Mix Design and Benefit Evaluation of High Solar Reflectance Concrete for Pavements

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ABSTRACT

The use of cool paving materials or 'cool pavements' has been identified as one strategy that can help mitigate urban heat island effect. One method of creating a cool pavement is to increase the solar reflectance or *albedo* of its surface. This can be achieved by many existing paving technologies. This study explores alternative ways of creating high albedo concrete for use in pavement applications. The key approach is to make concrete whiter by replacing cement with whiter constituents. Fly ash and slag are used as the main constituents since they are environment-friendly, readily available, and already accustomed with by the concrete industry.

Compared to a conventional concrete mix, concrete mixes containing fly ash have lower albedo whereas concrete mixes containing slag have higher albedo. Among all the mixes tested, the mix with 70% slag as cement replacement achieves the highest albedo of 0.582, which is 71% higher than the conventional mix. It also has better compressive strength as tested at 7 and 28 day and modulus of rupture as tested at 7 days. In addition to consuming 43.5% less energy, the production of the high solar reflectance concrete produces less pollutant emissions and greenhouse gases on the order of 20-60%. Furthermore, the analysis of some urban cities shows that the implementation of this high solar reflectance concrete can possibly increase the city albedo by 0.02-0.07. This amount of albedo modification has potential to provide great benefits to economics and the environment in many ways ranging from decreasing energy demand to improving air quality.

BACKGROUND

Man-made or built-up surfaces such as concrete and asphalt absorb more heat from sunlight, compared to other natural surfaces, due to their low solar reflectance or *albedo* (the ratio of the amount of light reflected from a material to the amount of light incident on the material). Albedo is measured on a scale from 0 to 1. An albedo value of 0 indicates a black body cavity that does not reflect any light while an albedo of 1 indicates a perfectly reflective surface. Low albedo surfaces can raise the local ambient air temperature in urban areas by as much as 6 °C (10 °F) over the surrounding areas *(1)*. This is so called urban 'heat island' effect.

There are several detrimental consequences which arise both directly and indirectly from the heat island effect. In summertime, the heat island effect can raise air temperatures to levels that result in heat-related illness and mortality *(2)*. A higher air temperature leads to an increased energy demand to cool down buildings, which results in larger air-conditioning bills *(3)*, and an increase in emissions from power plants *(4)*. In addition, a higher air temperature induces higher rates of photochemical reactions that form smog (ground-level ozone and its precursors) *(5)*.

Federal, state, local, and private agencies in the United States (U.S.) have increasingly realized the significance of mitigating urban heat islands on the economy, environment, and public health. Therefore, several programs have been established, for example, Cool Roof Rating Council (CRCC) and Leadership in Energy and Environmental Design (LEED). LEED provides a "Green Building" certificate to owners of buildings and developed areas that utilize energy and environment-friendly design and practices. An example of a credit in the LEED program is the use of surfaces having albedo higher than 0.3 for at least 30% of the non-roof paved surfaces *(6)*. Another major effort, which is spearheaded by the U.S. Environmental Protection Agency (EPA), is the Heat Island Reduction Initiative. Its current activities include promoting heat island mitigation strategies and providing outreach and education (*1*).

Cool Pavements as a Heat Island Mitigation Strategy

Methods of mitigating heat island involve the use of cool roofing/paving materials and extensive planting of vegetation. While strategically good ways to plant vegetation are well established and cool roofing products have been developed and identified, the idea of cool pavements has yet to gain wide dissemination and acceptance. In general, cool pavements can be achieved with existing paving technologies and do not require new materials. To date, many techniques of creating a cool pavement have been studied and proposed. These techniques can be grouped by the mechanism they use to lower pavement temperature as follows *(7)*:

1. *Increasing surface reflectance*: Higher solar reflectance of pavement surface reduces the solar energy absorbed by the pavement. This can be achieved by the use of conventional concrete, roller-compacted concrete, whitetopping and ultra-thin whitetopping, asphalt concrete and asphalt chip seals with light-colored aggregate, and asphalt pavements with modified color *(8)*.
2. *Increasing permeability*: High permeable pavements can be made of concrete, asphalt, open-celled stones, and gravel that are mixed in a manner that creates an open cell structure (15-25% void spaces) allowing air and water to pass through. So, they have less heat storage capacity and can lower their temperature through evaporation of water. These pavements are also known as 'porous pavement' or 'pervious pavement'. However, the applications of porous pavements are limited by their achievable compressive strength, which ranges from 3.5 to 27.5 MPa (500 to 4,000 psi) *(9)*.

Since research in the area of cool pavements is in an early stage, more techniques will continue to be discovered and disseminated. For example, it has recently been found that a composite structure of a rubberized asphalt layer over conventional concrete slabs emit lower levels of heat at night *(10)*. In this study, we explore alternative techniques to create high solar reflectance concrete for pavement applications. We target the improvement to concrete since it already has an advantage of being light-colored even in natural color. Concrete is normally utilized in the built environment and can account for a significant amount of the total surface area in urban regions. A typical albedo value for conventional concrete ranges between 0.35-0.40 (for new concrete) and 0.25-0.30 (for weathered concrete) *(8)*.

