requiring storage and monitoring. Fly ash can therefore be said to contribute significantly to sustainability.

<u>IIIa. Reduction in Energy and Emissions of Concrete:</u> The production of Portland cement is energy intensive and produces carbon dioxide as a by-product. The fly ash content of ready mixed concrete is typically 10% to over 30% of the total cementitious material. Replacing this much Portland cement with fly ash can significantly reduces the energy content and the emissions for a given volume of concrete. The fly ash contributes very little to the energy and emissions content of concrete. The energy is captured for power

generation and pollutants or carbon dioxide generated by power production have already been emitted.

IIIb. Beneficial Use of a Waste Product: The use of fly ash in concrete captures a material that would otherwise require disposal areas and control measures to prevent accidental release and possible contamination of surrounding areas. The EPA "… supports the beneficial use of coal fly ash in concrete…" (see the Final Report, Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard, released February, 2014, by the United States Environmental Protection Agency Office of Solid Waste and Emergency Response, available online at www.epa.gov).

The ready mixed concrete industry in North Carolina alone consumed over 800,000 tons (US) of fly ash in 2014; others, such as paving contractors, will also use fly ash. The total demand for fly ash in 2015 to 2030 in NC, SC, and VA will likely exceed $46^1/_2$ tons of fly ash. The ash recovered from the combustion process at the power plant cannot be used directly in concrete without processing, however. The coal combustion products will be separated and the part that will be sold for use in concrete must be "beneficiated" to remove excessive carbon content and maintain quality. The USGS reports that fly ash accounts for about 58% of coal combustion products produced (Kalyoncu, accessed 5 March, 2015, at http://minerals.usgs.gov/minerals/pubs/commodity/coal/coalmyb01.pdf). The American Coal Ash Association reports that the United States produced 131 million tons of coal combustion products in 2007, approximately 43% of which were used beneficially (accessed 5 March, 2015, at http://www.acaa-usa.org/).

The technical benefits of fly ash and lack of economically available alternates will require the concrete industry to seek sources of suitable fly ash from other areas if fly ash demand is not met from sources in North Carolina. The beneficiation process must be conducted at or near the power plant feed source or the reclamation source to maximize the economic benefits of reuse. Moving fly ash beneficiation to other states will export jobs and tax revenues to those locations as well.

Another alternative is, of course, simply moving the material to a landfill or ash pond. This alternate will require additional land area and additional monitoring and control features to help ensure the ash does not spill into streams or onto adjacent property. Compacted fly ash will have a density between 85 and 100 pounds per cubic feet at best (accessed 15 March, 2015 at http://www.fhwa.dot.gov/publications/research). The total demand for fly ash in concrete is estimated to be about 1.3 million tons per year on average from 2015 to 2030 (see below) in North Carolina alone. This would amount to a volume of compacted ash about 15 to 17 feet high if spread over 40 acres of landfill every year if not used beneficially in concrete; uncompacted ash would occupy a greater volume (about 25 feet deep over 40 acres). If the demand for all three states is considered, 2.3 million tons per year, a 40 acre site would be filled with compacted fly ash to a depth of about 3 stories (over 29 feet) every year.

Part 2: Prediction of Fly Ash Demand 2015-2030 in North Carolina, South Carolina, and Virginia

Methodology; Modeling Future Fly Ash Demand

Predictive models should be statistically robust, sufficiently accurate for the intended use, and no more complex than necessary to achieve the first two objectives, regardless of the reason for developing the model. A practical model should also be based on predictor variables that are readily available and have reasonably accurate projections of future predictor variable values. Model development and variable selection are often a balance between model accuracy, simplicity, and practicality.

This study was commissioned by the Carolinas Ready Mixed Concrete Association to estimate future, or projected fly ash demand in North Carolina, South Carolina, and Virginia. The study therefore required development of a practical, reasonably accurate, predictive model based on fundamental relationships and sound statistical principles. Simplicity and practicality were considered to be the more important aspects of the model for the purposes of this study.

Two elements are needed to estimate projected quantities of fly ash used in concrete production: (1) a model to predict future demand for concrete or its constituents, and (2) a method for estimating the average yearly fly ash use directly or the average fly ash content in the concrete. Modern concrete mixtures produced commercially in this area are composed of almost 65% aggregate (stone and sand) and approximately 15% cementitious material (Portland cement and fly ash) by volume, with the remaining approximately 20% by volume being water, chemical admixtures and entrained air. These quantities vary by strength level, intended purpose and, to a certain extent, construction methods.

Selection of Model Variables

A statistical model is comprised of dependent and independent variables. Dependent variables are those that are predicted by the model and so "depend" on the values of the predictor, or independent, variables. Either fly ash itself (preferably) or a surrogate variable correlated with fly ash demand was the desired dependent variable. Selection of the appropriate independent, or predictor variable or variables was not obvious.

Concrete, and therefore fly ash demand is a complex function of residential, commercial and industrial building demand, which is affected in general by market conditions and population. Widely accepted estimates of future population are readily available for most states but population alone does not capture important economic effects on concrete demand. Figure 1 shows the population and estimated volume of ready-mixed concrete produced by year from 1996 to 2014 in North Carolina; data from other states in this area is similar. There is clearly no simple linear relationship between concrete or fly ash demand and population during the period shown; market effects must be considered.

