Potential for Reduced Greenhouse Gas Emissions in Texas Through the Use of High Volume Fly Ash Concrete

Submitted to Transportation Research Board August 1, 2004, Revised November 15, 2004

Word Count: 7398

by

Cindy K. Estakhri, P.E.
Associate Research Engineer
Texas Transportation Institute
Texas A&M University System
College Station, TX 77843-3135
Phone (979) 845-9551
FAX (979) 845-0278
c-estakhri@tamu.edu

Donald Saylak, P.E.
Professor
Department of Civil Engineering
Texas A&M University
College Station, TX 77843-3136
Phone (979) 845-9962
FAX (979) 845-0278
d-saylak@tamu.edu

ABSTRACT
The objective of this study was to determine the potential for reductions in carbon dioxide emissions in Texas by substituting high volumes of fly ash in concrete production and to identify the resulting benefits and challenges.

Researchers reviewed the literature and determined that high volume fly ash (HVFA) can improve the properties of both the fresh and hardened concrete. It can improve workability, heat of hydration, strength, permeability, and resistance to chemical attack.

Researchers compiled data for 18 power plants located throughout Texas and determined that a total of 6.6 million tons of fly ash are produced annually in Texas and about 2.7 million tons (or 40%) are generally sold for use in concrete or other end products. Researchers estimated production of concrete in Texas and determined that if 60 percent of the portland cement used in Texas concrete production were replaced with fly ash, carbon dioxide emissions could potentially be reduced by 6.6 million tons annually by the year 2015.

More education is needed for design engineers and for the concrete industry regarding the performance and environmental benefits that can be realized through increased use of fly ash in concrete.

INTRODUCTION

Current trends show that infrastructure needs will continue to require large amounts of low cost building materials, such as portland cement concrete. This need will have to be balanced with the need for environmental preservation, natural resource conservation and pollution reduction. Portland cement concrete is the material of choice for many modern infrastructural needs. The world consumption of portland cement has risen from less than two million tons in 1880 to 1.3 billion tons in 1996 and is projected to increase to 2 billion tons by the year 2010.

The production of each ton of portland-cement clinker is accompanied by the release of approximately one ton of the greenhouse gas carbon dioxide (CO_2). Besides other raw materials, each ton of portland cement requires approximately 1.5 tons of limestone, and considerable amounts of both fossil fuel and electrical energy.

Eighty per cent of CO_2 emissions come from the combustion of fossil fuels, and approximately 30% of those emissions are from the transportation sector. The next largest source of CO_2 emissions is from the manufacture of cement and account for approximately 10% of all CO_2 emissions (1). When faced with the challenge to reduce greenhouse gas emissions, policy makers have traditionally targeted the transportation sector and fossil fuel combustion, the largest CO_2 sources. This task has been difficult. A promising alternative is to target reductions in CO_2 emissions from cement manufacture through the substitution of fly ash (a coal combustion by-product).

Canadian researchers have determined that CO_2 emission reductions can be accomplished by substituting high volumes of fly ash (a material that is otherwise landfilled) as a replacement for cement(2). Their research has shown that this high-volume fly ash (HVFA) concrete exceeds the requirements of conventional portland cement concrete and has all of the attributes of high-performance concrete. Use of fly ash in cement manufacture may also achieve complementary goals by reducing the waste stream, increasing material recycling and conserving energy. This can be accomplished without a significant economic impact to cement manufacturers or consumers.

To achieve sustainable development in the cement and concrete industry, we need to understand and appreciate what has happened to the world during our lifetime (3). R.N. Swamy (3) states that, "the world at the end of this century is very different from the world that we inherited at the beginning of the century. There have been unprecedented social changes, unpredictable upheavals in world economy, uncompromising societal attitudes, and pollution and damage to our natural environment. In global terms, the societal transformations that have occurred can be categorized in terms of population growth, technological revolutions, worldwide urbanization and uncontrolled pollution and creation of waste."

The impact of global urbanization has not just created a demand for construction materials but also on world energy, which again impinges finally on the construction industry (3). In the present context of the world, 25% of the world's population live in industrialized nations but they account for nearly 75% of the global energy consumption (3).

Whatever its limitations, concrete as a construction material is still rightly perceived and identified as the provider of a nation's infrastructure and indirectly, to its economic progress and stability because it is so easily and readily prepared and fabricated into all sorts of structural systems in the realms of infrastructure, habitation and transportation (3).

In spite of the excellent known performance of concrete in normal environments, there are two aspects of the material that have tarnished its image: it's environmental impact and its durability (3). The construction industry has a direct influence on world resources, energy consumption, and on carbon dioxide emissions. The record of concrete as a material of everlasting durability has been greatly impaired by the material and structural degradation that has become common in many parts of the world (3). We have assumed that the relative impermeability of concrete and protection of the embedded steel will be adequately provided for by the cover thickness and the presumed quality of the concrete(3). However, our experience has shown that neither can be achieved as a normal and natural consequence of the process of concrete fabrication (3).