LITERATURE REVIEW

High Solar Reflectance Concrete

A review of the literature was performed. It appears that only a few studies have been conducted in this subject area. One rather obvious method of increasing solar reflectance of concrete would be to paint the surface with a coating *(11)*. However, this method may be subject to a high initial cost premium, an increased labor cost, and further construction delay when drying. In addition, the coating would probably wear off. A much more viable approach would be to engineer the composition of the concrete itself. An earlier study on the effect of composition of the concrete on its reflectance showed a lot of promise in this method *(12)*. It experimentally demonstrated that concrete could be made whiter by using whitish ingredients such as white cement, white stone, and white sand, which would result in higher albedo values. Unfortunately, the study did not report engineering properties of such concrete mixes, giving no indication as to their suitability in the field. In addition, the use of white cement (which is typically twice as expensive as gray cement) and locally unavailable aggregates may not be economically feasible.

In this study, it was felt that the best way to design and promote high solar reflectance concrete was to innovatively modify the concrete mixture by incorporating readily available materials with which the concrete industry has already been accustomed. The main approach was to create a whiter concrete by replacing cement with whiter constituents. It should be noted that reduction in the consumption of cement resulting from the use of alternative materials is also beneficial to the economics and environment. As the raw materials must be heated to about 1,500 °C (2,700°F), the manufacture of cement consumes an enormous amount of energy. It also releases substantial quantities of Carbon Dioxide (CO_2) from both fuel combustion and the chemical reaction that decomposes calcium carbonate ($CaCO_3$) into lime (CaO) and CO_2 *(13)*. Despite of advancement in emission reduction technologies, as of 2004 cement manufacturing processes still produce about 672 kg (1,481 lbs) of gross CO_2 emission per tonnage of cement *(14)*. On a national scale, cement manufacture produces 45.6 million tons of CO_2 equivalent, which accounts for 3.3% of total industry-related CO_2 emissions in the U.S. in 2004 *(15)*.

Use of Fly Ash and Slag in Concrete

The two main constituents that are commonly used to replace cement are fly ash and ground-granulated blast furnace slag (referred to shortly as ‘slag’ throughout the remaining of this paper). Fly ash can vary in color from tan to gray; however, Class C fly ash is usually tan in color. Slag is of an even whiter shade than fly ash. Their color as compared to that of cement is shown in Figure 1. Fly ash is a waste product of powdered coal after being burned in power plants. It is known to improve several desirable properties of hardened concrete. These include higher ultimate strength, reduced permeability, reduced shrinkage, and increased durability *(16)*. Slag is a waste product from the blast furnace production of iron from ore. The benefits of slag in concrete include better paste-aggregate bond, higher strength, lower permeability, enhanced durability, improved resistance to chemical attack, and reduced heat generation *(17, 18)*. Both fly ash and slag are recovered resources, so the utilization of them promotes resource efficiency and conserves precious space in landfills. The use of fly ash and slag in concrete for building, parking lots, and non-roof structures also qualify for credits under the LEED green building program *(19, 20)*.

Many states allow the use of fly ash and slag to replace cement in concrete pavements and bridges. However, it is often limited to a certain percentage of replacement *(21)*. This is partially due to a lack of research in the properties and benefits of high volume fly ash and high slag content concrete. Recently, there has been a growing interest in this subject area. In Arkansas, concrete mixtures with up to 80% cement replacement were studied for strength, durability, and permeability properties. A preliminary recommendation was made that the existing limits of fly ash and slag be increased to 40% by weight and a ternary mix design of 20% fly ash plus 20% slag be allowed *(22)*. In Missouri, a 70% slag concrete mix was successfully used in a bridge pier and abutment mass concrete project. Using Type II low heat Portland cement, it was concluded that the said mix could be used to achieve moderate strength levels. *(23)*. Finally, based on an estimated concrete production in Texas it was determined that if 60% of the Portland cement used were replaced by fly ash, CO_2 emissions could potentially be reduced by 6.6 million tons each year by the year 2015 *(24)*.

OBJECTIVES OF THE STUDY

The primary goal of this study is to design and create concrete mixtures that have higher albedo than that of conventional concrete for use in pavement surfaces. The new mixtures should utilize environment-friendly ingredients and be economically attractive while maintaining or improving functional characteristics of concrete pavements. Specific objectives of the study are: (1) to design whitish concrete mixtures with the approach of substituting cement by Class C fly ash and Grade 120 slag, or utilizing white ingredients namely white sand and latex, (2) to measure albedo of each concrete mix and identify mixes with high albedo, (3) to test the strength of each concrete mix and determine if they meet performance specifications for concrete pavements, and (4) to quantify economical and environmental benefits of the chosen high solar reflectance concrete mix.

MIX DESIGN AND EXPERIMENTAL RESULTS

This study was conducted in Ohio and the specifications of Ohio Department of Transportation (ODOT) were used as a guideline. Table 1 lists the concrete mixtures that were tested in this study. Three standard mixes based on ODOT construction specifications (Mixes 1, 2, and 3) were used as control mixes *(25)*. Mix 1 is a conventional concrete mix without any cement replacement materials. Mixes 2 and 3 were high performance mixes. Mix 2 contains 24% fly ash and Mix 3 uses 30% slag by weight of the total cementation material. In order to compare the influence of fly ash and slag content on concrete's albedo, Mix 4 was designed based on the mixture of Mix 3 but with 30% fly ash. Mixes 5 and 6 utilize 60% cement replacement by fly ash and slag, respectively. This was aimed at evaluating the mixes with unconventionally high percentage of cement replacement. This would also allow for the identification of the relationship between the percentage of cement replacement materials and the albedo of concrete. Further, to explore the albedo result of ternary mixes (consisting of both fly ash and slag), mixes 7 and 8 were created. Alternatively, mixes 9 and 10 move away from the use of fly ash and slag. Instead, they contain other whitish ingredients, namely white sand and latex. Mix 11 was designed later in the study after the albedo results of the first 10 mixes had been obtained. It was designed to further increase the albedo of concrete. It is imperative to note that the albedo and other properties of aggregates can affect the albedo of the concrete produced *(12, 26)*. Therefore, every concrete mix was made with aggregates from the same batch. These aggregates were locally available in Ohio. The coarse aggregate used was #8 limestones, and the fine aggregate was ASTM C33 sand. Chemical admixtures added to the concrete mixes included a high range water reducer and an air entraining agent.