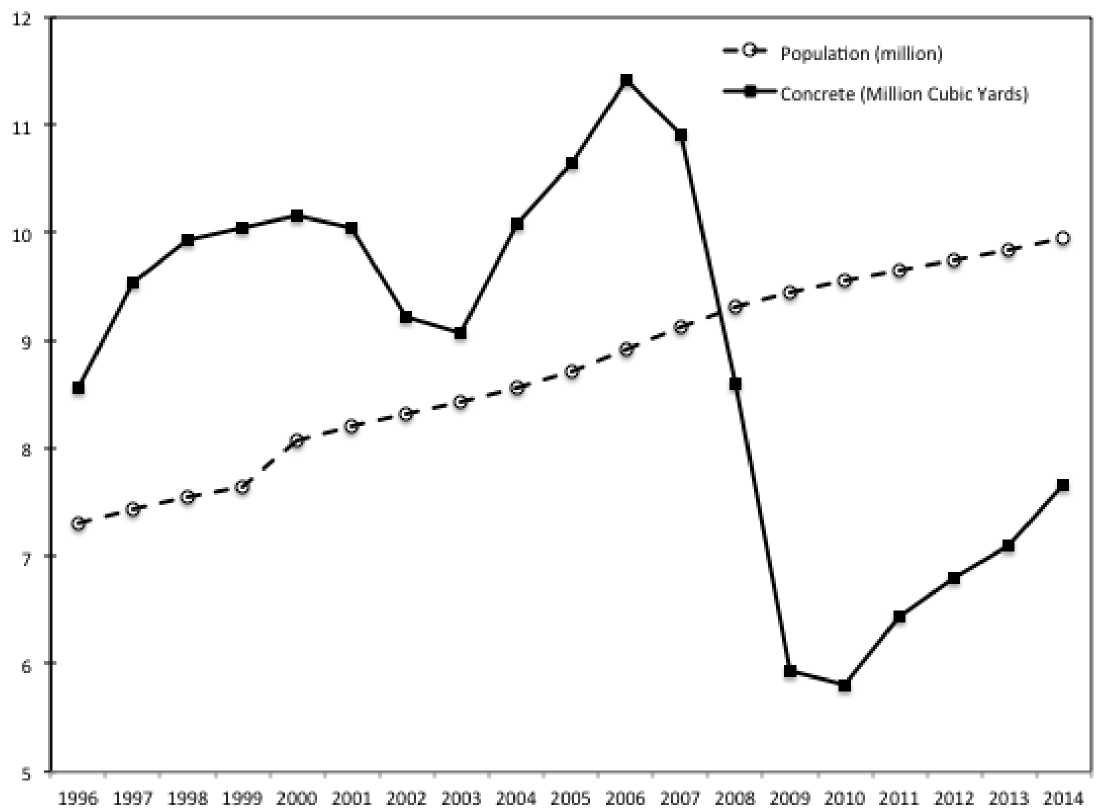


Figure 1. North Carolina Population and Volume of Concrete from 1996 to 2014

Dependent Variables: An obvious choice for the dependent variable would be to use past fly ash usage directly. This variable is not available directly, however. Values of yearly regional fly ash usage published by industry representatives are estimates based on the tonnage of Portland cement shipped in that region using a simple linear transformation.

Since fly ash can be estimated from the volume of concrete produced, the use of concrete volume (cubic yards) is a logical surrogate variable for fly ash. The use of concrete volume as the dependent variable in the model is also problematic from theoretical considerations since the concrete volume estimates are also derived rather than reported or measured directly. Individual concrete producers are hesitant to publicly release detailed information on volume or market. The ready mixed concrete industry has traditionally relied on total Portland cement tonnage shipped in an area to estimate the cubic yards of concrete produced by state or region. The estimate of concrete volume is a simple linear function of cement shipped based on experience and judgment. The relationship used in the industry was constant during the 1998-2014 period.

Since the relationship between reported values of cubic yards of concrete produced, tons of fly ash consumed in that production and tonnes (metric) of cement shipped is linear, the dependent variable used in the analysis could be either cubic yards of concrete, tons of fly ash or tons of cement, but a relationship between the predictor variable or variables and cement demand is technically preferred.

Fly ash specifications are typically based on percentage of cementitious material rather than volume or mass per unit volume of concrete. The report of American Concrete Institute (ACI) Committee 318, Building Code Requirements for Structural Concrete, is referenced in all US building codes. ACI 318 considers fly ash on a percentage basis. The percent fly ash is defined in ACI as the mass of fly ash expressed as a percent of the mass of the total cementitious material, the combination of all SCM and cement.

The dependent variable used in the state-based models to predict fly ash demand in the future was therefore tonnes (metric) of cement. Using cement tonnage as the dependent variable also has the advantage that all concrete is captured in this approach (including such markets as paving, precast production and block manufacture, as well as the ready-mixed concrete market). Regardless of whether volume of concrete or tons of cement was the dependent variable in the relationships examined, some estimate of the quantity of fly ash per unit of either volume of concrete or ton of cement was required. This issue is discussed in a subsequent section.

<u>Independent Variables:</u> A number of independent variables were considered since population alone is not a sufficient independent (predictor) variable. Additional factors were investigated in an attempt to capture market conditions or effects in the model.

Model Development; Estimation of Cement Shipped by State: Models were examined that considered both singular and multivariate factors, including cross-factors. The factors examined included housing starts, median household income, and state GDP, as well as state populations. Analysis was conducting with data from four (4) states, North Carolina, South Carolina, Virginia, and Georgia.

None of these factors or combination of factors provided statistically acceptable models for all four states simultaneously. In North Carolina and South Carolina for example, housing starts were highly correlated with tonnes of cement and volume of concrete, but correlations based on housing starts were weaker for data from Georgia and Virginia. Similarly, median household income was a statistically valid predictor variable of tonnes of cement based on population in both Carolinas, but did not work well with data for Georgia and Virginia. GDP failed to produce a statistically valid model with data for the Carolinas and was also discarded for the final analysis.

These factors also shared a practical weakness in predicting the quantity of fly ash required in the future. Reliable estimates of future values of housing starts and median household income by state are limited at best. Two of the factors are also affected by population. The use of population as a predictor variable was therefore reexamined with a simple temporal classification. The cement tonnage shipped was modeled as a function of population from 1996 to 2014 under three different, general market conditions:

a strong market, from 1996 to 2006 (inclusive),
a transition period, in 2007, 2008, and 2009, and
the recent market conditions, from 2010 to 2014 (inclusive).