Even when adequate concrete cover and concrete quality are achieved in practice, there is a high risk of premature corrosion deterioration in concrete structures exposed to aggressive salt-laden environments. The strong implication here is that with current design codes, premature deterioration due to steel corrosion is likely to continue. There is a need for a fundamental change in our thinking about concrete and concrete quality made of portland cement concrete (4-7).

The high strength which has traditionally been desirable in concrete may give misleading ideas of durability. Although strength is clearly the result of the pore-filling capability of the hydration products, there is considerable evidence to show that there is no direct relationship between concrete strength and impermeability, and hence durability (8).

Extensive research has now established that the most direct, technically sound and economically attractive solutions to the problems of reinforced concrete durability lies in the incorporation of finely divided siliceous materials in concrete. The fact that these cement replacement materials, or supplementary cementing materials, such as fly ash, ground blast furnace slag, silica fume, rice husk ash, natural pozzolans, and volcanic ash are all either pozzolanic or cementitious make them ideal companions to portland cement. Portland cement is the best chemical activator of these siliceous admixtures. Portland cement combined with fly ash can result in high quality concrete with intrinsic abilities for high durability with immense social benefits in terms of resources, energy and environment - the only way forward for sustainable development (3).

The objective of this study was to determine the potential for reductions in CO_2 emissions in Texas by substituting high volumes of fly ash in concrete production and to identify the resulting benefits and challenges.

FLY ASH PROPERTIES, PRODUCTION, AND AVAILABILITY

Characteristics of Fly Ash

Fly ash is a by-product of the combustion of coal in thermal power plants. It is a fine, powdery material that would "fly" out of the power plant's stacks if it were not captured. But power plants today collect their fly ash particles through the dust collection system before they are discharged into the atmosphere.

These fly ash particles are typically spherical, ranging in diameter from less than 1 μm up to 150 μm. The type of dust collection equipment determines the range of particle sizes in a particular fly ash. The type and amount of incombustible matter in the coal determines the chemical composition of the fly ash. Most of the fly ash contains compounds from the elements silicon, aluminum, iron, calcium, and magnesium. Fly ash produced from the burning of subbituminous coal contains more calcium and less iron than fly ash from bituminous coal. Unburned coal also collects with the fly ash as carbon particles. Fly ash from subbituminous coals contains very little unburned carbon.

There are two general classes of fly ash: Class C, which is normally produced from lignite or subbituminous coals and Class F, which is normally produced from bituminous coals. These two ashes differ in the ways they function in concrete mixtures. Class C ashes differ from Class F ashes in that they are self-hardening even without the presence of cement. In addition, Class C ashes contain higher levels of calcium. It should be noted that the American Society for Testing Materials (ASTM) specifications for fly ash (C618) do not make reference to the level of calcium in the ash as shown in Table 1. The different levels of calcium have led to the use of an alternative terminology commonly used: high-calcium and low-calcium ash for Class C and Class F, respectively.

One important characteristic of fly ashes is that they exhibit pozzolanic activity. A pozzolan is a siliceous or siliceous/aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Historically, Class C ash has been used much more in construction applications than Class F, primarily due to the self-hardening characteristics inherent in the Class C ash.

Production and Availability of Fly Ash in Texas

There are 18 coal-fired power plants located throughout Texas as shown in Figure 1. Utilities must report the production of coal combustion by-products at their facilities annually to the Department of Energy. Researchers compiled these data as presented in Table 2. While this is the production for a single year, it is typical for annual production. Of interest to this study, is the production of fly ash. Approximately 6.6 million tons of fly ash are produced annually in Texas and about 2.7 million tons (or about 40%) are generally sold to use in concrete and/or other end products. Just over half of the fly ash produced in Texas is a Class F ash. About 25 percent of the Class F ash is currently being sold or used and almost 60 percent of the Class C ash is sold or used.

Typical Composition of Fly Ashes from Plants in Texas

Composition of fly ashes will vary from plant-to-plant. Table 3 shows fly ash compositions from selected plants in Texas.

Future of Fly Ash in Texas

One of the concerns for engineers and officials responsible for specifying the use of fly ash in concrete regards the consistency of quality and future availability of that product. A recent trend for some of the plants in Texas is to supplement or replace their current coal source with Powder River Basin coal from Wyoming due to its low cost. This raises the question, "how will this new coal source in varying quantities affect the chemistry of the ash and thus the properties of concrete?" A plant which burns Powder River Basin coal will produce a Class C ash. What happens, though, when a plant which burns lignite coal and produces an F ash begins to supplement that coal with Powder River Basin coal which produces a C ash? This is also of concern to Texas Department of Transportation (TxDOT) officials who have recently been concerned about the use of Class C ash and would like to specify a Class F ash. The following is a discussion of a realistic scenario to show that supplementing lignite coal with Powder River Basin coal may produce no effective change in the quality of the fly ash.

