Sustainable Construction Case History: Fly ash Stabilization of Road-Surface Gravel

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INTRODUCTION

In response to calls by world leaders, there has been a new international commitment to promote engineering and technology towards solving global development problems and environmental issues but with a whole new vision and approach. The world is becoming crowded; can we satisfy the growing needs and preserve quality of life? It will not happen by following the traditional patterns of growth but requires adopting new approaches. Development and growth need to be sustainable. The needs of current generations can not be met at the expense of future generations. The World Commission on Environment and Development (WCED) took the lead in outlining a sustainable future. *Our Common Future*, a report published by WCED[1] provides the following definition for sustainable development "a process of change in which the exploitation of the resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." The key concept behind this definition is meeting the needs of the present without compromising the ability of the future generations to meet their own needs; in other words, achieving "environmentally sustainable development" [2].

Sustainable development requires that engineers employ sustainable engineering practices that meet additional constraints in terms of environmentally being sustainable. This concept of environmentally sustainable project is often referred to in a short hand as *green* such as "green buildings" and "green highways." This paper presents one aspect of design and construction of green highways, i.e., use of recycled materials.

SUSTAINABLE CONSTRUCTION – GREEN HIGHWAYS

The Green Highways Initiative is a voluntary, collaborative, public/private effort designed to identify and promote streamlining and environmental stewardship in transportation planning, design, construction, and/or operation and maintenance through integrated partnerships, flexibility, rewards, and market-based solutions (http://www.greenhighways.org). The goal of this initiative is to foster partnerships for improving upon the natural, built, and social environmental conditions in a watershed, while sustaining life-cycle functional requirements of transportation infrastructure (safety, structural and service levels) – providing for conditions that are "better than before". The Green Highways Initiative lists 10 guiding principles; one of these principles is promoting use of recycled materials. Similar groups have been formed in other countries such as Canada, Brazil, and Norway besides the U.S.A. One of the focus areas currently identified for development of green highway partnerships and joint ventures in the Mid-Atlantic region of the United States is "Recycling and Reuse" (Industrial By-products and Recycled Material Uses and Implementation).

Millions of metric tons of coal combustion products (CCPs) are generated each year by U.S. power industries, and still large quantities are landfilled as solid waste at considerable expense and not beneficially used. However, many CCPs have desirable properties and leach contaminants at such low concentrations that their use as geo-materials in construction applications does not present an environmental hazard. There also has been a shift in societal attitudes resulting in strong interest in developing beneficial re-use markets for industrial by-products in the context of sustainable development. As a result, environmental regulations are being developed or modified to permit re-use of these materials in a variety of applications. In some cases, government contracts require that a minimum fraction of the construction materials be industrial byproducts.

Ideal applications for CCPs exist in the transportation, construction, and environmental industries, where large volumes of earthen materials and aggregates are used each year. In fact, fly ash (FA), bottom ash (BA), flue gas desulfurization (FGD) materials have been or are in the process of being beneficially used as highway construction materials.

Replacement of natural soils, aggregates, and cements with solid CCPs or minimization of their use is desirable. In some cases, an industrial by-product may be inferior to traditional earthen materials, but its lower cost makes it an attractive alternative if adequate performance can be obtained. In other cases, a by-product may have attributes superior to those of traditional earthen materials. Yet, in other cases, a by-product may enhance the properties of traditional earthen materials or other waste materials or byproducts in mixtures. Often select materials are added together with industrial by-products to generate a material with well-controlled and superior properties.