These ranges were chosen based on visual examination of the tonnage figures over time for all four states, but other ranges were also checked. Analysis considering a shorter transition period, 2007 and 2008, for example, resulted in a weaker relationship. The ranges listed above were used since they were both reasonable visually and provided statistically valid models for the “recent market conditions” (current) period.

The results from the transition period were ignored as non-representative of long-term trends. The relationships between population and cement tonnage were not particularly strong for any state during the strong market period, indicating additional predictor values would be needed for analysis during that time. This was a period of unusually strong demand, however, and it was also not considered representative of long-term trends. This period was therefore not considered further in this study.

A relatively strong linear relationship was found between cement tonnage shipped and population during the recent time period for three states (North Carolina, South Carolina, and Virginia) and moderately strong for Georgia. Statistical analysis of the relationship between population and cement tonnage (as a direct indicator of concrete demand) is limited to only 5 data points for each state so the coefficient of sample correlation (r^2) terms are expected to be relatively high due to limited degrees of freedom. The relationships were strong enough, however, that projections based on most recent population and concrete demand trends are useful and believed to be sufficiently accurate for the purposes of this study. Since the recent economy has not been particularly strong, the estimates provided in this study are likely to be exceeded in a stronger market.

Source Data, Independent Variables; Projected Population Estimates: Estimates of projected population by state on the US Census website are currently based on 2005 analysis with projected yearly estimates based on the 2010 census apparently due out sometime during 2015. Current estimates are available from the US Census Bureau on 5 year intervals out to 2030. These estimates are generally consistent with estimates from sources in individual states. Several states generate publically available population estimates and these may be used as the independent variable for more detailed studies. Population data at 5 year intervals may be found through the U.S. Census Bureau, Population Division, Interim State Population Projections, 2005. These data were used to provide consistent estimates for all three states examined in detail in this study.

Additional population data for North Carolina, including yearly estimates, may be found through the North Carolina Office of State Budget and Management at http://www.osbm.state.nc.us/ncosbm/facts_and_figures/socioeconomic_data/population_estimates/demog/countytotals_2020_2029.html . Population data for South Carolina may be found at http://www.sccommunityprofiles.org/census/proj2020.php .

Findings

Estimation of Fly Ash Demand as a Function of Cement Tonnage

Definitions: A simple method to estimate the quantity of fly ash is to apply a percentage to the values of cement tonnage. As noted previously of this report, the percentage of fly ash used in specifications is the percentage of total cementitious material rather than a percentage of the cement alone, however. The percent of total cementitious material is more difficult to use in estimating fly ash quantities directly from cement quantities, so a simple percentage of cement (only) was used in estimating projected fly ash quantities in this study.

Values based on the two definition, percent of cement and percent of total cementitious materials, will be different for the same amount of fly ash used in a cubic yard of concrete. The concrete industry uses the percent of total cementious material in specifications and common practice so both types of percentages are used in this study. Conversion from percent cement to percent total cementitious material is shown in Equation 1.

$$\%TCM = \%Cmt / (1+\%Cmt) \qquad \text{Eq. 1}$$

where %TCM is the amount of fly ash based on the mass of total cementitious material, expressed as a decimal,

and %Cmt is the amount of fly ash based on the mass of cement, expressed as a decimal. [Note: these abbreviations are not standard, but convenient for this study.]

A value of %Cmt = 35% is therefore equal to %TCM = 26% rounded to the nearest whole percent.

Percentage Determined in the Study: Sources within the ready mixed concrete and fly ash industries suggest the concrete industry uses an average of about 25% of the total cementitious material per cubic yard of concrete, based on the definition in ACI 318. This figure is consistent with engineering analysis discussed below. Concrete and fly ash industry sources also noted that at least 800,000 tons (US) of fly ash had been consumed by the ready mixed concrete industry in North Carolina in 2014. North Carolina data were used to calibrate the model since they were readily available and included an estimate for actual cement tonnage shipped in 2014, determined in January, 2015. This quantity was used to help calibrate the model developed in this study.

A trial percentage of fly ash was selected and used to estimate fly ash usage based on cement tonnage. The percentage was adjusted such that the quantity of fly ash estimated for 2014 matched the amount projected by the model. This factor, the fly ash expressed as a percentage of cement only, was found to be 35%, which is approximately 26% when based on total cementitious material. The 26% of total cementitious material found by adjustment is identical for all practical purposes with the 25% suggested by industry representatives. Since this percentage was found to be consistent with common industry assumptions, it was used in with projections for South Carolina and Virginia, although there may be slight differences between regions.

Fly ash expressed as a percent of total cementitious material is typically limited to 40% in most commercial applications unless used in an element exposed to deicing salt, in which case the maximum percent of total cementitious material permitted by ACI 318 is 25%. The value of 26% average fly ash content, expressed as percent of total cementitious material, is therefore very reasonable. Concrete cast into formed elements can contain more fly ash (easily 30% or more); elements intended for fast-track construction may carry less. Much higher fly ash contents, some in excess of 60%, have been used successfully in mass concrete applications, although this is rare.

The general conformance of fly ash content used in the model to commonly found values in practice suggests that the model is internally consistent. This finding also implies that the methodology and model developed in this study provide rational results and that the projected fly ash quantities developed in this study are reasonable.

North Carolina Model Parameters

The statistics calculated using JMP Pro 10, SAS Institute, Inc. software for North Carolina are shown in Tables 2a and 2b. Values are given to the same number of decimals as provided by SAS rather than significant figures. The coefficient of determination (R^2) of the model equals 0.979884 (98.0%); the probability of exceeding the F ratio due to random variation only equals 0.0012. Both of these values indicate the model is statistically significant.