Scenario:

One plant located in east Texas has historically burned lignite coal mined in the area. This plant estimates that it has at least 10 years of lignite deposits at their mine to support this plant. This type of plant is not capable of handling 100% Powder River Basin (PRB) coal and plant officials have stated they could never supplement the lignite coal with more than 25% PRB at this plant.

If this plant burns 75% lignite coal and 25% PRB, what is the effect on the CaO content of the ash? Due to the efficiency of PRB coal, it only produces about 80 lbs of fly ash per ton of coal; whereas, lignite produces about 200 lbs of fly ash.

> *One ton of lignite coal produces about 200 lbs of fly ash with a CaO content of about 10% for a total of 20 lbs of CaO.*
>
> *One ton of PRB coal produces about 80 lbs of fly ash with a CaO content of about 30% for a total of 24 lbs of CaO.*

If the plant uses 75% lignite and 25% PRB what is the CaO content of the blend?

0.75 (20 lbs of CaO) = 15 lbs (for lignite)
0.25 (24 lbs of CaO) = <u>6 lbs (for PRB)</u>
21 lbs of CaO

Therefore, a ton of lignite coal produces 20 lbs of CaO and a blend of lignite and PRB (75/25) produces only 21 lbs of CaO which is not enough of a difference to affect the performance characteristics of the fly ash.

FLY ASH USAGE IN CONCRETE PRODUCTION

There are many benefits to using fly ash in concrete and the benefits associated with it being a recycled by-product is secondary to most engineers. Fly ash can improve the properties of fresh concrete and the hardened concrete. It reduces the amount of portland cement required in concrete which makes its use cost-effective. Typically, 15 to 30 percent of the portland cement in most concrete is replaced with fly ash.

Effects of Fly Ash on Properties of Fresh Concrete

Fresh concrete is a concentrated suspension of particulate materials of widely differing densities, particle sizes, and chemical compositions in a solution of lime and other components (9). When cement and water are mixed, chemical reactions occur which increases the temperature of the concrete. To effectively mix and place concrete, a certain degree of fluidity, or workability, is needed. Fly ash plays a role in these factors as described below.

Improved Workability/Decreased Water Demand

Fly ash is a very fine-grained, powder-like material consisting of spherical, glassy particles. These very small, spherical particles provide a lubricating effect in the concrete resulting in improved workability of the fresh concrete. This improved workability allows the amount of water used in the concrete to be reduced.

Reduced Heat of Hydration

When concrete begins to set or hydrate, a temperature rise occurs. Use of fly ash as partial replacement for portland cement reduces the temperature rise in the concrete. Cooling which occurs after a large temperature rise can lead to cracking in mass concrete.

Effects of Fly Ash on Properties of Hardened Concrete

Strength Development and Ultimate Strength

As mentioned previously, fly ash is available in two general types: Class C and Class F. Class C ash (high in calcium) is cementitious even in the absence of portland cement. When Class C ash is used, the rate of strength development in concrete is only slightly affected by the ash. Much of the early research on fly ash concrete was performed using Class F fly ash. In this early work, the ashes came from older plants producing a coarse particle size and were relatively inactive as pozzolans. These ashes showed a slow rate of strength development leading to the thinking that "fly ash reduces strength at all ages". (9) More recent research indicates that concrete containing fly ash has the potential to produce satisfactory compressive strength-development. The influence of the class of fly ash on the long-term compressive strength of the concrete is not significant.

In general, the compressive and flexural strengths of fly ash concretes is slightly lower at early ages than those of control concretes but exceeds those of concrete without fly ash at later ages.

The additional binder produced by the fly ash reaction with available lime allows fly ash concrete to gain strength over time. Mixtures designed to produce equivalent strength at early ages will ultimately exceed the strength of straight cement concrete mixtures.

Permeability

The key to a sustainable transportation infrastructure is in using materials with exceptional durability. The lack of durability in concrete is often related to excessive permeability. For concrete to remain durable it must be impervious to the aggressive environments in which it may be used. Concrete is often used in harsh marine environments. It is also sometimes in contact with sulphate and acidic waters. A permeable concrete pavement is also very susceptible to deterioration where salts are used by maintenance crews for deicing bridges and roadways.

The movement of aggressive solutions into concrete plays a primary role in determining the rate of concrete deterioration caused by chemical attack. The use of fly ash in concrete decreases the required water and this combined with the production of additional cementitious compounds reduces the permeability of the concrete. This reduced permeability results in improved long-term durability and resistance to various forms of deterioration.

