LIME – A SUSTAINABLE "GREEN" BUILDING PRODUCT*

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Abstract

This paper suggests that lime is both a sustainable and "green" building product. Sustainability is assessed through examination of limestone as a natural resource, energy requirements for lime production, and the carbon balance. Limestone availability is reviewed in the context of consumption, the limestone geochemical cycle, and the natural formation of limestone. Energy-efficiency in lime production and the carbon cycle in the production and use of lime are discussed. The "green" attributes of lime as a building product are presented. These attributes are discussed in terms of how the use of lime may assist in "green" building certification under programs such as LEED™.

Keywords

Lime, sustainable, green, building product

1 Introduction

This paper presents the hypothesis that lime is both a sustainable and "green" building material, and provides arguments in support of this hypothesis. As the issue of sustainability is a relatively new

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one, and one with a broad scope for exploration, the arguments presented are meant to provide direction and a framework for further discussion.

The first part of the paper presents arguments that lime production is a long-term sustainable activity. Macro-scale factors that influence limestone availability and process energy requirements to convert limestone to lime are examined in the context of current sustainability thinking.

The second part of the paper argues that lime is a "green" building product. This is done through examination of lime's "green" attributes as a building product and certification criteria under programs like LEED™ (U.S. Green Building Council).

2 Sustainability of lime production

Sustainable development has been defined as:

> "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987)

In this context, the production and use of lime can be said to be sustainable if these activities can be carried on through many future generations, say the next 10,000 years, without impairing those future generations in some way. The authors will argue that the production and use of lime for another 10,000 years, and indeed for far longer, is entirely feasible based on resource availability and current technology.

2.1 Limestone

Limestone is the common name for the family of rocks containing calcium and magnesium carbonates. Carbonate rocks are those that contain a salt of carbonic acid (they contain the anion CO_3). More specifically, limestone is composed primarily of the mineral calcite (calcium carbonate – $CaCO_3$) and/or the mineral dolomite (magnesium carbonate – $MgCO_3$), along with small amounts of other minerals. There are three distinct types of limestone that are defined by their magnesium carbonate concentrations:

a. Dolomitic limestone consists of 35 to 46% magnesium carbonate.
b. Magnesian limestone consists of 5 to 35% magnesium carbonate.
c. High-calcium limestone contains less than 5% magnesium carbonate.

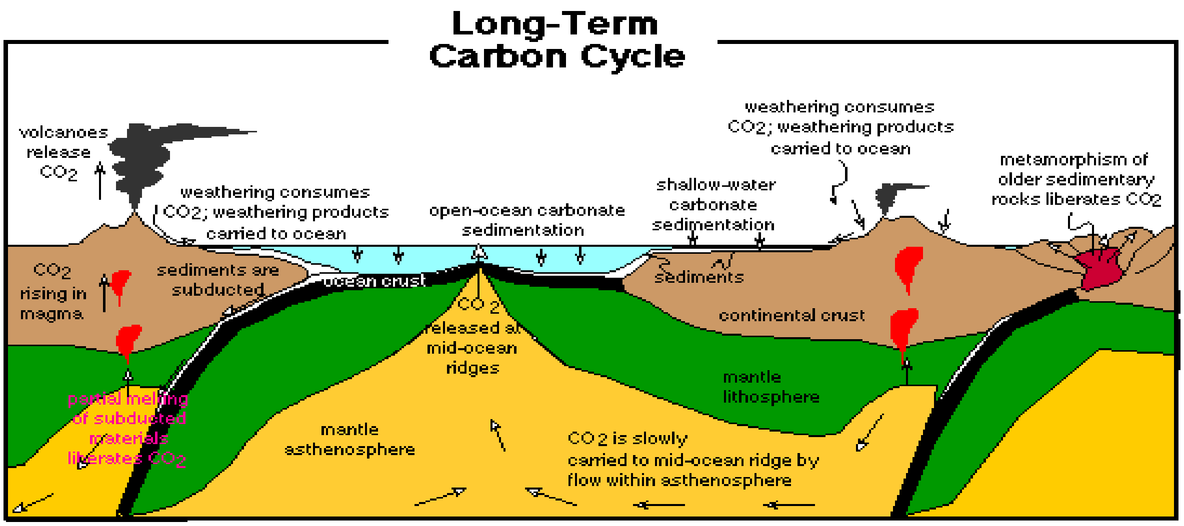
Limestone is an extremely abundant sedimentary rock. It is widely dispersed and is found on all continents on Earth. Limestone is continually being created and destroyed through natural processes of sedimentation and weathering. At present, more limestone is being created than destroyed through these natural processes (Bice, 1999; Morse and Mackenzie, 1990).