Table 2a. Parameter Estimates, Cement Tonnage, North Carolina

Intercept	Estimate	-10,069.08
	Standard Error of the Estimate	985.1814
	t ratio	-10.22
	Probability of Exceeding |t|	0.002
Coefficient	Estimate	0.0012213
	Standard Error of the Estimate	0.000101
	t ratio	12.09
	Probability of Exceeding |t|	0.0012

Table 2b. Model Fit Statistics, Cement Tonnage, North Carolina

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	139088.79	139089	146.1352
Error	3	2855.34	952	
C. Total	4	141944.13		

The relationship between population and cement tonnage shipped in North Carolina during the period 2010 to 2014 developed in this study is shown in Equation 2. Both the intercept and the population coefficient are statistically significant but the intercept is reported to excess significant figures.

$$Cmt_{NC} = -10{,}069 + 0.0012\ Pop_{NC} \quad \text{Eq. 2}$$

where Cmt_{NC} is the Portland cement shipped per year in North Carolina, in thousands of metric tonnes,

and Pop_{NC} is the population of North Carolina in that year.

South Carolina Model Parameters

The statistics calculated using JMP Pro 10, SAS Institute, Inc. software for South Carolina are shown in Tables 3a and 3b. Values are given to the same number of decimals as provided by SAS rather than significant figures. The coefficient of determination (R^2) of the model equals 0.91508 (91.5%); the probability of exceeding the F ratio due to random variation only equals 0.0108. Both of these values indicate the model is statistically significant.

Table 3a. Parameter Estimates, Cement Tonnage, South Carolina

Intercept	Estimate	-6668.95
	Standard Error of the Estimate	1365.585
	t ratio	-4.88
	Probability of Exceeding |t|	0.0164
Coefficient	Estimate	0.001642
	Standard Error of the Estimate	0.000289
	t ratio	5.69
	Probability of Exceeding |t|	0.0108

Table 3b. Model Fit Statistics, Cement Tonnage, South Carolina

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	66049.979	66050	32.3275
Error	3	6129.453	2043	
C. Total	4	72179.432		

The relationship between population and cement tonnage shipped in South Carolina during the period 2010 to 2014 developed in this study is shown in Equation 3. Both the intercept and the population coefficient are statistically significant but are reported to excess significant figures.

$$Cmt_{SC} = -6{,}669 + 0.0016\ Pop_{SC} \qquad \text{Eq. 3}$$

where Cmt_{SC} is the Portland cement shipped per year in South Carolina, in thousands of metric tonnes,

and Pop_{SC} is the population of South Carolina in that year.

Virginia Model Parameters

The statistics calculated using JMP Pro 10, SAS Institute, Inc. software for South Carolina are shown in Tables 4a and 4b. Values are given to the same number of decimals as provided by SAS rather than significant figures. The coefficient of determination (R^2) of the model equals 0.93095 (93.0%); the probability of exceeding the F ratio due to random variation only equals 0.0079. Both of these values indicate the model is statistically significant.

Table 4a. Parameter Estimates, Cement Tonnage, Virginia

Intercept	Estimate	-7108.838
	Standard Error of the Estimate	1361.047
	t ratio	-5.22
	Probability of Exceeding |t|	0.0137
Coefficient	Estimate	0.001058
	Standard Error of the Estimate	0.000166
	t ratio	6.36
	Probability of Exceeding |t|	0.0079

Table 4b. Model Fit Statistics, Cement Tonnage, Virginia

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	64484.764	64485	40.4448
Error	3	4783.168	1594	
C. Total	4	69267.932		

The relationship between population and cement tonnage shipped in Virginia during the period 2010 to 2014 developed in this study is shown in Equation 4. Both the intercept and the population coefficient are statistically significant but are reported to excess significant figures.

$$Cmt_{VA} = -7{,}108 + 0.00106\ Pop_{VA} \qquad \text{Eq. 4}$$

where Cmt_{VA} is the Portland cement shipped per year in Virginia, in thousands of metric tonnes,

and Pop_{VA} is the population of Virginia in that year.

Projected Estimates of Population, Cement Tonnage, and Fly Ash Demand

The projected population figures for 2015 to 2030, taken from the U.S. Census Bureau, Population Division, Interim State Population Projections, 2005, for North Carolina, South Carolina, and Virginia are shown in Table 5a. These values were used in combination with equations 2, 3, and 4 to estimate cement tonnage shipped to those states in the years 2015, 2020, 2025, and 2030. Projected estimates of cement tonnage (metric tonnes) are given in Table 5b. Projected estimates of fly ash demand (US tons) are given in Table 5c; these estimates are based on fly ash quantities averaging 35% of the mass of cement or about 26% of the mass of total cementitious material in a cubic yard of concrete.

Table 5a US Census Bureau Projected Populations for Selected States

Population	2015	2020	2025	2030
North Carolina	10,010,770	10,709,289	11,449,153	12,227,739
South Carolina	4,642,137	4,822,577	4,989,550	5,148,569
Virginia	8,466,864	8,917,395	9,364,304	9,825,019

projections for the years indicated

Table 5b Projected Estimates of Cement Demand by State (thousands of metric tonnes)

Cement	2015	2020	2025	2030
North Carolina	2,157	3,010	3,914	4,865
South Carolina	953	1,250	1,524	1,785
Virginia	1,849	2,326	2,799	3,286

projections for the years indicated

Table 5c Projected Estimates of Fly Ash Demand by State (thousands of US tons)

Fly Ash	2015	2020	2025	2030
North Carolina	832	1,162	1,510	1,877
South Carolina	368	482	588	689
Virginia	714	897	1,080	1,268

projections for the years indicated

The yearly quantities of projected fly ash may be estimated by averaging the estimates at the end points of a given period. For example, the average yearly fly ash demand from 2015 to 2020 in North Carolina may be estimated as the average of 832,000 tons and 1,162,000 tons, or 997,000 tons (US). The total amount used in 2015, 2016, 2017, 2018, and 2019 would then be 997,000*(5), or 4,985,000 tons (almost 5 million tons). The values given in Table 1, provided in the Executive Summary and duplicated below, are the total amounts anticipated to be used during the time periods indicated; years are inclusive.