Resistance to ASR and Sulfates

Fly ash also improves the resistance of concrete to alkali-silica reactivity (ASR) (10). It also improves resistance to sulfate attack by inducing three phenomena:

- fly ash consumes the free lime making it unavailable to react with sulfate,
- the reduced permeability prevents sulfate penetration into concrete,
- replacement of cement reduces the amount of reactive aluminates available.

High-Volume Fly Ash (HVFA) Concrete

The quantity of fly ash use in concrete generally ranges from 15 to 30 percent replacement of the portland cement. In 1985, the Canada Centre for Mineral and Energy Technology (CANMET) initiated studies on structural concrete incorporating high volumes (>50%) of low calcium fly ashes (9). This research resulted in HVFA concrete with adequate early-age strength and workability, low temperature rise, and high late-age strength.

Setting Time

One of the barriers to using HVFA concrete by the industry is its increased time to set. Malhotra and Ramazanianpour (9) report that research was performed to measure times of set in accordance with ASTM C403. Test results show that *initial* setting times were 7.5 hours which comparable to those of control concrete made with the same water content and water to cementitious ratio. However, final setting times were delayed by about 3 hours compared with the control concrete. These delays may be related to the problem of compatibility between cementitious materials and superplasticizers. This delay in setting time may be viewed by the industry to pose a scheduling problem. This could be a problem during winter construction; however, the delayed set can be a distinct advantage in a Texas summer.

Temperature Rise

Because of the low cement content in HVFA concrete, the rise in temperature during the first few days is minimal. This makes its use ideal in the construction of massive structures such as concrete dams.

Compressive Strength

High volume fly ash concrete exhibits adequate strength development at both early and late ages. Research in Canada has shown that the one-day compressive strength is more than adequate for formwork removal at normal temperatures and comparable to the strength of portland cement concrete. Twenty-eight day compressive strengths are also comparable to the values for normal portland cement concrete. Due to the slow pozzolanic reaction, the HVFA concrete achieves significant improvements in its mechanical properties at later ages compared to conventional portland cement concrete.

Durability

The water permeability of HVFA concrete is very low. Tests performed on 50-mm thick concrete discs under uniaxial flow and pressure conditions indicate a permeability less than or equal to 10^{-13} conditions (2).

Air-entrained, high-performance, HVFA concrete shows excellent resistance to repeated cycles of freezing and thawing. After 1000 cycles in ASTM C 666 Procedure A test (freezing and thawing in water), the durability factors are in excess of 90; conventional air-entrained portland cement concrete is considered satisfactory if it can withstand 300 cycles (2).

The high-performance, HVFA concrete shows very high resistance to the penetration of chloride ions in tests performed according to ASTM C 1202. Its resistance is considerably higher than conventional portland cement concrete of similar strength. The charge measured on HVFA concrete usually ranges from 500 to 2000 coulombs at 28 days, and from 200 to 700 coulombs at 91 days. A value of less than 600 coulombs is indicative of very high resistance, and hence, very low permeability (2).

The drying shrinkage strains of HVFA concrete are comparable to, or lower than that of conventional portland cement concrete, with measured values of the order of 500 x 10^{-6} after 64 weeks of air drying (2).

POTENTIAL FOR CARBON DIOXIDE EMISSION REDUCTIONS

Quantity of Concrete Produced in Texas

Several data sources were used to estimate the quantity of concrete produced in Texas. Some of the most reliable data comes from the United States Geologic Services (USGS) which annually publishes data on the amount of crushed stone and the amount of sand and gravel sold or used in Texas for the production of concrete (11). These statistics are listed in Table 4 and shown graphically in Figure 2. Based on the quantity of aggregate sold for the production of concrete, an estimate was made on the quantity of concrete produced with these aggregates, also shown in Figure 3.

The USGS also maintains data on the quantity of cement produced at cement plants in Texas as shown in Table 4.

For purposes of this study regarding use of the statistics given in Table 4, it is assumed that the aggregates and portland cement produced in Texas are used in Texas for concrete production and not exported to other states. This is probably a reasonable assumption in that there is no particular need for other states to use aggregates from Texas (except maybe near the borders where it is economically feasible). It is assumed, also, that the portland cement produced in Texas is likely to be used in Texas. This is assumed to be true because it is often difficult for cement plants to keep up with the demand during the busy construction seasons so there would be little need for transporting cement to other states. Also, the quantities of portland cement produced in the state correspond reasonably with the quantities of aggregate produced for concrete.

The estimated annual production of concrete is shown in Figure 3. In interviews with various industry representatives, it is estimated that about 30 percent of the concrete market is held by TxDOT projects as also shown in Figure 3.