Solar Reflectance (Albedo)

A concrete sample for albedo testing is a 5 cm x 5 cm x 5 cm (2” x 2” x 2”) cube. Four concrete cubes were made for each of the mixtures as shown in Figure 1. The top surface of these concrete cubes was tested for albedo according to ASTM C1549 at the age of 14 days. The mean albedo value for each of the 11 mixes tested is plotted in Figure 2(a). For a comparison purpose, the red horizontal line representing the mean albedo value of the conventional concrete mix (Mix 1) is drawn across the plot. The mean, standard deviation (SD), and coefficient of variation (CV) of the albedo results of each mix are also listed. Figure 2(b) shows the percentage difference in albedo for each mix as compared to the conventional mix. According to the figures, the following trends are observed:

- Concrete mixes containing fly ash (Mixes 2, 4, and 5) all have lower albedo than the conventional mix, but the trends between the albedo of concrete and the percentage of fly ash are not consistent. When considering Mixes 2 and 4, the albedo of Mix 4 is lower than that of Mix 2 as it contains a higher percentage of fly ash. However, when considering Mixes 4 and 5, the albedo of Mix 5 is higher despite of its higher percentage of fly ash.
- Concrete mixes containing slag (Mixes 3, 6, and 11) all have higher albedo than the conventional mix, and the albedo of concrete consistently increases as the percentage of slag increases.
- The albedo of ternary concrete mixes (Mixes 7 and 8) depends on the proportion of fly ash and slag used. A higher proportion of fly ash decreases concrete’s albedo while a higher proportion of slag increases concrete’s albedo.
- White sand and latex increase concrete’s albedo but not as high as the mixes with 60% or more slag content.

As indicated by the values of CV, the variation of albedo of cube samples is higher in ternary mixes than the binary mixes containing either fly ash or slag. Between the two constituents, the concrete mixes with fly ash have higher variation in albedo. The variation is also high for concrete mixes with white sand and latex. It should be noted that solar radiation encompasses a relatively narrow range in the spectrum of electromagnetic waves. About 43% of the energy in the solar spectrum comes from the visible light range (400-700 nm). Another 52% lies in the near-infrared (700-2500 nm) and 5% in the ultraviolet range (300-400 nm) *(26)*. This implies that a perfectly white surface to human eyes may reflect only half of all solar energy. According to this fact, it is interesting to observe that the concrete mixes containing fly ash are inferior in albedo than the conventional mix. This may be because fly ash reflects less energy in the near-infrared spectrum than cement although it looks lighter in color.

As per the test results, Mix 11 apparently has the highest albedo value of 0.582, which is equivalent to an increase in albedo of 71% over the conventional mix (albedo = 0.341). It is interesting that the mix with white sand does not achieve the albedo as high as the mixes with 60% or more slag. This finding, coupled with the fact that white sand is usually more expensive than slag, affirms the use of high slag content as a very attractive solution to produce high solar reflectance concrete.

Engineering Properties

In order to ensure their quality, all of the concrete mixtures were tested for strength properties which were checked against the performance specifications of ODOT *(25)*. The target specifications for the concrete include a minimum compressive strength of 27.6 MPa (4,000 psi) at 28 days, and a modulus of rupture (flexural strength) of 4.1 MPa (600 psi) at 7 days. For the compressive strength testing, concrete cylinders of 10 cm (4") in diameter and 20 cm (8") in height were tested at 7 and 28 days according to ASTM C39. For the flexural strength testing, beams of 15 cm x 15 cm (6" x 6") cross section were tested in third-point loading with a span of 45 cm (18") at 7 days according to ASTM C78. Figure 3(a) shows the mean compressive strength at 7 and 28 days of three cylinder samples. It can be seen that all mixes meet the specification in just 7 days. Concrete mixes that contain either fly ash or slag, or both, achieve superior compressive strength to the conventional mix. In Figure 3(b), the modulus of rupture of a beam sample is presented. Every mix meets the specification except for Mixes 5 and 8.

Findings

According to the test results, it is obvious that the high slag content concrete is a champion. It has high albedo values and excellent strength properties. Some possible concerns regarding the use of high slag content concrete include the availability of slag and the related transportation cost. Actually, the availability of slag in the U.S. has increased tremendously in the past several years, and this has spurred its utilization in concrete and construction applications from 1.1 million tons in 1996 to 3.5 million tons in 2005 *(18)*. With regard to the transportation cost, Figure 4 shows that slag production sources in the U.S. are mostly located in the Midwest area, especially Ohio and Indiana. This means that the cost of transporting slag to concrete plants in this region should be relatively low. This could be a significant incentive for the concrete industry in this region to use the high slag content concrete.