Limestone is an intimate part of the global carbon, calcium, and magnesium cycles, in that limestone acts as a large reservoir of these elements. Figure 1 below provides a diagrammatic representation of the long-term carbon cycle.

In Figure 1, limestone formation is represented as carbonate sedimentation. Limestone is formed by compaction of the remains of coral animals and plants on the bottoms of oceans around the world. The calcium and magnesium required for limestone formation in the oceans comes from both weathering of limestone on the continents and weathering of calcium/magnesium-bearing non-carbonate rocks such as calcium silicates.

In theory, a given atom of calcium can travel in a cycle over millions of years. From the Earth's surface, the calcium atom would weather and be transported to an ocean, where it would form limestone through sedimentation, (and then possibly undergo a subsurface loop of subduction and reintroduction into the ocean to sediment again) and then would be thrust back to the surface to start the process over again.

From a carbon perspective, the weathering of limestone and subsequent precipitation and sedimentation as new limestone is carbon-neutral. The weathering process consumes carbon dioxide from the atmosphere and the precipitation process releases the same carbon dioxide. However, in weathering of calcium/magnesium bearing non-carbonate rocks, the precipitation of the calcium/magnesium as carbonate and the sedimentation as new limestone is not carbon-neutral. Carbon dioxide from the atmosphere is consumed in this process.



Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation extracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly – if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

Figure 1: Long- Term Carbon Cycle (Bice, 1999)

There is an estimated 875 million billion tonne of limestone in the earth's crust (Morse and Mackenzie, 1990, pg, 578). The current net increase in limestone from natural processes is estimated to be on the order of 500 million tonne per year.

The current long-term net production of limestone through natural processes would have the effect of drawing down the atmospheric concentration of carbon dioxide. Morse and Mackenzie estimate that the atmosphere would be devoid of carbon dioxide in only 5,000 years as a result of this process, if there were no offsetting processes to regulate atmospheric carbon dioxide (1990, pg. 502).

Miller estimates current global lime production at 117 million tonne per year (2004a), which consumes about 209 million tonne per year of limestone.[3] If lime production were the only use of limestone, these figures imply that there are over four billion years of raw material supply available.

Of course, lime production is not the only use for limestone. Cement production also consumes limestone as a raw material. Van Oss estimates current global cement production at 1.86 billion tonne per year (2004), which consumes over two billion tonne of limestone per year.[4] Even at this level of combined lime and cement production, there is a 375 million year supply of limestone.

Clearly, from a limestone raw material perspective, lime production meets the 10,000 year criteria and can be considered sustainable. Indeed, the supply of limestone is so vast and widely dispersed that consideration of commercially-available current supplies as a limiting factor is not necessary (Miller, 2004a). To go further, limestone availability is potentially perpetually self-sustaining through geochemical processes working on long-term time scales (i.e., calcium in cement produced today will likely have weathered, been carried to an ocean, precipitated as calcium carbonate, formed limestone through sedimentation and been thrust back to the Earth's surface over 375 million years).

2.2 Lime production

Lime is produced through the process of calcining limestone. The limestone is subject to intense heat in a kiln in order to release or dissociate carbon dioxide from the stone. Carbon dioxide from this process typically goes into the atmosphere. The remaining material is calcium oxide or lime.

CaCO3	+	Heat	=>	CaO	+	CO2
Calcium carbonate				Calcium oxide		Carbon dioxide
Limestone				Lime		Carbon dioxide

Lime is a very unstable compound; it reacts easily with various materials. This reactivity is the reason for lime's usefulness and its use in so many applications. It also means that lime can easily revert back to limestone, as shown in Figure 2.

