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EARTH MASONRY UNIT: SUSTAINABLE CMU ALTERNATIVE

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ABSTRACT: This paper provides a justification for a masonry building block fabricated from soil materials that could radically improve the environmental profile of concrete masonry. Conventional concrete masonry units depend on the reaction of ordinary Portland cement to provide strength and durability. While effective at meeting structural requirements, a study has shown that production of ordinary Portland cement causes 6-7% of global greenhouse gas emissions. In contrast, the principal component of stabilized earth mix designs is soil, a ubiquitous, innocuous, and almost unlimited resource that offers the potential of sustainable cradle-to-cradle environmental performance over a full life cycle of products. The paper presents research investigating the characteristics of a range engineered soil blends and natural soil sources. The research is applied toward the production of an environmentally sustainable stabilized earth masonry building block capable of meeting current ASTM concrete block performance specifications while reducing embodied energy by as much as 50% due to the reduction of energy-intensive Portland cement binders, dramatically reducing CO_2 emissions of one of the most common construction materials on the planet.

Keywords: Sustainable Construction Materials, Concrete Masonry, Sustainable Architecture, Nanotechnology

1. INTRODUCTION

This paper presents a vision and justification for developing a reduced cement structural masonry building block fabricated primarily from soil materials that could reduce a significant amount of green house gas emissions, radically improve the environmental profile of one of the most common construction materials on the planet. The paper discusses existing concrete masonry unit (CMU) manufacturing practices and their associated impacts, as well as come techniques currently in use to incrementally improve environmental impacts. These conventional practices offer a backdrop against which as radical cement-free block is proposed that would make use of advances in nanotechnology and geopolymerization. The paper briefly describes the current masonry marketplace in the US, identifying the commercial potential of a cement-free masonry building block, and sketches a development pathway to take advantage of the opportunity. These arguments provide justification for the development of a structural masonry building block fabricated from engineered soil materials.

2. BACKGROUND AND CONTEXT

Concrete is the most voluminous manufactured product in the world, with annual consumption approaching 20,000 million metric tons (MMT). The production of each metric ton of cement results in roughly 900 KG of CO_2 released into the atmosphere [1] and a study has shown that production of cement causes 6-7% of global greenhouse gas emissions [2]. CMUs, the technical term for common concrete masonry blocks used in construction, are ubiquitous unitized building materials that contain between 10-16% cement by weight. In 2007, 8 billion CMUs were produced in the US, requiring the use of approximately 15.2 million metric tons (MMT) of cement. The manufacture of this cement released approximately 13.7 MMT of CO_2 into the atmosphere. This represents approximately .25% of the 6,000 MMT of CO_2 emissions resulting from energy and industry overall in the US during the same year [3].

The standard CMU is a rectangular 200x200x400 mm (8x8x16-inch) unit comprised of ordinary Portland cement (OPC), gravel, sand, and water. The concrete mixture may also contain ingredients such as supplementary cementitious materials (SCMs), accelerators, retarders, and plasticizers governing setting time and workability, air-entraining agents, coloring pigment, and water repelling admixtures. During the conventional CMU manufacturing process, a machine molds moist, low-slump concrete into the desired shapes, which undergo accelerated curing at elevated temperatures inside a semi-enclosed curing chamber. This is generally followed by a drying and storage phase. The manufacture of CMUs has been characterized by modest, incremental improvement since its introduction over one hundred years ago.

2.1 Environmental Impacts of Conventional Concrete Masonry Units

A cradle to gate LCA study conducted by the Portland Cement Association in 2007 indicates that

91% of the GHG released by the manufacture of CMUs are attributable to the OPC constituent used as a binder [4]. This is mainly due to the intense heat required for cement manufacture, together with the CO_2 released during the calcination phase, in which the raw limestone is converted to calcium oxide and CO_2 [5]. It follows that reducing the cement content of a CMU will significantly reduce its overall environmental impact.

Currently, the leading method for reducing the environmental impact of concrete is to replace a portion of OPC binder constituent with SCMs. This class of materials includes fly ash, silica fume, metakaolin and natural pozzolans. In practice, the most commonly used SCMs are industrial by-products such as fly ash and ground granulated blast furnace slag, due to their low cost and widespread availability. When added to concrete mixes, it has been demonstrated that these materials can reduce the need for OPC binders significantly [6], effectively reducing GHG emissions with only small reductions of strength and durability. However, despite widespread use of fly ash and other SCMs derived from industrial byproducts as a means to reduce embodied energy in the manufacture of concrete, recent research suggests that their use may be limited by geographical availability, and that these materials may also contain significant hazards to human health.