Quantity of Fly Ash Used in Concrete Production

Most concrete produced in Texas contains some quantity of fly ash and it varies throughout the state. It is generally used to enhance the workability and economics of concrete without regard to the improved performance expected through the use of fly ash. It is estimated by industry representatives that concrete in Texas, on average, contains 10 to 15 percent fly ash replacement. This quantity can be verified to some degree by comparing to the quantity of fly ash sold as reported by the utilities in Table 2. In Table 2, it is reported that 2,653,200 tons of fly ash was sold in 2000; however, the end use for this fly ash is not documented. Some of this fly ash is used for stabilization purposes. It is also known from discussions with one of the utilities, that some Class F ash was railed to Florida for concrete production there. If all of the fly ash which was sold in Texas in 2000 was used in concrete production, it is estimated that this would comprise about 30 percent replacement of portland cement with fly ash in concrete production. If the actual use in concrete is closer to about 15 percent as estimated by industry representatives, then one can conclude that about half of the fly ash being sold (or 20% of that being produced) in Texas is for use in the production of concrete in Texas.

Potential for the Reduction of Carbon Dioxide Emissions

The production of one ton of cement produces about one ton of carbon dioxide. Therefore, every ton of portland cement that is replaced with fly ash, could result in a one-ton reduction in the emission of carbon dioxide. A similar study in Canada estimates a significant decrease in greenhouse emissions (up to 3.6 million tons by the year 2010) with fly ash replacing 60% of cement in concrete (12). For the study presented herein, projections are made to the year 2015 on the quantities of fly ash available for use in concrete in Texas and the estimated potential reduction of carbon dioxide emissions associated with concrete production in the following scenarios:

Scenario 1: fly ash continues to replace about 15 percent of portland cement in concrete,
Scenario 2: fly ash replaces 30 percent of portland cement in concrete beginning in 2005, and
Scenario 3: fly ash replaces 60 percent of portland cement in concrete beginning in 2005.

Based on a linear regression of the eight years of data shown in Figure 3 for the production of concrete, it is estimated that concrete production in the year 2005 would be 39 million tons and in 2015 would be about 44 million tons. According to the three scenarios presented above, the potential for carbon dioxide emission reductions are presented as follows:

Potential Carbon Dioxide Emission Reductions	***2005***	***2015***
Scenario 1	1,462,500 tons	1,650,000 tons
Scenario 2	2,925,000 tons	3,300,000 tons
Scenario 3	5,850,000 tons	6,600,000 tons

By the year 2015, carbon dioxide emissions associated with concrete production could be reduced by 6.6 million tons if 60 percent of cement were replaced with fly ash.

Fly Ash Availability versus Potential Demand

Replacing portland cement with as much as 60 percent fly ash produces what is called a HVFA concrete as described in detail previously. Most of the research associated with HVFA concrete involves the use of a Class F fly ash. An obvious question regarding the use of HVFA concrete is, “Will there be enough Class F fly ash available to meet that level of demand?”

Based on the data presented in Table 2, about 3.1 million tons of Class F fly ash were produced in the year 2000. Using estimated quantities of concrete for the same year, a 60 percent replacement of cement with fly ash would require about 6.9 million tons. If TxDOT alone were using a HVFA concrete, about 2.1 million tons of Class F ash would be required. If all concrete purchased by TxDOT contained the maximum amount of fly ash allowed by TxDOT specifications (35% replacement), it is estimated that a total of 1.2 million tons of fly ash would be required. Based on these data, the annual production of Class F fly ash is sufficient to replace 60 percent of the cement used in TxDOT concrete projects.

Most of the research on HVFA concrete has been performed with Class F fly ash because the work was done in Canada where that is the type of ash available. However, there is also the potential for using high volumes of Class C ash in concrete but more research is needed in Texas to verify the performance properties.

Identifying and Overcoming Barriers to Increased Fly Ash Use in Concrete

The concrete industry has accepted fly ash use in concrete. Most concrete plants have a silo which contains fly ash that is used routinely for concrete production. However, the use of large volumes of fly ash in concrete is an unknown technology to many. Many plants produce concrete mixes with a Class C ash. It is not feasible for concrete plants to build an additional silo so that they could also have a Class F ash available to produce HVFA concrete. Some report this investment for a silo to be as high as $1 million. There is currently no incentive for the concrete industry to change current ways.

Another barrier to the increased use of fly ash is the limitation placed by agency specifications. TxDOT as well as many other agencies allow a maximum of 35 percent fly ash replacement in concrete. A relaxation in these specifications will certainly allow any potential economic incentives that exist to take hold.

Much of the Canadian research with HVFA concrete has been performed with a Class F ash which is available in Texas. However, additional research is needed to verify performance with Texas fly ashes and climatic conditions. This research should also include developing the performance characteristics of HVFA concrete produced with a Class C ash which makes up about half of the fly ash produced in the state.

Researchers believe that many of the barriers to increased fly ash use can be overcome through education: education for design engineers and for the concrete industry regarding the performance and environmental benefits which can be realized through the increase use of fly ash in concrete.

ACKNOWLEDGEMENTS

Support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center, Texas A&M University System, College Station.