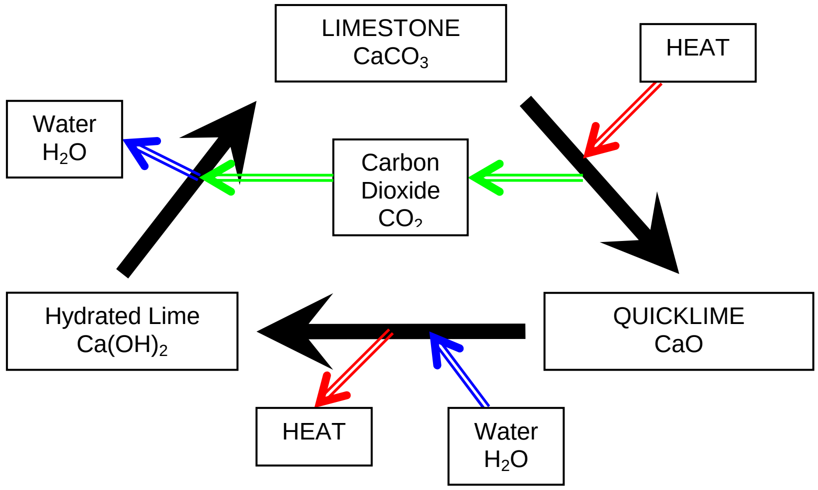


Figure 2: The Limestone, Lime, Hydrated Lime,

[3] Assumes pure calcium carbonate limestone; 1.79 tonne $CaCO_3$ per tonne CaO.
[4] Assumes an emission intensity of 0.51 tonne CO_2 per tonne cement and 2.27 tonne limestone per tonne CO_2.

Typically, the moisture in air is enough to create hydrated lime from lime that is left exposed to atmospheric conditions. If exposed for a longer period, the carbon dioxide in the air will recarbonate the hydrated lime back into limestone. This lime to limestone cycle occurs naturally in many end-use applications, such as most building lime applications. Up to 25% of carbon dioxide released from limestone during lime production is estimated to be reabsorbed by lime in end-use applications (U.S. EPA, 2004, pg 121-2). In this way, short-term net emissions of carbon dioxide from lime production are offset. In the long term, as we have seen above, carbon dioxide emissions from limestone used to produce lime would be neutral or net zero as a result of natural processes.

Lime production is an energy-intensive process. The theoretical minimum heat requirement to produce lime is 764 kcal/kg of lime (2.8 MMBtu per ton). As a practical matter though, the heat requirement will be greater due to heat loss from the lime kiln and related equipment. Kiln design, product requirements, and operating conditions will dictate energy intensity of lime production at any specific facility. For example, straight rotary kilns are typically required to manufacture lime used in steelmaking. Typical energy intensities appear in Table 1:

Table 1: Typical Energy Intensities of Lime Kilns (Oates, 1998)

Kiln Type	**Typical Energy Intensity (kcal/kg product)**
Vertical kilns	860 – 1,100
Preheater rotary	1,200 – 1,800
Straight rotary	1,550 – 1,800

While little reliable data on historical energy-intensity of lime kilns is available, energy-intensity of the lime production process has clearly improved considerably over the past few hundred years, as illustrated in Figure 3. Two hundred and fifty years ago, the energy requirement could have been as high as 5600 kcal/kg of lime.[5] At the turn of the last century, it was perhaps in the range of 3800 kcal/kg[6] to 1600 kcal/kg[7].