BENEFITS OF HIGH SOLAR REFLECTANCE CONCRETE

Benefits Associated with Using Cement Replacement Materials

The benefits of using cement replacement materials can be determined from a life cycle inventory (LCI) of concrete production. LCI is a compilation of the materials, energy inputs (in the form of electricity, natural gas, diesel fuel, and other fuel oils), and emissions outputs associated with the production of one unit of concrete. LCI of concrete production encompasses all the processes from manufacturing cement and replacement materials, aggregate production, transporting materials to plant, to concrete plant operations.

Table 2 compares the energy consumption and emissions between conventional concrete and the high solar reflectance concrete based on data from earlier studies *(27, 28)*. It is shown that in addition to the 8% saving in total material cost, the use of high solar reflectance concrete helps decrease net energy consumption by 43.5%. It also reduces pollutant emissions in the order of 20-60% where the largest emissions reduction is in CO_2. Using an arbitrary highway project as an example, if this high solar reflectance concrete was used in place of a conventional concrete to pave 260 lane-km or about 160 lane-mi (a 20-mi divided highway segment with 4 lanes in each direction) of a typical 10-inch-thick concrete pavement, the benefits would turn out to be approximately 315,000 GJ (228,400 million Btu) of energy saving plus 48,250 metric ton (106 million lbs) of CO_2 reduction. In addition, the utilization of slag in high solar reflectance concrete helps minimize the waste that would otherwise take up space in landfill.

Benefits as a Result of Mitigating Heat Island Effect

Recently, the U.S. EPA has launched the heat island mitigation impact screening tool (MIST) to help estimate the expected impacts of heat island mitigation strategies on air temperature, air quality, and energy demand, averaged at the city-scale *(29)*. Under certain assumptions, the tool employs state-of-the-science methods involving meteorology modeling and mitigation simulation to provide qualitatively accurate assessments of the net benefits of albedo modification, vegetation modification, and/or temperature reduction for over 200 U.S. cities *(30)*. To compute the potential albedo change ($\Delta\rho$) of averaged U.S. urban cities due to the implementation of the high solar reflectance concrete, the information regarding the existing surface composition of the cities is needed. Analyses in cities such as Chicago *(31)*, Houston *(32)*, Sacramento *(33)*, and Salt Lake City *(34)* have shown that pavements account for about 29 to 45 percent of urban surface. These pavements include roads (10-27%), parking spaces (13-17%), and sidewalks (2-6%), as shown in Table 3(a). They are composed mainly of asphalt and concrete surfaces.

Over time, the albedo of asphalt can increase from 0.05-0.10 (average = 0.075) at initial installation to 0.15-0.20 (average = 0.175) because of the exposure of aggregates after wearing and the oxidation that causes the binder to fade. On the other hand, the albedo of concrete can decrease from 0.35-0.40 (average = 0.375) when it is new to 0.25-0.30 (average = 0.275) after wearing and weathering *(8)*. That means the albedo of exposed concrete is about (0.275/0.375)*100 = 73% of its original value. If the albedo of the high solar reflectance concrete was to drop at the same rate, its albedo would be about 0.582*73% = 0.425 after exposure. Thus, the albedo difference between high solar reflectance concrete and asphalt is 0.425-0.175 = +0.25, and the albedo difference between high solar reflectance concrete and typical concrete is 0.425-0.275 = +0.15. With these information and the assumptions pertaining to the percentage of each surface type for each pavement facility listed under Table 3, the citywide $\Delta\rho$ can be calculated using Equation (1).

$$\Delta\rho = \sum_{i,j} \left(\rho_{ij}^{A} f_{ij}^{A} - \rho_{ij}^{B} f_{ij}^{B} \right) \tag{1}$$

where ρ_{ij}^{A} and ρ_{ij}^{B} are albedo of surface *i* of structure *j* after and before the change
f_{ij}^{A} and f_{ij}^{B} are fraction of surface *i* of structure *j* after and before the change

Table 3(b) presents the calculated citywide $\Delta\rho$ if the high solar reflectance concrete was paved in place of the conventional concrete and asphalt surfaces. For the four cities analyzed, the $\Delta\rho$ vary from +0.06 to +0.09 with the average value of +0.07. Table 3(c) shows the result for the scenario that the high solar reflectance concrete was paved in place of the conventional concrete only. In this scenario, the average value of $\Delta\rho$ is +0.02. In Table 4, the estimated benefits as a result of a citywide albedo increase are shown for those large U.S. cities within 250 miles from the slag production sources. According to the results, the estimated mean temperature reduction could vary between 0.1 and 0.5 °C (0.2 and 0.9 °F). The estimated decreases in ozone peak concentrations could range from 0.2 to 2.6 parts per billion (ppb) for 1-hour averaged concentration and from 0.2 to 2.1 ppb for 8-hour averaged concentration. Lastly, the estimates of energy saving reveal that these cities could be entitled to the net energy savings worth multi-million dollars annually. One of earlier studies demonstrated the simulation results that increasing the albedo of 1,250 sq km (483 sq mi) of roadways in Los Angeles by 0.25 would save cooling energy worth $15 million per year, and would reduce smog-related medical and lost-work expenses by $76 million per year *(3)*. It is possible that the implementation of high solar reflectance concrete could play a role in achieving such an albedo increase.