Table 1
Projected Fly Ash Demand in in North Carolina, South Carolina and Virginia
2015 to 2030 (in thousands of US tons)

	2015 - 2019	2020 - 2024	2025 - 2030	2015 - 2030
North Carolina	4,985	6,680	10,161	21,826
South Carolina	2,125	2,675	3,831	8,631
Virginia	4,028	4,943	7,044	16,014
NC+SC+VA	11,138	14,298	21,036	46,471

The total amount of fly ash that is anticipated to be required for concrete production by North Carolina, South Carolina, and Virginia combined in the next 15 years (2015 to 2030, inclusive) is 46,471,000 tons, or almost $46^{1}/_{2}$ million tons. North Carolina alone is projected to need at least almost 5 million tons of fly ash between 2015 and 2020 and all three states will consume in excess of an estimated 11 million tons in the next five years.

The yearly average between 2015 and 2030 is estimated at well over 1.3 million tons in North Carolina, and just over 2.9 million tons for all three states combined. These are average demands based on current market conditions; those quantities will increase if market conditions strengthen. Demand for fly ash in North Carolina would likely rise from almost 5 million tons to well over 6 million tons in that period with only a slight increase in demand for concrete, for example.

General Conclusions

Fly ash is a beneficial product when used in Portland cement concrete and contributes favorably to concrete durability, economy, and sustainability. The quantities of fly ash needed from 2015 to 2030 are anticipated to be over 2.9 million tons per year in the three state region of North Carolina, South Carolina, and Virginia. A total of almost $46^{1}/_{2}$ million tons of fly ash is anticipated to be needed during that time in all three states combined. These values will be higher if the economy grows faster during that time than in recent years.

Appendices

A1. Data used in analysis

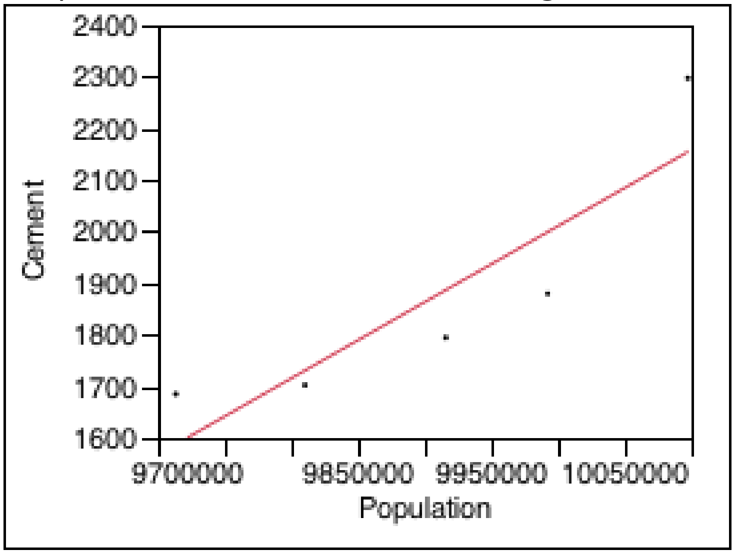
Year	State	Population	Estimated CY	Market	Cement x1000
1996	NC	7,307,658	8,557,718	bubble	2,329
1997	NC	7,428,672	9,545,139	bubble	2,598
1998	NC	7,545,828	9,932,574	bubble	2,703
1999	NC	7,650,789	10,040,607	bubble	2,733
2000	NC	8,081,614	10,157,588	bubble	2,764
2001	NC	8,210,122	10,044,388	bubble	2,734
2002	NC	8,326,201	9,224,733	bubble	2,511
2003	NC	8,422,501	9,071,923	bubble	2,469
2004	NC	8,553,152	10,078,927	bubble	2,743
2005	NC	8,705,407	10,656,005	bubble	2,900
2006	NC	8,917,270	11,425,752	bubble	3,109
2007	NC	9,118,037	10,909,272	transition	2,969
2008	NC	9,309,449	8,608,146	transition	2,343
2009	NC	9,449,566	5,923,965	transition	1,611
2010	NC	9,559,533	5,808,005	recent	1,581
2011	NC	9,651,377	6,438,839	recent	1,752
2012	NC	9,748,364	6,799,643	recent	1,851
2013	NC	9,848,060	7,091,748	recent	1,930
2014	NC	9,943,964	7,651,784	recent	2,083
1996	SC	3,738,974	4,263,608	bubble	1,160
1997	SC	3,790,066	4,408,209	bubble	1,200
1998	SC	3,839,578	4,681,680	bubble	1,274
1999	SC	3,885,736	4,986,013	bubble	1,357
2000	SC	4,024,223	4,842,698	bubble	1,318
2001	SC	4,064,995	5,091,078	bubble	1,386
2002	SC	4,107,795	5,027,724	bubble	1,368
2003	SC	4,150,297	5,507,659	bubble	1,499
2004	SC	4,210,921	6,400,523	bubble	1,742
2005	SC	4,270,150	6,532,631	bubble	1,778
2006	SC	4,357,847	6,805,625	bubble	1,851
2007	SC	4,444,110	5,941,752	transition	1,617
2008	SC	4,528,996	4,562,023	transition	1,242
2009	SC	4,589,872	3,018,857	transition	821
2010	SC	4,636,361	3,421,474	recent	931
2011	SC	4,673,509	3,652,967	recent	994
2012	SC	4,723,417	4,013,533	recent	1,092
2013	SC	4,774,839	4,532,030	recent	1,233
2014	SC	4,832,482	4,488,511	recent	1,222
1996	VA	6,665,491	6,591,223	bubble	1,794