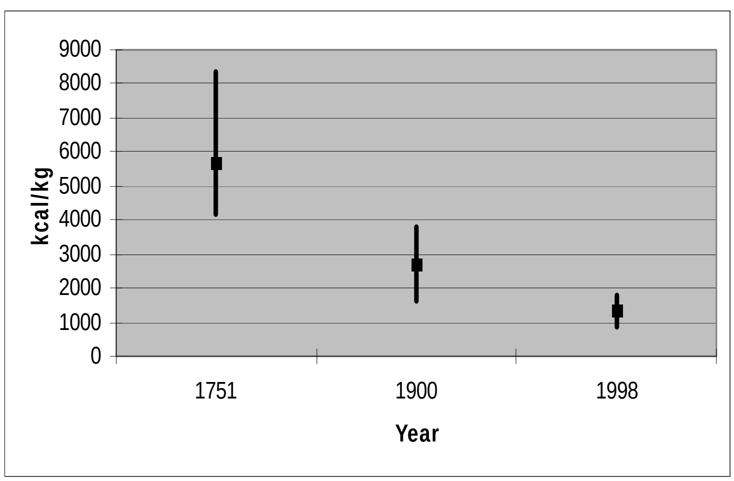


Figure 3: Historical Lime Production Energy Intensity

Today, the energy requirement of most energy-efficient kilns is an energy efficiency of 89% (89% of energy contained in the fuel is used to transform limestone to lime and only 11% of the energy is lost).

[5] Derived from Francis (1965)
[6] Derived from Azbe (No date), pg. 3.
[7] Derived from Eckal (1905)

Compare this to the energy-efficiency of a typical power plant, where about 35% of the energy is converted to electricity, or a combined-cycle heat and power plant, where about 80% of the energy is converted to electricity and usable heat, or an internal combustion engine, where about 20% of the energy is converted to mechanical work. The lime industry is an energy-efficient industry, both in terms of current average performance and proven leading edge performance.

From an energy and energy-related carbon dioxide perspective, lime production is also sustainable. Arguing that lime production based on fossil fuel use is sustainable over a 10,000 year time horizon is difficult given that reserves of fossil fuels are typically estimated at a much shorter time horizon. However, lime production based on biomass fuel use is sustainable. History tells us that biomass in the form of wood is a suitable fuel for producing lime; in fact, lime has been produced for thousands of years using this fuel.

An order of magnitude estimate indicates that a forested area of 15,700 square miles (4 million hectares), harvested on a sustainable basis, would be required to fuel today's Canadian and U.S. lime production.[8] This is an area about 65% of the size of West Virginia, or about 0.6% of forested areas in the two countries [Canada has about 400 million hectares of forest (Natural Resources Canada, 2004) and the United States about 300 million hectares (U.S. Department of Agriculture, 2001)].

3 Lime: a "green" building product

Lime can be assessed as a "green" building material on the basis of its "green" attributes and/or on the basis of how the use of lime can gain points towards "green" certification under a program such as LEED™ (Leadership in Energy and Environmental Design).

3.1 Lime attributes

Lime has many attributes that qualify it as a "green" building material. Lime is a low cost, natural material produced only through heating limestone. It does not contain or release toxic or harmful ingredients; in fact, it is likely to react with or absorb substances that are harmful in the built environment. Lime production is widely distributed just as limestone is. As a result, lime producers typically service a local market with minimal shipping distances.

Lime can be an important component of masonry, stucco and plaster systems. These systems have several "green" advantages:

- Each of these systems is durable and long lasting.
- In masonry applications, lime provides significant benefit despite being a small percentage of the mortar mix. Locally-available sand is a large part of the mortar formulation. For example, in a Type S cement-lime mortar formulation, the mix design (weight percent) is:
    - Lime 4.2%
    - Cement 19.8%
    - Sand 75.9%

  Mortar formulations containing only lime and sand contain approximately 15% lime.
- Each of these systems contributes to high thermal mass of wall assemblies. High thermal mass minimizes temperature swings by storing heat/cooling energy for release at later times. This reduces peak energy loads and reduces the size of the heating and/or cooling units required.
- Each of these systems can reduce indoor air pollutants. The Occupational Safety and Health Administration lists 13 possible interior pollutants (2002). A number of these pollutants can be

[8] Based on current average energy requirements, 148 cuft per Ha sustainable harvest, 32 #/cuft (air dry), and 6000 Btu/# (air dry).

reduced by use of a lime-based interior coating system. These systems contribute positively to indoor air quality as follows:

- Lime-based systems typically release only water vapor as they cure and dry.
- Interior hydrated lime-based systems help to remove impurities from air by reacting chemically with certain gases. Hydrated lime's ability to absorb carbon dioxide from the air to convert back to limestone is well known. The absorption of carbon dioxide strengthens the lime-based building material and can bridge and seal hairline cracks through a process called autogenous healing. The ability of hydrated lime to remove other pollutants, such as SO2 and HCL, from the air has been studied for pollution-control equipment (Gooch 1988), but not in wall systems. The ability of wall systems containing lime to react with these pollutants depends on environmental conditions near the wall and requires further study.
- The alkalinity of lime-based finishes, such as plaster, serves as a poor environment for growth of micro-organisms. Many lime-based mixes do not incorporate organic materials that could serve as food for mold species (Wiedner 2003).
- The addition of hydrated lime can favorably impact the vapor permeability of renders (Jacob 1989, pg 62-70).
- Lime-based mortars have been shown to resist water penetration through exterior walls (Brown 1979) (Matthys1988) (Schuller et al 1998). Reduction of water infiltration reduces the potential for mold growth within the building.

Furthermore, lime products can be used in several ways for developing sustainable sites for "green" building construction:

- Site Remediation - Lime products and lime kiln dust have been used with cement and/or pozzolans, such as fly ash, to remediate soils with low pH or heavy-metal contamination. The alkalinity of lime is beneficial in raising the soil pH and treating heavy-metal contamination. Studies performed under USEPA's BDAT program on contaminated soil show that cement- and lime-based stabilization/solidification processes can be effective for treating soils contaminated with arsenic, lead, zinc, copper, cadmium and nickel (Musser, 1990). Lime can also be added together with pozzolans, such as fly ash, to improve soil structure and further bind potential contaminants.
- Site Sub-Soil Improvement - Almost all fine-grained soils can be improved by the addition of lime. This is particularly true for clay soils of moderate- to high-plasticity. Lime modifies these soils by two mechanisms. First, lime agglomerates fine clay particles into coarse, friable particles through the substitution of calcium cations from the lime with cations normally present on the surface of the clay mineral. Secondly, lime can react with the available silica and alumina compounds in the soil to form a cementitious product (Boynton, 1980, pg.461). This can improve the soil by providing the following benefits:
  - Reduction of the plasticity index
  - Reduction in moisture-holding capacity
  - Swell reduction
  - Production of coarser and more friable soils that can be manipulated more easily
  - Improved stability
  - Ability to construct a solid work platform

  Lime-stabilized areas that undergo mechanical compaction can be quite hard and resistant to water penetration. Without compaction, however, permeability of the ground could increase due to the agglomeration of clay particles. Further work is needed in this area to define the potential impact of lime soil modification on site permeability and reduction of storm water runoff. Lime products can also be used to dry wet sites in order to speed construction.

- Top-Soil - Lime from treated biosolids provides alkalinity along with calcium and magnesium components that are beneficial for plant growth together with the organic matter from the biosolids. The addition of quicklime to biosolids is a cost-effective way to achieve “Class A” biosolids stabilization (Rothberg, Tamburini & Winsor, Inc.). “Class A” biosolids contain extremely low levels of pathogens and have few, if any, use restrictions. One common use for treated biosolids is as top soil in site reclamation. The U.S. EPA (2000) indicates that lime-treated biosolids provide the advantage of being:

  “*Consistent with the EPA’s national beneficial reuse policy. Results in a product suitable for a variety of uses and is usually able to be sold*.” (pg. 3)
- Limewash - Limewashes can be used as a reflective coating to reduce building heat island effect. The Building Research Establishment (cited in The British Quarrying and Slag Federation LTD, 1974, pg. 29) recommends the use of whitewash on bituminous roof coatings due to its high reflection coefficient. Limewashes have also been used as a roof coating to improve the energy efficiency of buildings (National Lime Association, 1955). Limewashes can be prepared from hydrated lime or lime putty for use as an exterior or interior coating. Limewashes are typically white in color, but can be tinted and are vapor-permeable. Traditionally, limewashes have been used as a protective coating over historic structures with weak masonry units.
- Water Treatment - Lime is used to treat drinking and waste waters. The lime is commonly used for neutralization and removal of silica and heavy metals from wastewater streams. The alkalinity of lime can be used to treat sewage and produce a useable “synthetic soil”, which has been discussed above.

3.2 LEED™

The Leadership in Energy and Environmental Design (LEED™) Green Building rating system has been developed by the U.S. Green Building Council to define and measure parameters that designate “Green Building” construction. The focus of this tool is to improve occupant well-being, environmental performance, and economic returns of buildings (U.S. Green Building Council, 2003).