Other Benefits

Additional benefits are also expected from using high solar reflectance concrete. For instance, concrete pavements will experience less temperature rise and therefore be subjected to less thermal stress. This will minimize cracking, which in turn leads to more durable structures and lower maintenance costs *(35)*. Highly reflective pavements will also provide better nighttime illumination, so they will require less lighting energy and improve nighttime safety *(7)*.

CONCLUSIONS AND RECOMMENDATIONS

The high solar reflectance concrete which utilizes 70% slag as cement replacement achieves the albedo of 0.582 at 14 days, which is 71% higher than the conventional concrete. It also has compressive and flexural strengths that meet the performance specification of ODOT and are superior to those of the conventional concrete. These results warrant the use of this concrete as one alternative for creating a cool pavement for many applications including highway pavement. Besides that the material cost is 8% cheaper, the production of the high solar reflectance concrete consumes 43.5% less energy. It also produces less pollutant emissions and greenhouse gases on the order of 20-60%. Furthermore, the analysis of some U.S. cities shows that the implementation of this high solar reflectance concrete can possibly increase the city albedo by 0.02-0.07. This amount of albedo modification has potential to provide great benefits to economics and the environment in many ways ranging from decreasing energy demand to improving air quality. Although specific cool pavement technologies may not always be appropriate or feasible in every pavement application and in every region of the country, the implementation of the high reflectance concrete wherever it is appropriate for will at least partially contribute to energy conservation, pollution reduction, and environment preservation.

There are several market barriers to the use of high reflectance concrete pavement, for example, lack of information and knowledge, lack of contractors with experience, lack of standards, and lack of stakeholder support *(7, 8, 36)*. Some of these barriers can be overcome by the dissemination of the results from research studies including this one to related professions, industries, agencies, and the public. Pertaining to the standards and stakeholder support, many public agencies currently put a limit on the allowable percentage of slag to be used in concrete. Based on the findings from this study, it is recommended that agencies interested in taking the potential benefits of the high solar reflectance concrete conduct a comprehensive study of the properties of the high slag content concrete made with local aggregates and possibly adjust the specifications accordingly.

Future works will include the investigation of other properties of the high solar reflectance concrete such as emissivity, conductivity, permeability, and freeze-thaw durability. In addition, the alteration of its albedo after exposure to traffic and environment will be studied.

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TABLE 1 Concrete mixtures and their mix proportion (lbs/cu yd concrete)

Mix #	Description	Portland Cement	Fly Ash	Slag	Water	Coarse Aggregate	Fine Aggregate
1	ODOT base mix	600	0	0	355	1410	1320
2	ODOT high performance concrete 1 (HP1) – 24% fly ash	530	170	0	263	1480	1310
3	ODOT high performance concrete 2 (HP2) – 30% slag	490	0	210	264	1495	1330
4	ODOT HP2 but with 30% fly ash	490	210	0	245	1495	1330
5	ODOT HP1 with 60% fly ash	280	420	0	233	1480	1310
6	ODOT HP2 with 60% slag	280	0	420	258	1495	1330
7	ODOT HP2 with 40% fly ash + 20% slag	280	280	140	233	1495	1330
8	ODOT HP2 with 20% fly ash + 40% slag	280	140	280	245	1495	1330
9	ODOT base mix with white sand	600	0	0	355	1410	1320[b]
10[a]	ODOT base mix with latex	611	0	0	131	1410	1320
11	ODOT HP2 with 70% slag	210	0	490	256	1495	1330

[a]*This mix includes 220 lbs of latex (24% solids content);* [b]*White sand*

TABLE 2 Comparison of energy consumption and emissions associated with the production of conventional and high solar reflectance concrete (calculated using data from *(27, 28)*)

Attribute	Mix 1	Mix 11	Difference	% Difference
% Portland cement	100%	30%		
% slag	0%	70%		
Total material cost[a], $/cu yd concrete	39.32	36.22	-3.10	-7.9
Energy consumption, million Btu/cu yd concrete (1 million Btu/cu yd = 1.379 GJ/cu m)				
Portland cement manufacturing	1.370	0.480	-0.891	-65.0
Slag cement manufacturing	0	0.153	+0.153	n/a
Aggregate production	0.074	0.077	+0.003	+4.2
Transporting materials to plant	0.054	0.059	+0.004	+8.3
Concrete plant operations	0.179	0.179	0	0
Total	1.678	0.948	-0.730	-43.5
Emissions, lbs/cu yd concrete (1 lb/cu yd = 0.5933 kg/cu m)				
Carbon dioxide (CO_2)	585	245	-340	-58.1
Carbon monoxide (CO)	0.722	0.426	-0.296	-41.0
Sulfur dioxide (SO_2)	1.357	0.704	-0.653	-48.1
Oxides of Nitrogen (NO_x)	1.763	0.785	-0.978	-55.5
Volatile organic compound (VOC)	0.060	0.047	-0.013	-21.6
Particulate matter (PM)	2.272	1.392	-0.880	-38.7
Methane (CH_4)	0.027	0.014	-0.013	-47.3

[a]*Based on the following unit costs: slag $60/ton (37); Portland cement $93.36/ton, coarse aggregate $8.58/ton, and fine aggregate $7.98/ton (38)*

TABLE 3 Estimates of potential albedo increase due to the implementation of high solar reflectance concrete

(a) Percentage of each type of pavement structure in a city (calculated using data from *(31-34)*)