1997	VA	6,732,878	7,016,799	bubble	1,910
1998	VA	6,789,225	7,354,634	bubble	2,002
1999	VA	6,872,912	7,620,313	bubble	2,074
2000	VA	7,105,817	8,143,495	bubble	2,216
2001	VA	7,198,362	8,544,824	bubble	2,326
2002	VA	7,286,873	7,786,975	bubble	2,119
2003	VA	7,366,977	7,717,849	bubble	2,101
2004	VA	7,475,575	9,105,709	bubble	2,478
2005	VA	7,577,105	9,794,719	bubble	2,666
2006	VA	7,673,725	9,695,603	bubble	2,639
2007	VA	7,751,000	8,709,293	transition	2,370
2008	VA	7,833,496	7,416,233	transition	2,018
2009	VA	7,925,937	5,605,495	transition	1,526
2010	VA	8,024,417	5,025,082	recent	1,368
2011	VA	8,105,850	5,322,897	recent	1,449
2012	VA	8,186,628	5,929,079	recent	1,614
2013	VA	8,260,405	5,961,054	recent	1,622
2014	VA	8,326,289	6,167,950	recent	1,679
1996	GA	7,332,225	11,687,566	bubble	3,181
1997	GA	7,486,094	11,852,069	bubble	3,225
1998	GA	7,636,522	12,987,538	bubble	3,535
1999	GA	7,788,240	12,441,597	bubble	3,386
2000	GA	8,227,303	12,617,963	bubble	3,434
2001	GA	8,377,038	12,538,604	bubble	3,413
2002	GA	8,508,256	11,340,602	bubble	3,086
2003	GA	8,622,793	12,661,500	bubble	3,446
2004	GA	8,769,252	15,096,338	bubble	4,109
2005	GA	8,925,922	16,148,650	bubble	4,395
2006	GA	9,155,813	16,404,603	bubble	4,484
2007	GA	9,349,988	14,750,102	transition	4,014
2008	GA	9,504,843	11,435,450	transition	3,112
2009	GA	9,620,846	6,933,657	transition	1,856
2010	GA	9,713,248	6,192,928	recent	1,685
2011	GA	9,810,181	6,256,767	recent	1,703
2012	GA	9,915,646	6,594,886	recent	1,795
2013	GA	9,992,167	6,907,144	recent	1,880
2014	GA	10,097,343	8,442,655	recent	2,298

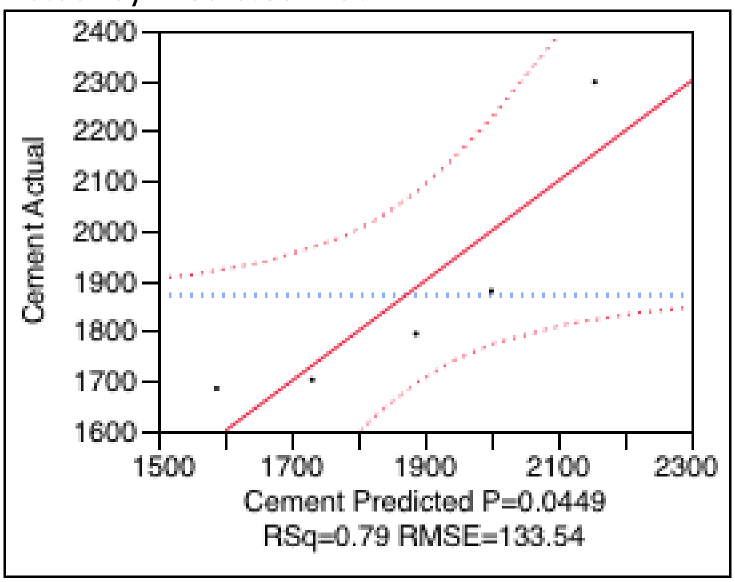
A2. Summary of Statistical Analysis (JMP Pro 10, SAS Institute, Inc.)

Where(:Market == "recent" & :State == "GA")

Response Cement Whole Model Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.786604
RSquare Adj	0.715472
Root Mean Square Error	133.5367
Mean of Response	1872.1
Observations (or Sum Wgts)	5

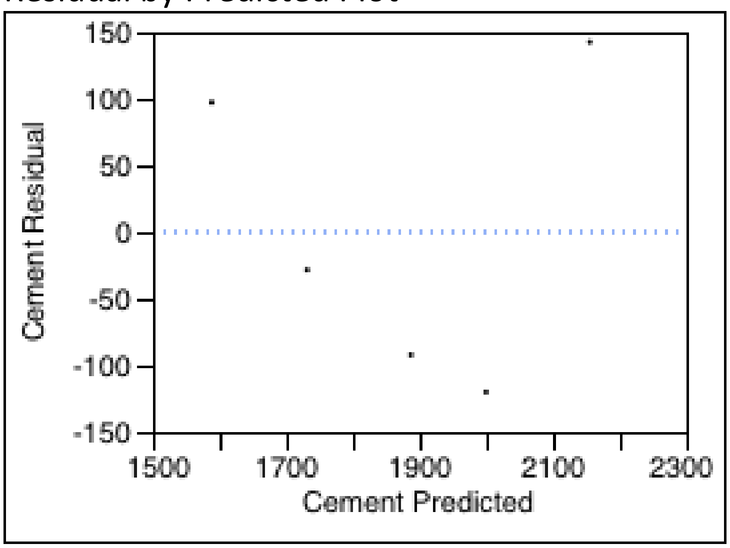
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	197193.14	197193	11.0583
Error	3	53496.18	17832	Prob > F
C. Total	4	250689.32		0.0449*

Parameter Estimates

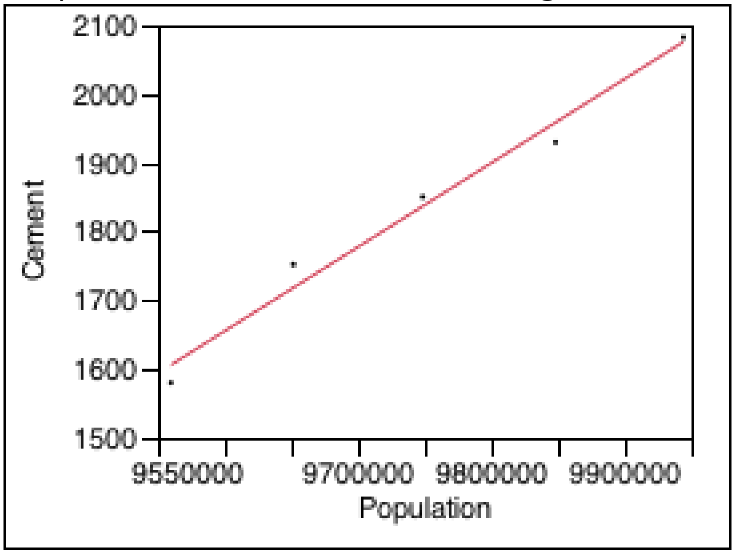
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-12752.82	4398.336	-2.90	0.0625
Population	0.0014764	0.000444	3.33	0.0449*