The LEED™ rating system categories for new construction and major renovations (LEED-NC) and their associated point values are shown in Table 2. Each category is broken down into optional requirements called credits. Each credit has a point value. Buildings can be certified according to the LEED-NC rating system if a minimum of 26 points are earned out of a possible 69 total points. The four levels of certification for LEED™ are listed in Table 3.

Table 2: LEED Rating Categories

Category	Points
Sustainable Sites	14
Water Efficiency	5
Energy & Atmosphere	17
Materials and Resources	13
Indoor Environmental Quality	15
Innovative Design	5

Table 3: LEED Certification Levels

Type	Points Required
Certified	26-32
Silver	33-38
Gold	39-51
Platinum	52-69

Individual building materials cannot be LEED™ certified. They can, however, contribute toward obtaining certification for building projects. Lime can serve as an important ingredient in obtaining points in each LEED™ rating category.

3.2.1 Sustainable site credits potentially impacted by the use of lime

Credit 3 – **Brownfield redevelopment** –Lime can be used to remediate the site. Also, lime-treated biosolids can be used as an artificial soil or fertilizer as part of the site reclamation. Lime kiln dust or FGD scrubber sludge containing lime could also be used for site stabilization. Lime-treated soils from the site could potentially be beneficially reused for its reclamation. This would eliminate the need to remove unsuitable soils and replace them with offsite materials.

Credit 5.1 – **Reduce site disturbance** - Lime-based treatment technologies can be used to remediate sites and restore green space for previously-developed sites.

Credit 6.1 – **Stormwater management** – Through lime-soil modification at appropriate sites to provide more soil permeability, stormwater run off may be decreased.

Credit 7.1 – **Heat island effect: non-roof** - Limewashes can be used as a coating on absorptive exterior stucco, brick or block surfaces.

Credit 7.2 – **Heat island effect: roof** – Limewash can be used to increase roof reflectance.

3.2.2 Water efficiency credits potentially impacted by the use of lime

Credit 2 – **Innovative wastewater technologies** - A lime-based process could be used to treat 100% of the waste water to tertiary water quality standards.

3.2.3 Energy and atmosphere credits potentially impacted by the use of lime

Credit 1 – **Optimize energy performance** – Building wall systems that use lime provide high thermal mass to improve energy efficiency. The white color of lime, utilized in mortars or whitewash, will produce a more reflective surface on the exterior of the building.

3.2.4 Material and resources credits potentially impacted by the use of lime

Credit 1 – **Building reuse materials and resources** - Lime-based mortars, stucco and plaster have proven durability that allows for reuse of existing walls, floors, and roofs in structures that contain these products.

Credit 2 – **Construction waste management** – Bag wastes at the construction site can be eliminated by using lime blends that are packaged in bulk bags or delivered to silos on-site. Left-over lime can be used to stabilize soil or as a soil sweetener for agricultural application.

Credit 3 – **Resource reuse** - Old mortar, stucco and plaster could be crushed and screened for use as an aggregate in mortar or stucco mixes.

Credit 5.1 – **Regional materials: 20% manufactured locally** – High-calcium lime products used for stabilization, whitewash, and remediation applications are manufactured at facilities located throughout North America. Type S hydrated lime products are commonly used for masonry, plaster and stucco applications. As seen in Figure 4, most major North American metropolitan areas are within a 500-mile radius of Type S hydrated lime producers. Water, sand, portland cement and gypsum are raw materials that are used with lime to create mortars, stuccos and plasters. These materials are also available locally.