Urban Area	Roads	Parking Lots	Sidewalks	Total
Sacramento, CA	27%	13%	5%	45%
Chicago, IL	19%	16%	3%	37%
Salt Lake City, UT	17%	13%	6%	36%
Houston, TX	10%	17%	2%	29%
Average	*18%*	*15%*	*4%*	*37%*

(b) Potential albedo increase due to paving high solar reflectance concrete in place of conventional concrete and asphalt surfaces

Urban Area	Roads[a]	Parking Lots[b]	Sidewalks[c]	Total
Sacramento, CA	0.06	0.02	0.01	0.09
Chicago, IL	0.04	0.03	0.00	0.07
Salt Lake City, UT	0.04	0.02	0.01	0.07
Houston, TX	0.02	0.03	0.00	0.06
Average	*0.04*	*0.03*	*0.01*	*0.07*

(c) Potential albedo increase due to paving high solar reflectance concrete in place of conventional concrete

Urban Area	Roads[a]	Parking Lots[b]	Sidewalks[c]	Total
Sacramento, CA	0.00	0.01	0.01	0.02
Chicago, IL	0.00	0.01	0.00	0.01
Salt Lake City, UT	0.00	0.01	0.01	0.02
Houston, TX	0.00	0.01	0.00	0.01
Average	*0.00*	*0.01*	*0.01*	*0.02*

[a]*Assume 3% of roads are concrete surface, 87% are asphalt surface, and the remaining 10% are unpaved (7).*
[b]*Assume 45%/45%/10% of concrete/asphalt/other surfaces for parking lots*
[c]*Assume 80%/10%/10% of concrete/asphalt/other surfaces for sidewalks*

TABLE 4 Potential benefits from a citywide albedo increase for large cities within 250 miles from slag production sources

(a) A citywide albedo increase of 0.07

Rank in 2005	City	2005 Population[a]	Projected Average Reduction[b]			Projected Annual Energy Savings ($ per 1000 sq ft of Roof Area)[c]		
			Air Temp (°F)	Max 1-hr O_3 (ppb)	Max 8-hr O_3 (ppb)	Residential	Office	Retail
1	New York City, NY	8,153,197	0.9	2.6	2.1	5.23	9.35	9.93
3	Chicago, IL	2,842,518	0.9	2.5	2	0.96	4.71	4.75
5	Philadelphia, PA	1,463,281	0.8	1.8	1.4	3.45	6.13	6.51
11	Detroit, MI	886,671	0.7	1.9	1.6	0.96	4.73	4.77
12	Indianapolis, IN	784,118	0.6	1.3	1	1.02	4.04	4.16
15	Columbus, OH	730,657	0.6	1.3	1	1.18	4.96	5.12
17	Memphis, TN	672,277	0.6	0.9	0.7	4.21	5.99	6.20
18	Baltimore, MD	635,815	0.7	1.4	1.1	2.85	5.59	6.12

(b) A citywide albedo increase of 0.02

Rank in 2005	City	2005 Population[a]	Projected Average Reduction[b]			Projected Annual Energy Savings ($ per 1000 sq ft of Roof Area)[c]		
			Air Temp (°F)	Max 1-hr O_3 (ppb)	Max 8-hr O_3 (ppb)	Residential	Office	Retail
1	New York City, NY	8,153,197	0.3	0.7	0.6	1.60	2.73	2.86
3	Chicago, IL	2,842,518	0.3	0.7	0.5	0.33	1.36	1.36
5	Philadelphia, PA	1,463,281	0.2	0.5	0.4	1.05	1.79	1.87
11	Detroit, MI	886,671	0.2	0.5	0.4	0.33	1.36	1.36
12	Indianapolis, IN	784,118	0.2	0.4	0.3	0.29	1.14	1.20
15	Columbus, OH	730,657	0.2	0.4	0.3	0.34	1.40	1.47
17	Memphis, TN	672,277	0.2	0.2	0.2	1.24	1.76	1.76
18	Baltimore, MD	635,815	0.2	0.4	0.3	0.86	1.66	1.81

[a]*Based on data from (39)*
[b]*Calculated using data from (29)*
[c]*Estimates are for post-1980 electric-heated buildings; calculated using data from (29,40).*