STRATEGIES FOR USE OF CCPs

Specific issues that relate to development of CCPs as geo-materials include[3]:

1. Identification of the application
2. Selection of the key properties required for the application
3. Environmental suitability

4. Selecting and implementing appropriate laboratory testing protocols
5. Modeling engineering behavior
6. Constructability and field verification of performance
7. Construction specifications
8. Long-term performance
9. Dissemination of technical information

Identification of appropriate geo-applications for a CCP is the most crucial step. This step requires consideration of the salient properties of the CCP and a comprehensive knowledge and understanding of geotechnical construction, economics, and environmental regulations. Each application requires a set of key properties that need to be evaluated for assessing the suitability of a given product. Properties related to design are needed, along with those important to constructability and environmental suitability. ASTM standards are the main source for information regarding measuring various properties of soil and rock; however, nearly all of these standards have been developed for naturally occurring earthen materials. Therefore, their direct application to CCPs is unwarranted without an investigation of applicability. Material handling and workability typically require field demonstration and trials for optimization.

The applications often evolve spontaneously; however, every new application needs to cycle through the 9 steps listed above to reach it full potential. Sometimes, these steps based on previous experience with a similar application require relatively less effort but sometimes the novelty of the application requires significant basic effort for full maturation of the application.

To illustrate the point, a CCP geotechnical application case history involving stabilization of a gravel road to form a base for hot mix asphalt in reconstruction of a county road in Minnesota is presented.

STABILIZATION OF GRAVEL ROADS AS BASE FOR PAVING

There are over 2.6 million km of unpaved gravel roads (53% of all roads) in the United States. Increased development, and its associated increases in traffic and vehicle loads, has put significant pressure on local governments to upgrade these roads at considerable expense. There is a strong interest in developing effective, convenient, and economic methods to upgrade these roads. One solution is to stabilize the existing unpaved roadway *in situ* using self-cementing CCPs and then to overlay the stabilized material with hot mix asphalt (HMA). In addition to the direct benefit of improved economy, CCP-stabilized gravel road recycling provides several additional advantages over alternative upgrade methods to convert to paved roads:

- Since road material is not removed from the site, a disposal area is not necessary.
- There is little change in grade from the original road surface; therefore, road narrowing is avoided by raising the grade due to additional materials.

- Scarce aggregate resources are not required. Aggregate availability is becoming an increasingly difficult problem.
- CCP that is used does not require disposal.
- Construction progresses quickly. An increasingly important issue.
- The final material has a high modulus and likely to have good durability against frost action.
- Rutting is not a problem.
- CCP-stabilized bases are more uniform than natural soils and reduce stress concentration and fatigue cracking.
- Construction can be done at significantly lower cost

Despite these advantages, this high volume application of CCPs has received little attention to date. However, this application can be expected to have major impact on fly ash markets once it is shown to work effectively and a rational design procedure is made available due to the enormous amount of gravel roads awaiting improvement. Minnesota has many gravel roads (109,000 km) some of which need paving and that is why we are conducting the research related to this application in Minnesota in respond to local needs. Successful application of the technology can result in significant savings (some estimates go as high as 66%) relative to conventional total reconstruction costs while also providing a beneficial use for an industrial byproduct. Life cycle costs are also expected to be lower, as stronger and longer lasting roads are obtained.

Despite the expected advantages, limited testing has been conducted on coarse-grained soils, especially gravels stabilized by fly ash. Moreover, the testing conducted to date suggests that strength and stiffness gains in coarser soils stabilized with fly ash may follow a different pattern than that observed in fine-grained soils. In addition, research by others on fly-ash stabilization of coarse soils has focused on stabilizing open-graded aggregates typically used in base course of highways, which have considerably lower fines content compared to road-surface gravels. Therefore, there is a specific need for an in-depth evaluation of strength, stiffness and durability gain of road-surface gravel with fly ash and establishing optimum mix characteristics. As a first step to demonstrate the efficacy of this approach, the authors worked with Chisago County to stabilize a segment of the gravel surfaced county road (CR 53) and to pave it (Fig. 1).