Residual by Predicted Plot

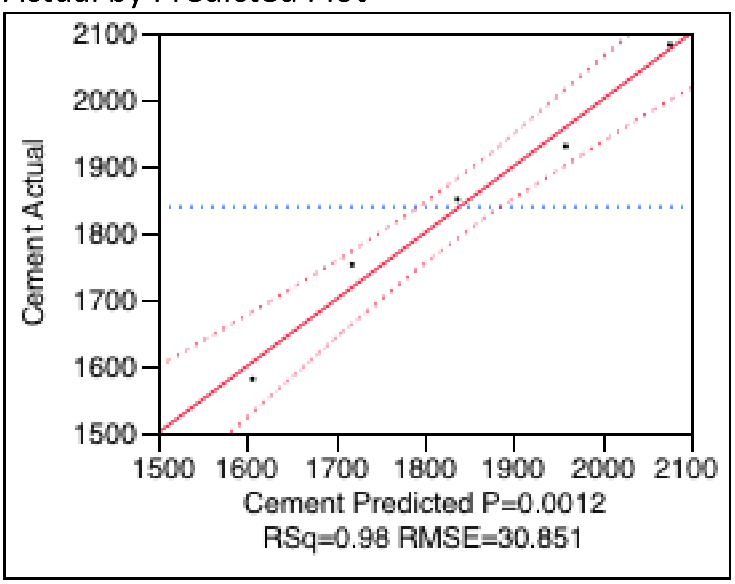


Where(:Market == "recent" & :State == "NC")

Response Cement Whole Model Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.979884
RSquare Adj	0.973179
Root Mean Square Error	30.85096
Mean of Response	1839.26
Observations (or Sum Wgts)	5

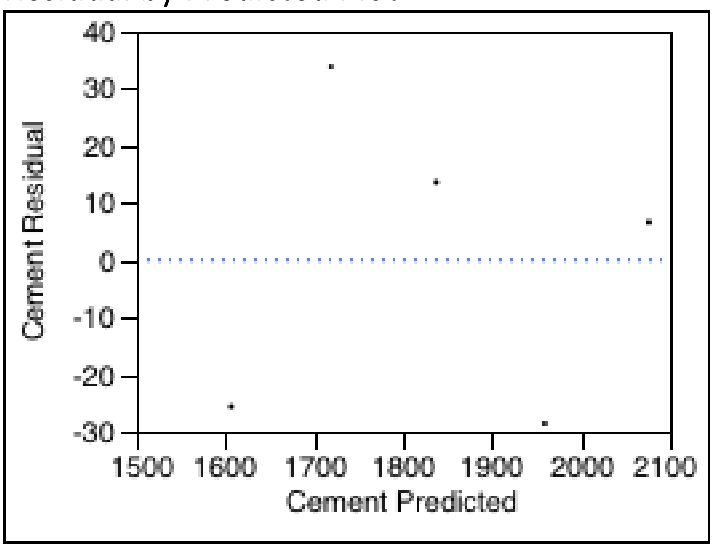
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	139088.79	139089	146.1352
Error	3	2855.34	952	Prob > F
C. Total	4	141944.13		0.0012*

Parameter Estimates

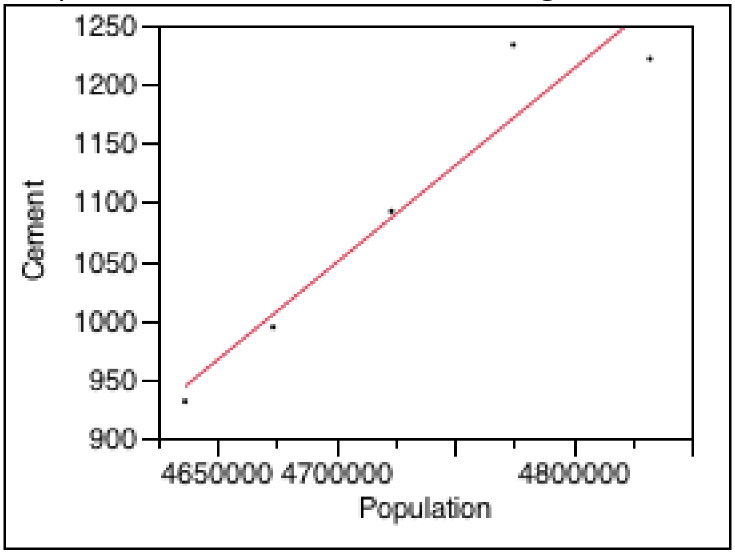
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-10069.08	985.1814	-10.22	0.0020*
Population	0.0012213	0.000101	12.09	0.0012*