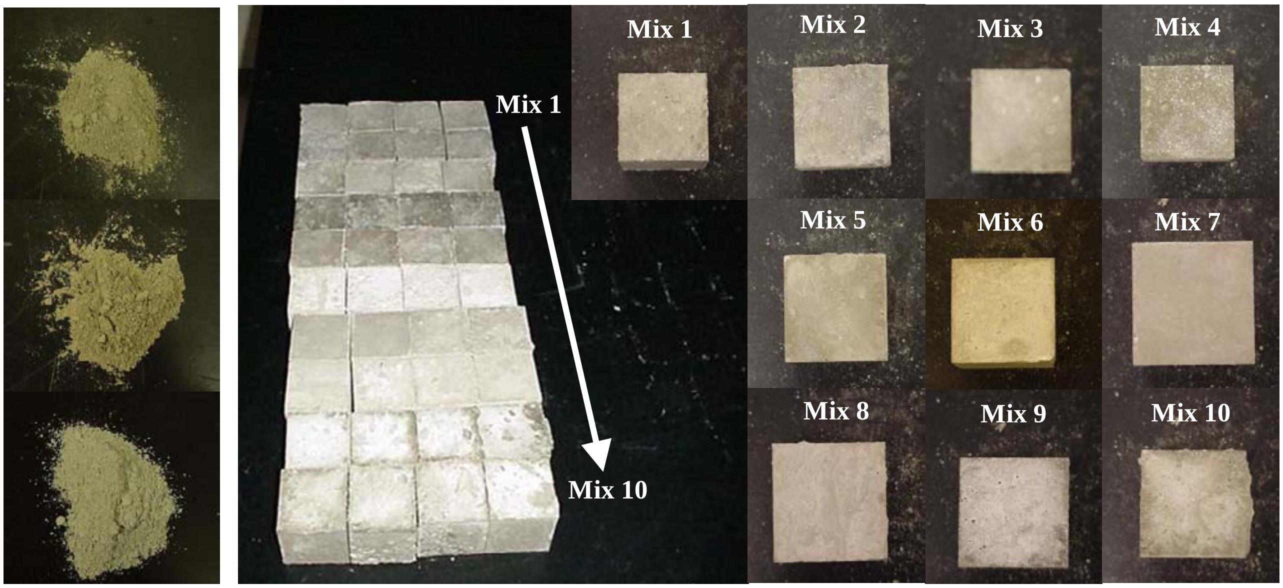
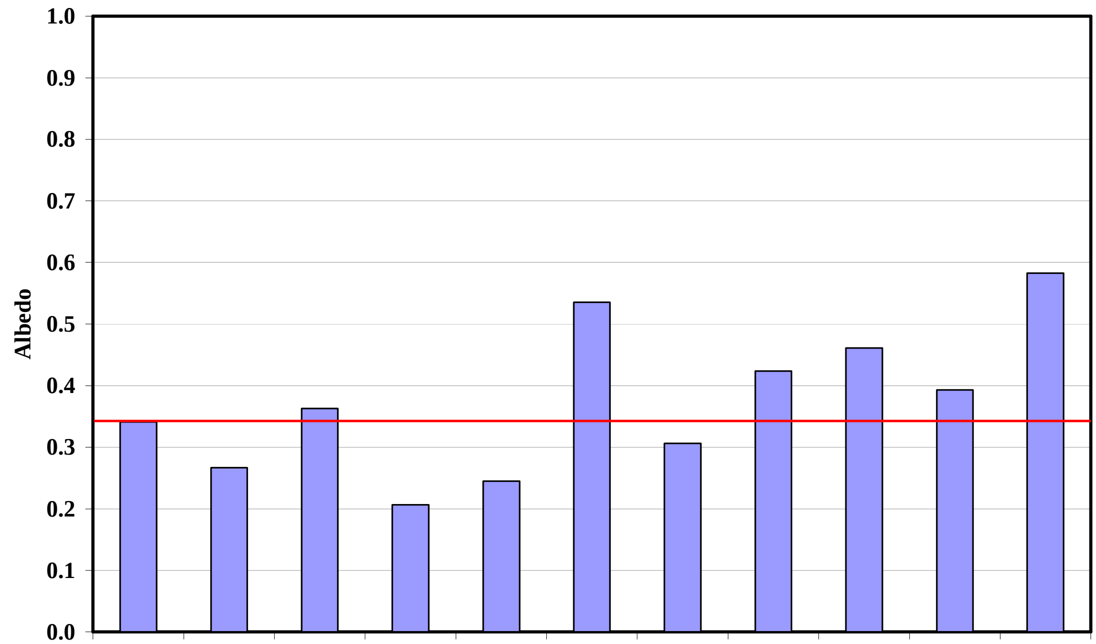
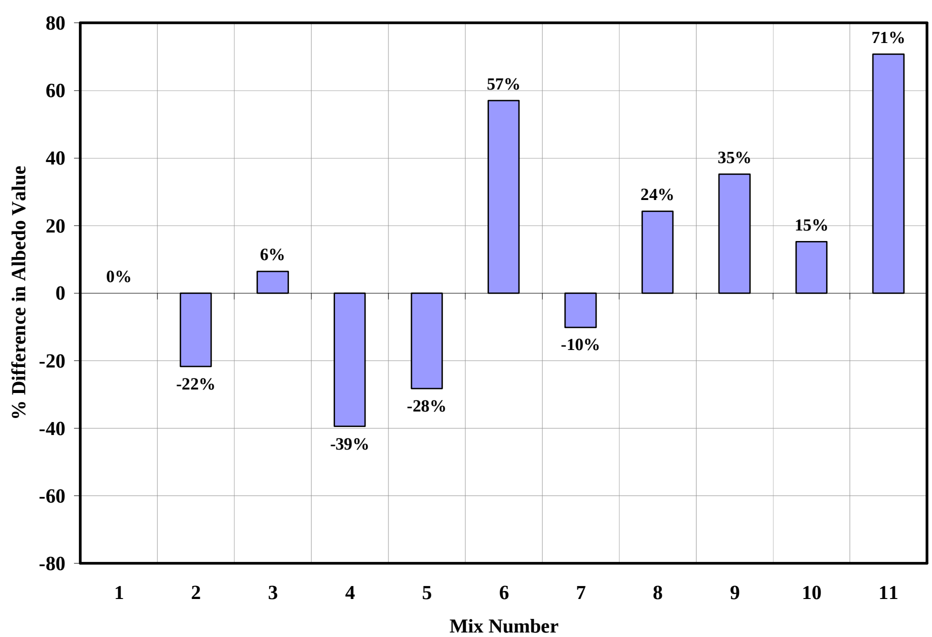