CASE HISTORY: RECONSTRUCTION OF CR 53, MINESOTA

A case history is described where Class C and off-specification self-cementing fly ashes were used to stabilize road-surface gravel (RSG) during conversion of a 3.5-km section of a gravel road to a flexible pavement in Chisago County, MN (≈ 88 km north of Saint Paul, MN)[4]. This approach is consistent with “green highways” concept where pavement base was formed without using any additional natural materials. It consisted of mixing fly ash (10% by dry weight) and water into the gravel surface (referred as road surface gravel – RSG) to a depth of 254 mm and compacting the mixture to form a firm base, and placement of a hot mix asphalt surface. A series of laboratory tests, i.e., California bearing ratio (CBR), resilient modulus (M_r), and unconfined compression (q_u)

Fig. 1. Gravel surfaced County Road 53 being stabilized in situ with fly to form a firm base to for asphalt pavement

tests, were conducted on samples of the RSG alone and the fly-ash stabilized RSG (referred as S-RSG) samples prepared in the field and laboratory to evaluate how addition of fly ash improved the strength and stiffness. *In situ* testing was also conducted on the subgrade and S-RSG with a soil stiffness gauge (SSG), dynamic cone penetrometer (DCP), and falling weight deflectometer (FWD). A pan lysimeter was installed beneath the roadway to monitor the quantity of water percolating from the pavement and the concentration of trace elements in the leachate with time. Column leach tests were conducted in the laboratory for comparison. Additional environmental monitoring program consists of monitoring temperatures and water contents within the pavement profile, and meteorological conditions (air temperature, humidity, and precipitation).

SITE CONDITIONS AND MATERIALS

CR 53 lies on a flat topography in this area formed in Pine City ground moraine (primarily classified as lean clay). Twenty one borings were performed along the length of the construction site that indicated presence of approximately 0.6-m thick gravelly clayey sand (RSG) fill forming the pavement structure. Its thickness was less than 0.3-m when sand subgrade was encountered. Groundwater level is about 1 m below the existing gravel road. The pavement fill was underlain mostly by silty sands (SM and SP-SM) or sandy low plasticity clays (CL and CL-ML) according to the Unified Soil Classification System. According to the AASHTO Soil Classification System, most subgrade soils at this site are A-2-4 with a group index (GI) of 0. Other subgrade soils classify as A-3, A-4, and A-5. CBR of the subgrade soils ranges from 5 to 33 (mean = 14).

The RSG samples consist of well-graded gravelly sand with fines mostly in the range of 11 to 14%. The sand content is consistently around 60% and the gravel content is about 25%. A composite sample of RSG is classified as gravelly clayey sand according to Unified Soil Classification system (ASTM D2487).

Fly ashes from Unit 7 and Unit 8 of Riverside power station at Saint Paul, MN were used for stabilization. Chemical composition and physical properties of the fly ashes are given in Table 1 along with the composition of typical Class C and F fly ashes as well as the ASTM and AASHTO specifications for class C fly ash. Calcium oxide (CaO) contents of Riverside 7 and Riverside 8 fly ashes are 24% and 22% and silicon oxide (SiO_2) contents are 32% and 19% respectively. CaO/SiO_2 ratios, which are indicative of cementing potential, are 0.75 and 1.18. Loss of ignition (LOI), which is the indication of the amount of unburned coal in the fly ash are 0.9% and 16.4%, respectively. According to ASTM C 618, Unit 7 fly ash is a Class C fly ash whereas Unit 8 fly ash is an off-specification (i.e., does not meet Class C or F specifications) self-cementing fly ash. In this project, 10% fly ash by weight was mixed with RSG.

Table 1. Chemical composition and physical properties of Riverside 7 and 8 fly ashes, typical Class C and F fly ashes, and specifications for Class C fly ash

PARAMETER	Percent of Composition				Specifications	
	Riverside 7*	Riverside 8*	Typical Class C	Typical Class F	ASTM C 618 Class C	AASHTO M 295 Class C
SiO_2 (silicon dioxide), %	32	19	40	55		
Al_2O_3 (aluminum oxide), %	19	14	17	26		
Fe_2O_3 (iron oxide), %	6	6	6	7		
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	57	39	63	88	50 Min	50 Min
CaO (calcium oxide), %	24	22	24	9		
MgO (magnesium oxide), %	6	5.5	2	2		
SO_3 (sulfur trioxide), %	2	5.4	3	1	5 Max	5 Max
CaO/SiO_2	0.75	1.18				
$CaO/(SiO_2+Al_2O_3)$	0.47	0.68				
Loss on Ignition, %	0.9	16.4	6	6	6 Max	5 Max
Moisture Content, %	0.17	0.32	-	-	3 Max	3 Max
Specific Gravity	2.71	2.65	-	-		
Fineness, amount retained on #325 sieve, %	12.4	15.5	-	-	34 Max	34 Max