Toxicity is the most pressing issue with respect to SCMs derived from industrial byproducts. The composition of fly ash, one of the most plentiful and widely-used OPC substitutes, varies widely with fuel source, and has been shown to contain such highly toxic elements such as arsenic, beryllium, cadmium, chromium and lead, among others, along with dioxins and polycyclic aromatic hydrocarbons compounds in concentrations that can be up to several percent of the total material [7]. Questions remain as to whether the hydration reaction of fly ash and cement is capable of sufficiently immobilizing the toxic elements in fly ash and leaching of heavy metals, which is of special concern where concrete comes into contact with water [8,9]. Past experiences with lead paint, asbestos and arsenic-treated wood should prevent the widespread use of a product until the impacts on human health [7] are fully understood, and additional research is needed to assure the non-toxicity of concrete incorporating significant amounts of fly ash and other SCMs over the life of these materials, particularly where residential construction is concerned.

Issues of toxicity aside, inadequate supply of conventional SCMs in proximity to areas with the greatest demand for cement presents another problem. In 2010, the annual global demand of cement was close to 3,300 million tons [10], while the global combined production of fly ash, iron and steel slag, and silica fume accounted for 750 million tons [11,12,13], much of it highly toxic and potentially unusable.

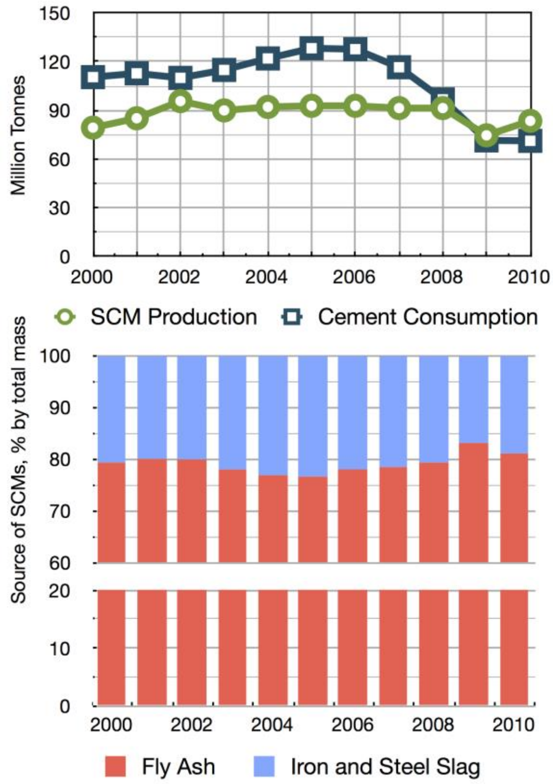

Fig. 1 Evolution of SCM production and cement consumption in U.S. [10-12]

As shown in Figure 1, between 2000 and 2010, fly ash accounted for approximately 80% of the production of these SCMs in the U.S. Life cycle analysis shows that transporting fly ash more than 50 miles from its origin dramatically increases its environmental impacts, reducing its viability as a cement replacement [14]. Fly ash and other combustion co-products must be produced in proximity to cement production sites to ensure their economic and environmental viability as a sustainable cement substitutes.

Cost-effective fly ash availability around the country corresponds to the pattern of coal-fired plant distribution from which it is derived, resulting in uneven geographical availability, as portrayed in Figure 2. For example, in the North, South East Central, and West North Central regions, fly ash production exceeds cement demand. In contrast, other regions such as the Northeast and West Coast US produce insufficient amounts of fly ash to maintain pace with demand, limiting its use as a viable sustainable cement replacement in these areas. Even where fly ash is available in significant quantities, as fly ash is transformed from a liability to a co-product that can be sold at a profit, its widespread utilization as an OPC substitute could subsidize coal-fired electricity generation, which is currently responsible for 20% of the world's total GHG emissions [16].