Residual by Predicted Plot

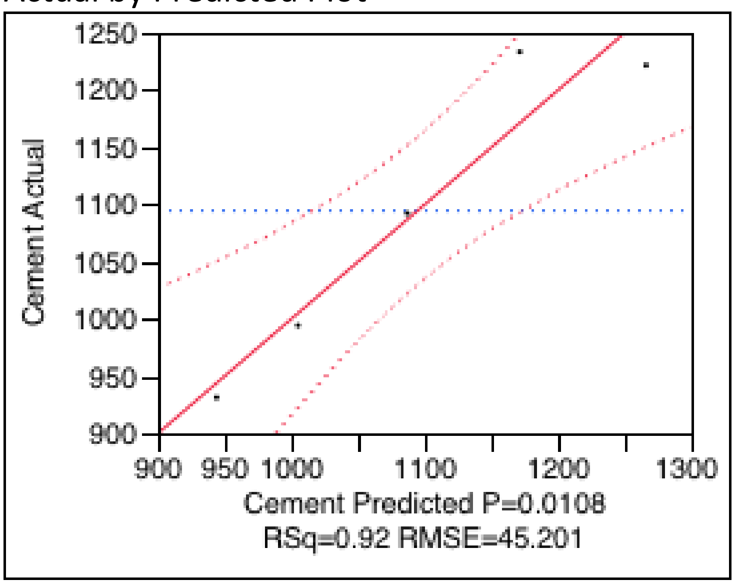


Where(:Market == "recent" & :State == "SC")

Response Cement Whole Model Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.91508
RSquare Adj	0.886774
Root Mean Square Error	45.20123
Mean of Response	1094.54
Observations (or Sum Wgts)	5

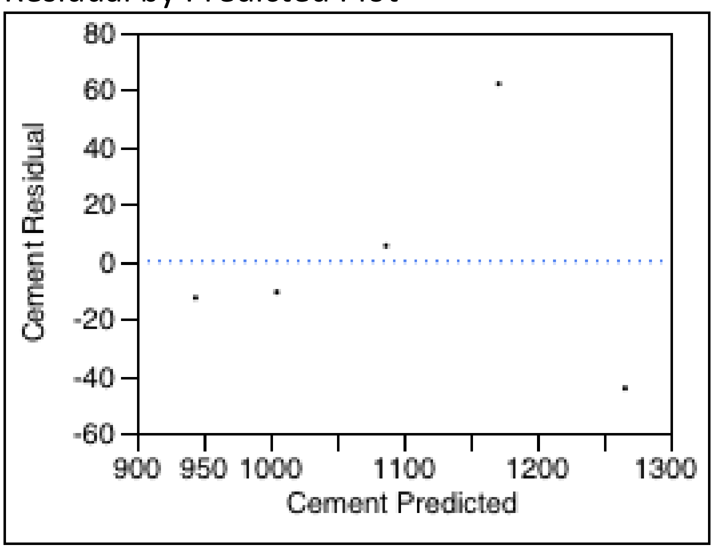
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	66049.979	66050.0	32.3275
Error	3	6129.453	2043.2	Prob > F
C. Total	4	72179.432		0.0108*

Parameter Estimates

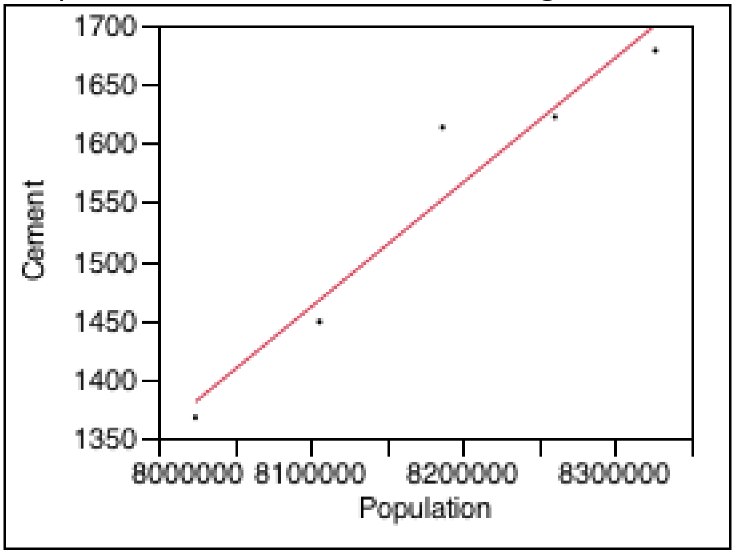
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-6668.952	1365.585	-4.88	0.0164*
Population	0.001642	0.000289	5.69	0.0108*

Residual by Predicted Plot

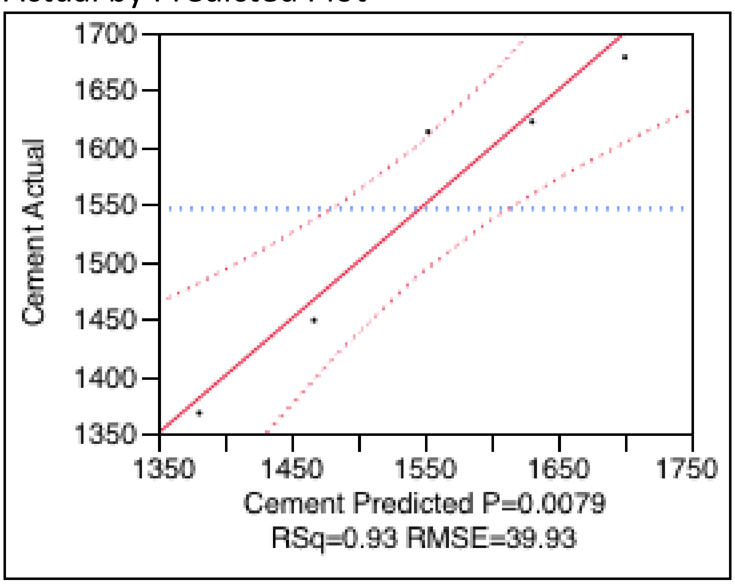


Where(:Market == "recent" & :State == "VA")

Response Cement Whole Model Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.930947
RSquare Adj	0.907929
Root Mean Square Error	39.9298
Mean of Response	1546.16
Observations (or Sum Wgts)	5

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	64484.764	64484.8	40.4448
Error	3	4783.168	1594.4	Prob > F
C. Total	4	69267.932		0.0079*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7108.838	1361.047	-5.22	0.0137*
Population	0.001058	0.000166	6.36	0.0079*

Residual by Predicted Plot