REFERENCES

1. U.S. Environmental Protection Agency, Office of Policy.1998, *U.S. Greenhouse Gas Emissions and Sinks,* Washington, D.C.
2. Bilodeau, A. and V. Malhotra, 1999. *High-Volume Fly Ash System: The Concrete Solution for Sustainable Development*, CANMET/ACI International Symposium on Concrete Technology and Sustainable Development, Vancouver, BC.
3. Swamy, R.N., 1999. *Designing Concrete and Concrete Structures for Sustainable Development,* CANMET/ACI International Symposium on Concrete Technology and Sustainable Development, Vancouver, BC.
4. Mehta, P.K., 1994. *Concrete Technology at the Crossroads - Problems and Opportunities,* Concrete Technology, Past, Present, and Future, Mohan Malhotra Symposium, ACI Special Publication SP-144, pp 1-30.
5. Swamy, R.N., and J.C. Laiw, 1995. Effectiveness of Supplementary Cementing Materials in Controlling Chloride Penetration into Concrete, ACI Publication SP-164, Volume 2, pp 657-674.

6. Swamy, R.N., Design for Chloride Contaminated Harsh Environments: The Key to Durability Service Life, Concrete Protection, Unpublished Report.
7. Rasheeduaazfar, 1992. "Influence of Cement Composition on Concrete Durability", *ACI Materials Journal*, Volume 89, No. 6, pp 574-586.
8. Swamy, R.N. and A.A. Darwish, 1997. *Effectiveness of Mineral Admixtures and Curing Regime on Air Permeability of Concrete,* Durability of Concrete, ACI Publication SP-170, pp 207-230.
9. Malhotra, V.M. and A.A. Ramezanianpour, 1994. *Fly Ash in Concrete,* 2nd Edition, Canada Centre for Mineral and Energy Technology, Natural Resources Canada, Ottawa, Ontario.
10. Estakhri, C.K., D. Saylak, and S.D. Mohidekar, 2004. *Potential for Reduced Greenhouse Gas Emissions in Texas Through the Use of High Volume Fly Ash Concrete,* Southwest University Transportation Center, Texas Transportation Institute, Texas A&M University, College Station.
11. U.S. Geological Survey, 1994 - 2001. "The Mineral Industry of Texas", University of Texas, Bureau of Economic Geology, Austin.
12. Venta, G.J., 1999. *Potential for Reduction of CO_2 Emissions in Canada Through Greater Use of Fly Ash in Concrete*, CANMET/ACI International Symposium on Concrete Technology and Sustainable Development, Vancouver, BC.

TABLE 1 ASTM C618-98 Specifications for Fly Ash

Class of Ash	ASTM Specification
Class C	$SiO_2 + Al_2O_3 + Fe_2O_3$ >50%
Class F	$SiO_2 + Al_2O_3 + Fe_2O_3$ >70%

TABLE 2 Coal Combustion By-Products Produced and Sold by Texas Power Plants for the Year 2000

Plant Name	**Total Fly Ash Produced** thousand short tons	**Total Fly ash Sold**, thousand short tons	**Total Bottom Ash Produced,** thousand short tons	**Total Bottom Ash Sold**, thousand short tons	**Total FGD or Gypsum Produced,** thousand short tons	**Total FGD or Gypsum Sold,** thousand short tons
Oklaunion	110.8	110.8	43.1	43.1	0	0
Limestone*	191.0	191.0	485.8	36.4	1278.9	0
WA Parish	344.0	296.7	115.8	40.2	48.2	47.8
Big Brown*	576.0	189.7	229.8	24.4	0	0
Gibbons Creek	69.9	69.6	23.3	13.7	0	0
Welsh	211.5	188.3	25.8	25.8	0	0
Martin Lake*	1165.4	425.8	574.0	30.3	603.4	0
Monticello*	1355.5	192.8	553.7	8.4	47.6	0
Coleto Creek	118.8	24.3	29.7	0	0	0
Sam Seymour	238.0	212.0	102.0	36.0	37.0	4.0
JT Deely	127.2	126.2	38.1	19.7	0	0
San Miguel	688.9	5.8	229.6	0	338.1	0
Harrington Station	197.3	185.6	49.3	49.3	0	0
Tolk Station	186.2	152.4	52.5	49.6	0	0
Sandow*	352.0	97.9	150.9	27.7	134.5	0
TNP One	252.8	92.8	103.9	18.4	0	0
JK Spruce	92.3	91.5	26.8	13.8	46.3	46.3
Pirkey	323.3	0	107.8	0	384.4	0
Total	**6600.9**	**2653.2**	**2941.9**	**436.8**	**2918.4**	**98.1**

Based on information reported by utilities to the EIA DOE on form 767.
*Produces a Class F fly ash.