*Chemical analysis and physical analysis provided by Lafarge North America

CONSTRUCTION

Fly ash was spread uniformly in strips directly over the gravel road until the width of the whole road cross section was covered. The fly ash was spread by special truckmounted lay-down equipment (Fig. 2). This equipment deposits fly ash with minimum dust and well-controlled thickness to meet the design mixing percent. Top 254 mm of working platform was mixed with fly ash using a CMI RS-650-2 road reclaimer. During the mixing process, water was added from a water tanker truck attached to the reclaimer to provide optimum water content. Immediately after the mixing process, a pad foot compactor and a vibratory compactor with steel drum were used to compact the mixture in sequence to complete the stabilization process (Fig. 3). Compaction was completed within 1 to 2h after mixing. The mixed material was compacted to a target relative compaction of 95% based on standard Proctor energy (ASTM D 698). The standard Proctor maximum dry unit weight was 21.9 kN/m^3 and the optimum water content of 6%. Working platform stabilized with fly ash was stiff and ready to be covered by HMA within 3 to 7 d. Asphalt pavement consisted of 51 mm non-wearing course and 38 mm wearing course (total 89 mm).Construction started on August 23, 2005 and ended on August 26, 2005. The bituminous non wear course was paved on September 8, 2005 and the bituminous wear course was paved on September 9, 2005.

Fig. 2. Spreading of fly ash on gravel road with lay-down equipment

RESULTS

Addition of fly ash improved the stiffness and strength of the RSG significantly. After 7 d of curing, the S-RSG prepared in the laboratory using materials sampled during construction had CBR mostly ranging between 48 and 90, M_r between 96 and 195 MPa, and unconfined compressive strengths between 197 and 812 kPa, whereas the RSG alone had CBR of 24, M_r of 51 MPa, and no unconfined compressive strength for being a granular material. CBR and unconfined compressive strength indicate how much load the material can support before failing and M_r indicates how deformable the material is under wheel loads. M_r is considered the primary pavement design property.

Fig. 3. Mixing process of fly ash, road-surface gravel, and water by a reclaimer (compaction is performed right after mixing by tamp-foot compactor seen in the background).

