Potential for Reduced Greenhouse Gas Emissions in Indonesia Through the Use of High-Volume Fly Ash Concrete for Transportation Infrastructures

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Abstract: The objective of this study was to determine the potential for reductions in carbon-dioxide emissions in Indonesia by substituting high volumes of fly ash in concrete production and to identify the resulting benefits and challenges. From literature, it is known that fly ash can improve the properties of both the fresh and hardened concrete. High-volume fly ash (HVFA) can further improve workability, heat of hydration, strength, permeability, and resistance to chemical attack. From a power plant located in East Java, it is determined that tons of fly ash are produced annually and about 40 percent are generally sold for use in concrete or other end products. The estimated production of concrete in East Java determined that if 60 percent of the Portland cement used in East Java concrete production were replaced with fly ash, carbon-dioxide emissions could potentially be reduced by million tons annually.

Key Words: carbon-dioxide emissions, chemical attack, concrete, high-volume fly ash, permeability

1. 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 two 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 (CO₂). 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 percent of CO₂ emissions come from the combustion of fossil fuels, and approximately 30 percent of those emissions are from the transportation sector. The next largest source of
CO₂ emissions is from the manufacture of cement and account for approximately 10 percent of all CO₂ emissions (U.S. Environmental Protection Agency, 1998). When faced with the challenge to reduce greenhouse gas emissions, policy makers have traditionally targeted the transportation sector and fossil fuel combustion, the largest CO₂ sources. This task has been difficult. A promising alternative is to target reductions in CO₂ emissions from cement manufacture through the substitution of fly ash (a coal combustion by-product).

Canadian researchers have determined that CO₂ emission reductions can be accomplished by substituting high volumes of fly ash (a material that is otherwise land-filled) as a replacement for cement (Bilodeau and Malhotra, 1999). The 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 (Swamy, 1999). It 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. In the present context of the world, 25 percent of the world’s population live in industrialized nations but they account for nearly 75 percent of the global energy consumption.

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.

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 is environmental impact and its durability. 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. 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. However, our experience has shown that neither can be achieved as a normal and natural consequence of the process of concrete fabrication.

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 (Mehta, 1994; Swamy and Laiw, 1995; Swamy; Rasheeduaazfar, 1992).

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 (Swamy and Darwish, 1997).

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.

The objective of this study was to determine the potential for reductions in CO₂ emissions in Indonesia by substituting high volumes of fly ash in concrete production and to identify the resulting benefits and challenges.

2. FLY ASH PROPERTIES, PRODUCTION, AND AVAILABILITY

2.1 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 sub-bituminous 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 sub-bituminous coals contains very little unburned carbon.

There are two general classes of fly ash: Class C, which is normally produced from lignite or sub-bituminous 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.

<table>
<thead>
<tr>
<th>Table 1 ASTM C618-98 specifications for fly ash</th>
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<tbody>
<tr>
<td>Class of Ash</td>
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<tr>
<td>Class C</td>
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<tr>
<td>Class F</td>
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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.

2.2 Production and Availability of Fly Ash in East Java
Utilities must report the production of coal combustion by-products at their facilities annually to the Department of Energy. 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 2 million tons of fly ash are produced annually in East Java and about 40 percent are generally sold to use in concrete and/or other end products. Just over half of the fly ash produced in East Java 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.

2.3 Typical Composition of Fly Ash from a Plant in East Java
Composition of fly ashes will vary from plant-to-plant. Table 2 shows fly ash composition from a selected plant in East Java.

<table>
<thead>
<tr>
<th>Table 2 Typical fly ash composition and properties</th>
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<tbody>
<tr>
<td>Chemical Analysis</td>
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<tr>
<td>Silicon Dioxide, %</td>
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<tr>
<td>Aluminum Oxide, %</td>
</tr>
<tr>
<td>Iron Oxide, %</td>
</tr>
<tr>
<td>SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$, %</td>
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<tr>
<td>Magnesium Oxide, %</td>
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<tr>
<td>Sulfur Trioxide, %</td>
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<tr>
<td>Moisture Content, %</td>
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<tr>
<td>Loss on Ignition, %</td>
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<tr>
<td>Available Alkalis as Na$_2$O, %</td>
</tr>
<tr>
<td>Calcium Oxide, %</td>
</tr>
<tr>
<td>Physical Analysis</td>
</tr>
<tr>
<td>Fineness: Amount retained on 325 sieve, %</td>
</tr>
<tr>
<td>Water Requirement, % control</td>
</tr>
<tr>
<td>Specific Gravity</td>
</tr>
<tr>
<td>Autoclave Expansion, %</td>
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<tr>
<td>Strength Activity Index with Portland Cement, %, 28 days</td>
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</tbody>
</table>
3. 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.

3.1 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 (Malhotra and Ramezanianpour, 1994). 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.

3.1.1 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.

3.1.2 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.

3.2 Effects of Fly Ash on Properties of Hardened Concrete

3.2.1 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”. 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.
3.2.2 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.

3.2.3 Resistance to ASR and Sulfates
Fly ash also improves the resistance of concrete to alkali-silica reactivity (ASR). 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.

3.3 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 percent) of low calcium fly ashes (Malhotra and Ramezanianpour, 1994). This research resulted in HVFA concrete with adequate early-age strength and workability, low temperature rise, and high late-age strength.

3.3.1 Setting Time
One of the barriers to using HVFA concrete by the industry is its increased time to set. A research was performed to measure times of set in accordance with ASTM C403 (Malhotra and Ramezanianpour, 1994). 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 hot season.

3.3.2 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.

3.3.3 Compressive Strength
High volume fly ash concrete exhibits adequate strength development at both early and late ages. Research 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.

3.3.4 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.

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.

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.

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 $500 \times 10^{-6}$ after 64 weeks of air drying.

4. POTENTIAL FOR CARBON DIOXIDE EMISSION REDUCTIONS

4.1 Quantity of Fly Ash Used in Concrete Production
Most concrete produced in East Java contains some quantity of fly ash. 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 East Java, 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. It is reported that tons of fly ash was sold in 2000. Some of this fly ash is used for stabilization purposes. If all of the fly ash which was sold in East Java 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 percent of that being produced) in East Java is for use in the production of concrete in East Java.

4.2 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.
4.3 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?”

About 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 million tons. Most of the research on HVFA concrete has been performed with Class F fly ash because the work was done in East Java 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 East Java to verify the performance properties.

4.4 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. 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. 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 research with HVFA concrete has been performed with a Class F ash which is available in East Java. However, additional research is needed to verify performance with East Java 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.

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