TABLE 3 Typical Fly Ash Composition and Properties

Chemical Analysis	*Class C Ash, W.A. Parish Plant*	*Class F Ash, Limestone Plant*	*Class F Ash, Big Brown Plant*
Silicon Dioxide, %	33.39	57.03	56.38
Aluminum Oxide, %	1.57	19.08	6.8
Iron Oxide, %	6.27	10.03	20.82
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	59.23	86.14	84.00
Magnesium Oxide, %	5.27	1.89	2.57
Sulfur Trioxide, %	2.24	0.67	0.64
Moisture Content, %	0.06	0.01	0.11
Loss on Ignition, %	0.23	0.01	0.41
Available Alkalis as Na_2O, %	1.29	0.19	1.12
Calcium Oxide, %	*27.45*	*7.66*	*11.57*
Physical Analysis			
Fineness: Amount retained on 325 sieve, %	10.40	34.17	16.11
Water Requirement, % control	94	95	93
Specific Gravity	2.63	2.38	2.44
Autoclave Expansion, %	-0.01	-0.03	-0.03
Strength Activity Index with Portland Cement, %, 28 day	93	80	97

TABLE 4 Amount of Concrete and Concrete Components Produced in Texas

Year	Portland Cement Sold or Used in Texas, short tons	Crushed Stone Sold or used for Concrete Production in Texas, short tons	Sand and Gravel sold or used for Concrete Production in Texas, short tons	Estimate of Concrete Sold or Used in Texas, short tons
2002	9,630,000	Not Available	Not Available	Not Available
2001	9,360,000	10,089,000	21,060,000	38,936,000
2000	8,343,000	12,033,000	24,930,000	46,204,000
1999	7,812,000	14,067,000	23,040,000	46,383,000
1998	7,587,000	16,830,000	17,280,000	42,637,000
1997	7,452,000	14,787,000	20,790,000	44,471,000
1996	7,416,000	12,501,000	20,880,000	41,726,000
1995	7,281,000	14,310,000	18,630,000	41,175,000
1994	7,758,000	14,229,000	20,700,000	43,661,000
1993	7,317,000	11,439,000	Not Available	Not Available