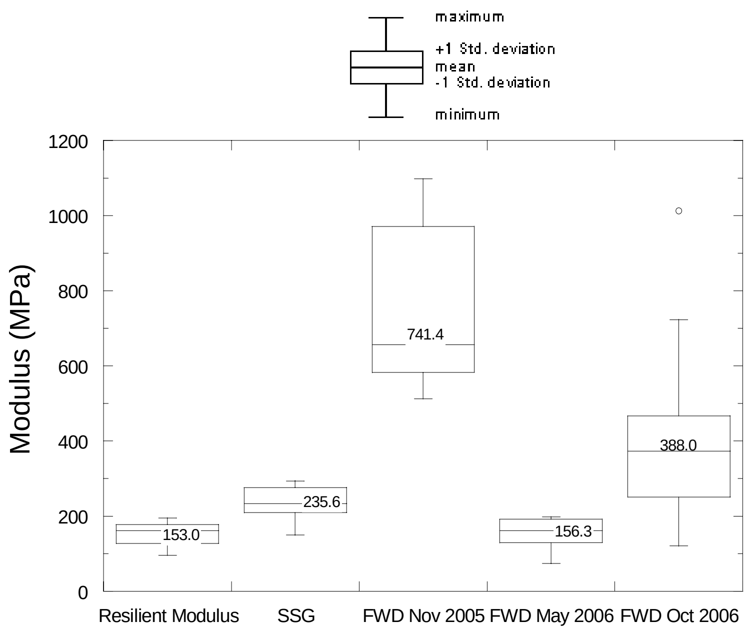

Fig. 4. Moduli obtained from different procedures and at different times

Moduli can also be obtained from the FWD inversion and from the stiffness measured with the SSG and are compared with those obtained from the resilient modulus tests on field-mix specimens in Fig. 4. Moduli obtained from the resilient modulus test in the laboratory on field-mix samples are markedly lower than those obtained from November 2005 FWD but comparable to those from May 2006 FWD. SSG gives 50% higher moduli compared to the modulus obtained from the resilient modulus test. November 2005 FWD data appear anomalously high compared to other data here and elsewhere and it is attributed to frozen subsurface conditions in November 2005. This is confirmed by the subsurface temperature and volumetric water content data shown in Fig. 5. The temperatures in the S-RSG layer are subfreezing and the volumetric water content gages do not register a reading when the pore water freezes. October 2006 FWD data appear to be more reasonable. The October 2006 FWD data are lower than November 2005 but higher than May 2006 data consistent with seasonal effects. Laboratory freeze-thaw tests indicate 17% drop in resilient modulus of the S-RSG after 5 cycles of freeze-thaw. Confirmation of this in the field will require longer term monitoring with FWD tests.

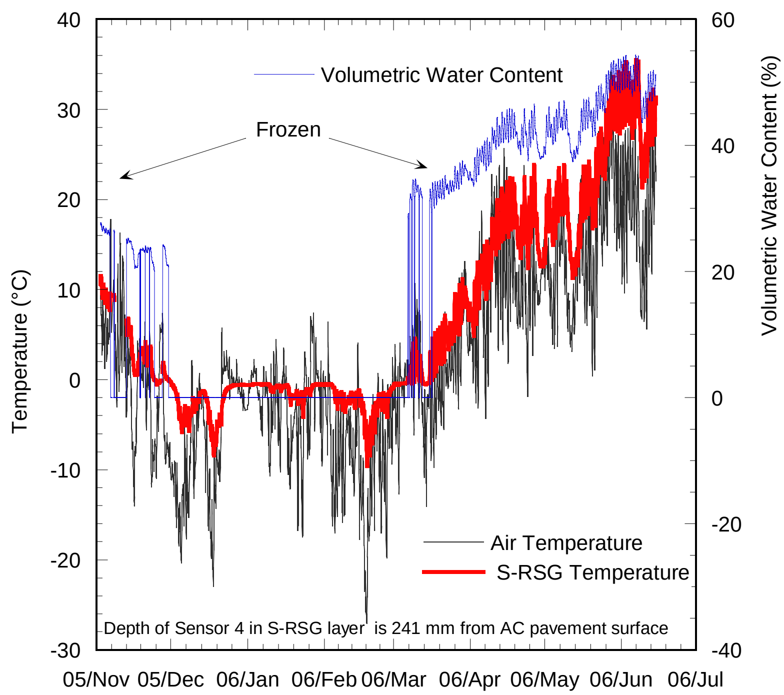

Fig. 5. Air temperature and temperature and volumetric water content of fly ash-stabilized layer

The pan lysimeter that was installed beneath the roadway to monitor the quantity of water percolating from the pavement and the concentration of trace elements in the leachate is 4 m wide, 4 m long, and 200 mm deep and is lined with 1.5-mm-thick linear low density polyethylene geomembrane. The base of the lysimeter was overlain by a geocomposite drainage layer (geonet sandwiched between two non-woven geotextiles). S-RSG was placed in the lysimeter and compacted using the same method employed when compacting S-RSG in other portions of the project. Photographs showing the lysimeter construction are in Fig. 6.

Fig. 6. Construction of pan lysimeter under 7th Avenue before fly ash stabilized base is constructed and the street is paved. Lysimeter collects percolating water through the pavement and fly ash stabilized base for quantity and quality determination.