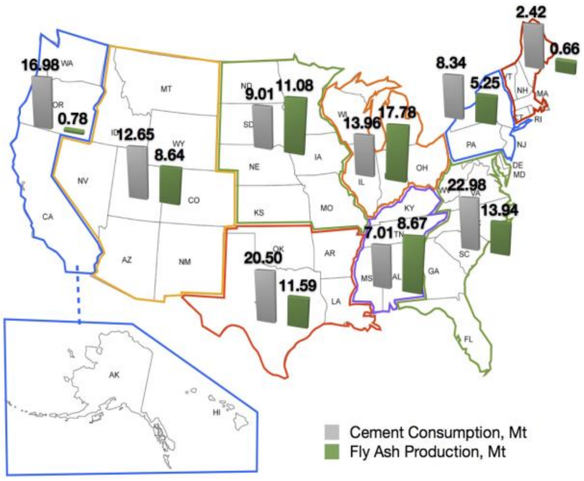

Fig. 2 Cement consumption and fly ash production by US regions in 2007 [10,15]. Fly ash production is estimated from coal consumption data, assuming that 10 tons of coal produce 1 ton of coal combustion products (CCP) [15] and approximately 70% by weight of the total CCP corresponds to fly ash [11]

Despite their growing popularity, the incorporation of conventional SCMs are at best a partial solution to reduce the environmental impacts of cement, and in some cases can even have the opposite effect. The toxicity of the many SCMs discourages their widespread use, particularly in residential applications and where concretes come in contact with moisture. Finally, a geographically uneven supply requires transporting SCMs long distances, adding to their embodied energy and limiting their effectiveness as sustainable cement alternatives.

3. EARTH MASONRY UNITS

In contrast to the incremental environmental gains offered by conventional SCMs derived from industrial byproducts, properly engineered stabilized soils have the capacity to radically transform traditional concrete-based masonry products at a global scale. Soil, the principal component of stabilized earth materials, is a ubiquitous, innocuous and almost unlimited resource that promises the possibility of sustainable cradle-to-cradle life cycle performance.

CMUs typically contain between 10-16% OPC by weight. In contrast, masonry blocks made with minimally processed engineered soil blends are capable of fulfilling the mechanical and durability requirements of contemporary structural applications with as little as 5% OPC content and no additional SCMs, significantly reducing environmental impacts without sacrificing strength and durability. However, challenges must be met before reduced-OPC masonry blocks composed of engineered soil materials will be capable of meeting the structural requirements of CMUs.

3.1 Earth masonry materials: opportunities and limitations

Earth-based masonry building materials have been used extensively over the last half-century in civil engineering projects, but poor durability due to the ingress of water [17] has limited their broader acceptance as a replacement for conventional concrete and masonry products. However, research suggests that key aspects of the earth materials such as packing density, soil mineralogy, and type of chemical binder can be manipulated to improve overall durability, suggesting new uses and applications for these materials.

3.1.1. Packing Density

The pore structure of the mixes is the major factor controlling the durability of the soil cement materials. The size and the pore connectivity in the stabilized earth system are linked to the pressure applied, the packing efficiency, and the moisture content. An optimization of the gradation ensures a better packing of the particles and therefore less inter-particle space [18]. The results are mixtures with high density, and lower water and binder demand. Therefore, these mixes will have higher resistance to freeze-thaw damage.

3.1.2 Quantity and Type of Microfines

The amount of microfines (P200 material), together with their mineralogy, is another important factor with direct impact on the durability of the earth masonry materials. Different soils exhibit diverse mineralogies depending on their geographic location, but a common attribute of soils suitable for stabilization is the presence of clay minerals. The presence of clay minerals plays an important role in the durability of the overall material due to their water absorption demand. The effects of quantity and type of P200 material on dry density and water absorption of soil-cement are illustrated in Figure 3. Increasing content of P200 materials with significant content of clays reduces packing efficiency (low dry density) causing an increase in overall porosity and water absorption.

Different strategies based on the nature of the clay minerals can be adopted to mitigate the clay mineral water demand. These strategies can be classified as traditional and non-traditional techniques. The use of cement, lime, fly ash, and bituminous products are considered traditional techniques. Other less conventional methods are the use of ionic stabilizer, lignosulfonates, salts, or enzymes. The objective of these two types of products is to impair the water demand of the clay minerals. This is achieved through a variety of mechanisms such as cation exchange, flocculation and agglomeration, pozzolanic reaction, and basal charge destabilization, among others. These treatments have shown to be effective on the stabilization of pavement subgrades [19, 20]. The type of clay mineral to be stabilized dictates the suitability of each particular treatment.