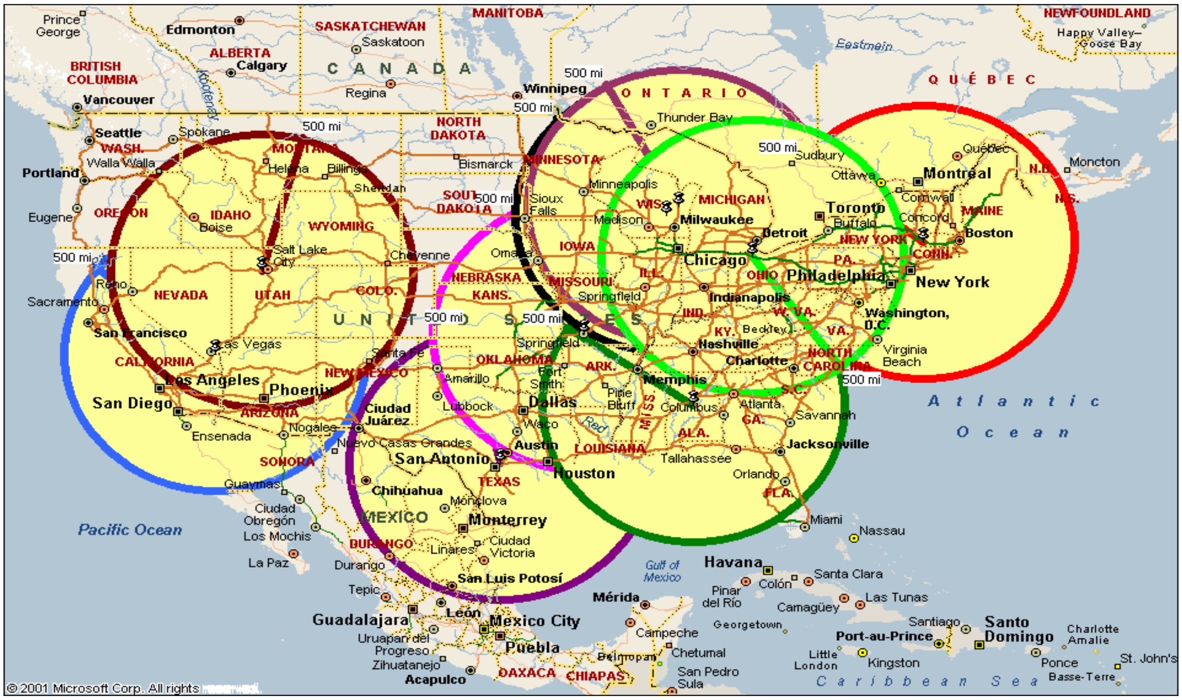


Figure 4: Areas (in yellow) within 500 Mile Radius of Type S Hydrated Lime Producers

Credit 5.2 – **Regional materials: 50% extracted locally** –Lime production economics favor extraction of limestone near the manufacturing facility. Therefore, lime has likely been produced with materials that were extracted locally. At the end of 2003, there were 60 lime manufacturing facilities in the United States and, of these, 48 used stone that was extracted from a local mine or quarry (Miller, 2004b).

3.2.5 Indoor environmental quality credits potentially impacted by the use of lime

Credit 2 – **Carbon dioxide (CO_2) monitoring –** Hydrated lime absorbs carbon dioxide and, in so doing, converts back to its original form, limestone.

Credit 5 – **Indoor chemical and pollutant source control** – As discussed in Section 3.1, lime-based interior systems can be beneficial in reducing indoor air pollutants.

Credit 7.1 – **Thermal comfort: compliance with ASHRAE 55-1992** – As indicated under **Energy and atmosphere credits**, lime-based systems have thermal mass that reduces temperature fluctuations.

3.2.6 Innovative design credits potentially impacted by the use of lime

Credit 1 – **Innovation and design process** – As seen in the previous discussion, lime can be used in a wide variety of ways to enhance “Green Building” projects in creative ways.

4 Conclusion

Evidence exists that lime is both a sustainable and "green" building material.

Lime production and use is sustainable on the basis that the limestone resource from which lime is produced is widely available in vast quantities that will not be exhausted for tens of thousands of years, if ever. In addition, lime production is energy-efficient and capable of being fuelled with biomass.

Lime has many "green" attributes as a building material when viewed from the perspective of building occupant comfort and environmental performance. Lime has a place in all aspects of "green" building development from site preparation, through construction, and use. This is evidenced in the wide variety of LEED™ certification points that can be gained through using lime-based systems as materials in construction.

In closing, there is little material in the literature that examines the issue of lime as a sustainable and "green" building material from first principles. Significant evidence was found that indicates lime is already considered a "green" building material. However, more work must be completed to flesh out concepts introduced here and provide a rock-solid foundation for promotion of lime as a sustainable and "green" building product.

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