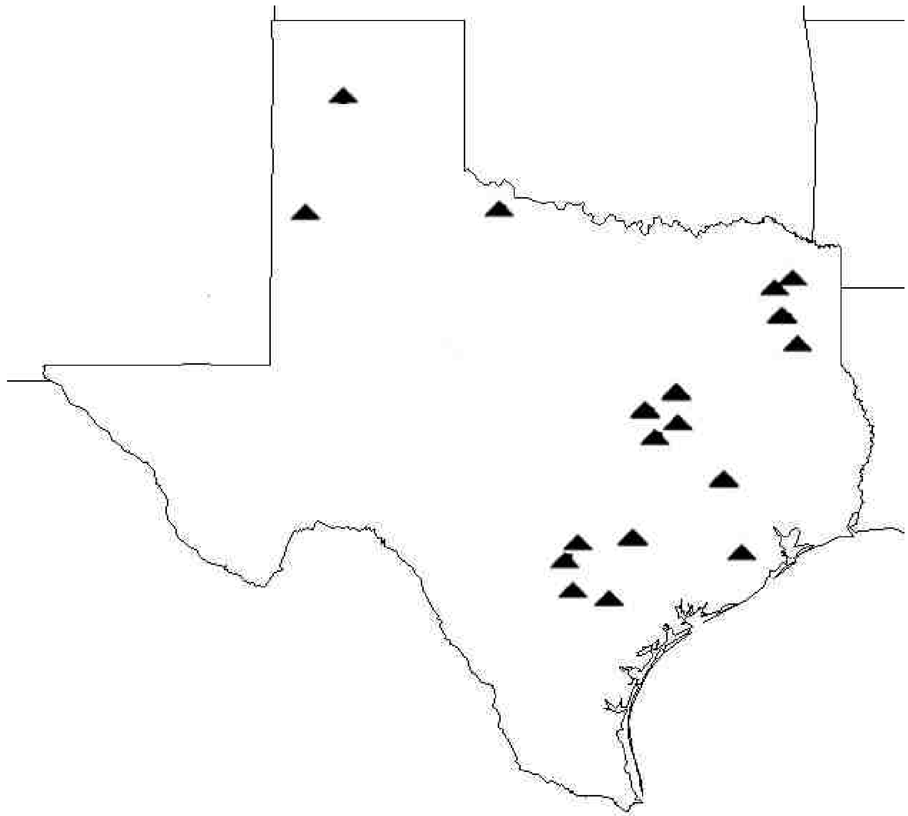

FIGURE 1 Location of Coal-Fired Power Plants in Texas

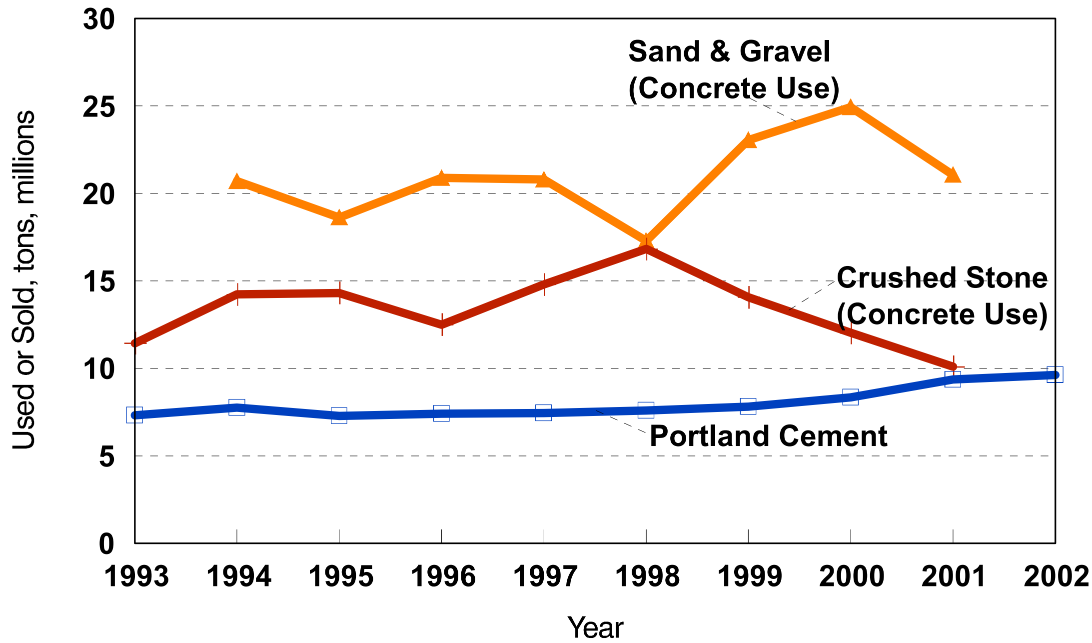

FIGURE 2 Annual Production of Portland Cement and Aggregate in Texas for Use in Concrete

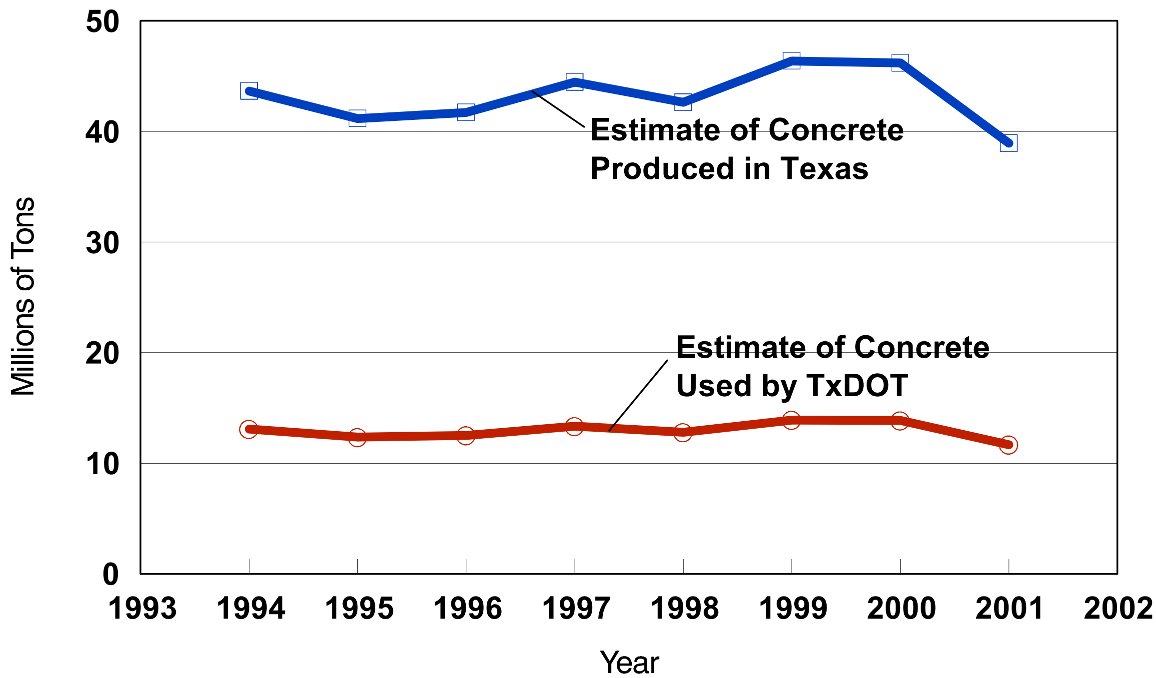

FIGURE 3 Estimated Production of Concrete in Texas and Portion Used by TxDOT