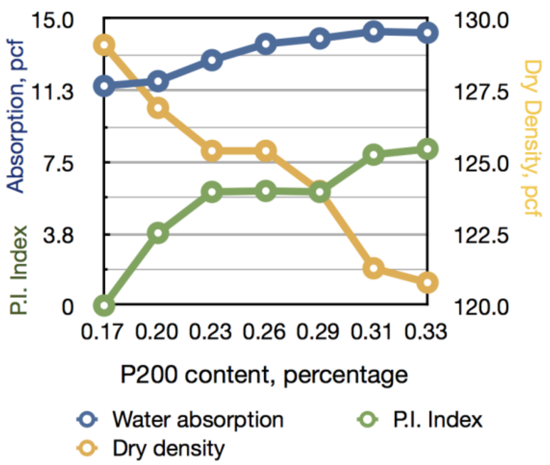

Fig. 3 Effect of varying P200 content and plasticity index (P.I.) on dry density and water absorption of soil-cement materials. Note: 1 pcf is equivalent to 10.018 Kg/m^3

3.1.3 Chemical Binder

Finally, the type and amount of chemical binder is another factor with a high degree of influence on the final performance of the product. Portland cement is the most widely used binder on stabilized earth materials. However, the cement content can be significantly reduced with adequate optimization of above factors. Research conducted to date has established positive results designing size-engineered mixtures of soil and aggregate by-product stabilized with 6% Portland cement by weight to produce a reduced-cement earth masonry building units that meets the compressive strength, water absorption and wet-dry durability of the ASTM C90 Standard Specification for Loadbearing Concrete Masonry Units and ASTM D559 Standard Specification for Wetting and Drying Compacted Soil-Cement Mixtures. These results already represent a 40% reduction in cement from a conventional CMU.

While significant challenge remain to be solved, packing density, microfine ratios, and careful control over chemical binders have the capacity to transform traditional concrete-based masonry products at a global scale.

4. NANOTECHNOLOGY IN EARTH MATERIALS

The application of advances in nanotechnology is another approach that offers great promise in addressing the lack of durability in conventional earth masonry products. It is instructive to look at the evolution from regular to high-performance concrete in this regard. Continuous refinement of the particle size of the additives played an important role in making the transition to high strength concretes as illustrated in Figure 4. Similar understanding of characteristics at the nano scale can be applied to earth masonry to increase its strength and durability.

In earth materials, the specific surface area of the microfine fraction can be modified to influence the void fraction and the capillarity suction of stabilized earth materials [22, 23]. Currently, the aggregate industry offers a wide selection of mineral products and by-products that can be used to engineer the soil's finer fraction from 150 microns down to nanoscale. This enables significant enhancements to the overall performance of the material and, more precisely, the durability of the finished product.

Current scientific advances in nanomaterials may further reduce the energy-intensive cement content in earth masonry building blocks in the future. As an example, the precipitation reaction of the Portland cement binder can be improved by the addition of nano-size materials, which is known as nano-seeding effect. This approach has been proved to be successful to accelerate the hydration reaction of Portland cement and its degree of hydration [24, 25].

The characterization of amorphous hydration gels responsible for the cohesiveness and strength of cementitious materials is another promising area. Thanks to the progress in analytical technique, the structure of these gels can be characterized down to nanoscale, and correlations have been established with mechanical performance at the microscale. The structure of calcium silicate hydrated gel (C-S-H) formed during the hydration of Portland cement has been well studied [26, 27]. Significantly, recent studies have indicated that calcium aluminum silicate gels [28, 29] and minerals [30] could achieve even better performance than C-S-H.

It is hypothesized that smaller amount of these gels would need to be nucleated to improve the durability in earth masonry than in cement-based materials. Earth masonry products are dense systems characterized by aggregates with a high degree of connectivity.