Approximately 29.6 m^3 of leachate corresponding to 3,183 mm of total drainage occurred in the lysimeter during the monitoring period from November 2005 to June 2006. This corresponds to 48 pore volumes of flow by June 15, 2006. The low lying topography of the area and the heavy precipitation that occurred in Spring 2006 may have led to flooding of the lysimeter as these are very high numbers. All of the trace element concentrations (with the exception of Mn) are below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs). Most of the concentrations appear to be stabilizing and persistent. Concentrations of some elements appear to be low and decreasing (e.g., Pb, Sb and Sn).

The trace element concentrations in the column leach test (CLT) effluent typically are higher than concentrations in the drainage collected in the field in the lysimeters. The poor agreement suggests that the CLT test method that was used may not be appropriate for evaluating leaching of trace elements from S-RSG, unless a conservative estimate of the trace element concentrations is acceptable. It is also possible that flooding of the lysimeter by water entering laterally may be responsible for dilution of trace elements. Longer term monitoring of the lysimeter is planned. Despite the higher concentrations obtained from the CLT, most of the elements have concentrations below USEPA MCLs and Minnesota HRLs. The exceptions are B, Be, Cr, Ba, As, and Se. Additional study is also needed to define laboratory leach testing protocols that can more accurately simulate leaching of trace elements from S-RSG.

A user-friendly computer model (WiscLEACH) was developed to predict the maximum concentration of chemicals in groundwater adjacent to roadways using fly ash stabilization[6]. Analyses with WiscLEACH showed that in most cases where fly ash is placed above the groundwater table, impacts to groundwater are negligible. However, the level of impact depends on the type and amount of metals in the fly ash. The previous research on leaching from fine-grained subgrade soils stabilized with fly ash suggests this problem is unlikely. Nevertheless, this environmental aspect requires further scrutiny when gravel roads or recycled pavement materials are stabilized because these materials have lower soil fines content compared to soils predominantly fine-grained, which could result in less attenuation and more leaching than associated with stabilized subgrade soils. In addition, an environmental evaluation will be needed to satisfy state environmental protection agencies that the technology is safe both in the short-term but also in the long-term since leaching is a slow process.

SUMMARY AND CONCLUSIONS

Industries worldwide produce millions of metric tons of by-products annually. Only small portions of these materials are used beneficially; most are landfilled as solid waste. Large quantities of non-hazardous industrial by-products can be used beneficially as geo-materials in civil construction, especially in the transportation sector. Such recycling will save millions of dollars annually to the industries in avoided landfill costs, generate cost-effective alternatives to traditional aggregates, minimize environmental damage and energy consumption due to aggregate mining, and provide engineers with new construction materials sometimes with superior qualities and cheaper than natural materials. Sustainable development requires that engineers employ sustainable engineering practices that meet additional constraints in terms of environmentally being sustainable. Recycling is an important element of green highways initiative. Expansion of beneficial use of industrial by-products requires a well-planned and deliberate development plan. The elements of such a plan have been presented and demonstrated with a case history where Class C and off-specification cementitious fly ashes (10% by weight) were used to stabilize road-surface gravel (RSG) during reconstruction of a gravel road as asphalt paved.

Moduli obtained from the FWD inversion of the stabilized layer are compared with those obtained from the resilient modulus tests on field-mix specimens and the moduli computed from the stiffness measured with the SSG. Overall modulus is comparable or higher than the modulus of crushed rock a year after construction. It may increase due to further hydration reactions or decrease due to frost action and wet conditions. Longer-term monitoring is needed to confirm that the modulus of fly ash-stabilized road surface gravel will persist after multiple winter seasons. Chemical analysis of the draining leachate from the stabilized layer showed that the concentrations of many trace elements are reasonably steady toward the end of the monitoring period (about 1 year). Furthermore, during the monitoring period, all of the concentrations (with the exception of Mn) were below USEPA maximum contaminant levels (MCLs) and Minnesota health risk levels (HRLs) established by the Minnesota Department of Public Health.

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