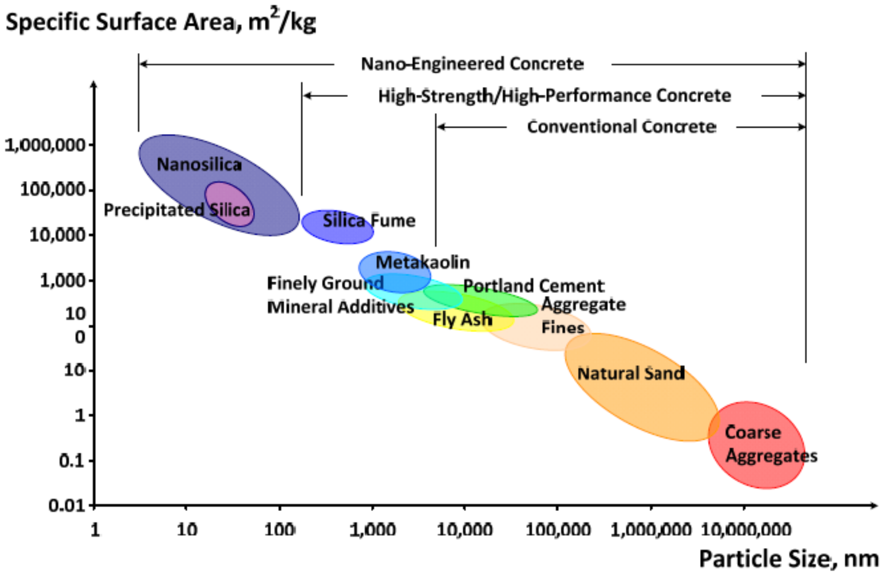

Fig. 4 Particle Size vs. Specific Surface Area of Principal Components and SCMs of Concrete Materials [21]

It is therefore logical to assume that slight chemical reactions at their surface might potentiate the formation of new amorphous phases. The new-formed phases will reinforce the connectivity between particles through direct chemical bond or through cohesiveness attractions (Van der Waals forces). This connectivity among aggregates is capable of creating a rigid skeleton inside the matrix of the earth specimens, contributing to the overall improvement of the integrity and durability of the system.

Applying current advances in nanotechnology offers great promise in generating a new class of earth masonry materials capable of delivering structural performance with significantly reduced environmental impacts.

5. MASONRY MATERIALS MARKETPLACE

The green building industry currently represents a US$49B market in the US and is the fastest growing segment of the construction market. It is characterized by the following attributes:

- 280% growth in 5 years, from $17B in 2005 to $49B in 2010
- Green Building market is projected to be $96–140 billion market by 2014
- $14.3B (12% of total) of this will be spent on masonry materials

The authors have co-founded a company dedicated to the development of a new class of durable sustainable masonry building blocks called Earth Masonry Units (EMUs) capable of offering reliable structural performance with reduced OPC binder content. To date the company has developed an environmentally sustainable masonry building block with recycled aggregates and 50% less cement than conventional CMUs that meets standard CMU specifications. The company has constructed two demonstration houses utilizing over 13,000 of these blocks, marketed under the name of E-CMUs. The company will continue to capitalize on its existing product line of E-CMU during the development of the transformational zero-cement EMUs. This phased market entry strategy will generate early revenue for the company that will defray development efforts for the future range of radically sustainable masonry materials and products.

Fig. 5 Watershed Materials' demonstration house under construction in the Bay Area of California. Photo by David Easton

6. CONCLUSION

This paper presents a vision for developing a structural masonry building block fabricated from soil materials. The adoption of the block in the US could reduce or eliminate the need for 15.2 million metric tons (MMT) of cement and the release of 13.7 MMT of CO_2 into the atmosphere. Moreover, soil-based masonry building block could represent a viable business opportunity. In contrast to the modest environmental gains offered by current practices aimed at reducing cement use, geopolymerisation of abundant minerals such as aluminosilicates has the capacity to radically transform traditional cement-based masonry products on a global scale. Soil, the principal component of stabilized earth mix designs, is a ubiquitous, innocuous and almost unlimited resource that promises the possibility of sustainable cradle-to-cradle environmental performance over a full life cycle of products. Using geopolymerisation to eliminate cement is a valuable social and environmental benefit to the public in the form of reduced CO_2 emissions, increased economic activity, and improved public health.

Existing CMU manufacturing practices are ripe for transformative change that a radical cement-free masonry block could provide. Such an effort could make use of existing manufacturing capability and distribution networks on the way to developing the commercial potential of cement-free masonry building block. These arguments provide justification for the development of a structural masonry building block fabricated from engineered soil materials.

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