FIGURE 1 (Left) from top to bottom: cement, fly ash, and slag, respectively; (Right) cube samples for albedo testing



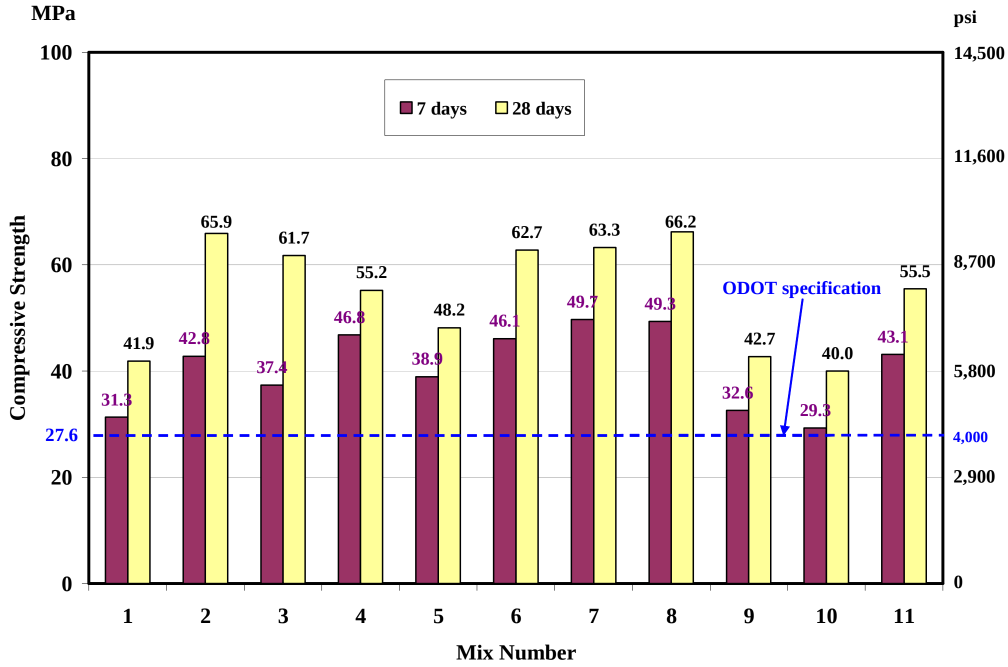
Mix #	1	2	3	4	5	6	7	8	9	10	11
Mean	0.341	0.267	0.363	0.207	0.245	0.535	0.307	0.424	0.461	0.393	0.582
SD	0.007	0.021	0.005	0.017	0.013	0.023	0.027	0.036	0.034	0.036	0.004
CV, %	2.1	8.0	1.4	8.4	5.2	4.2	8.7	8.4	7.5	9.1	0.7

(a) Mean, SD, and CV

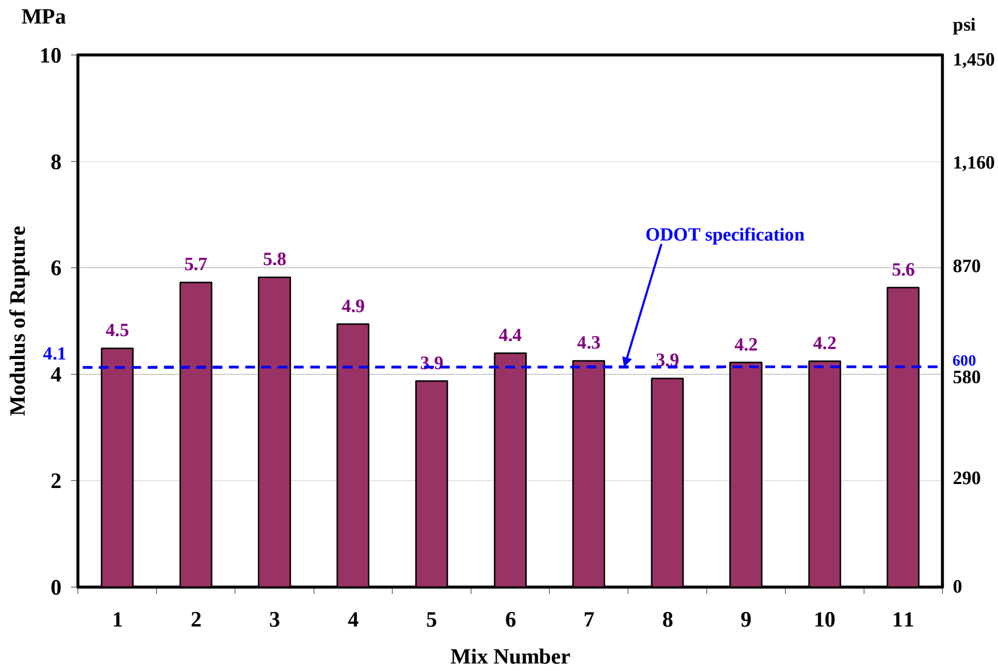


(b) Percentage difference in albedo value as compared to conventional concrete (Mix 1)

FIGURE 2 Albedo results of tested concrete mixes



(a) Average compressive strength at 7 and 28 days



(b) Modulus of rupture at 7 days

FIGURE 3 Strength properties of concrete mixes

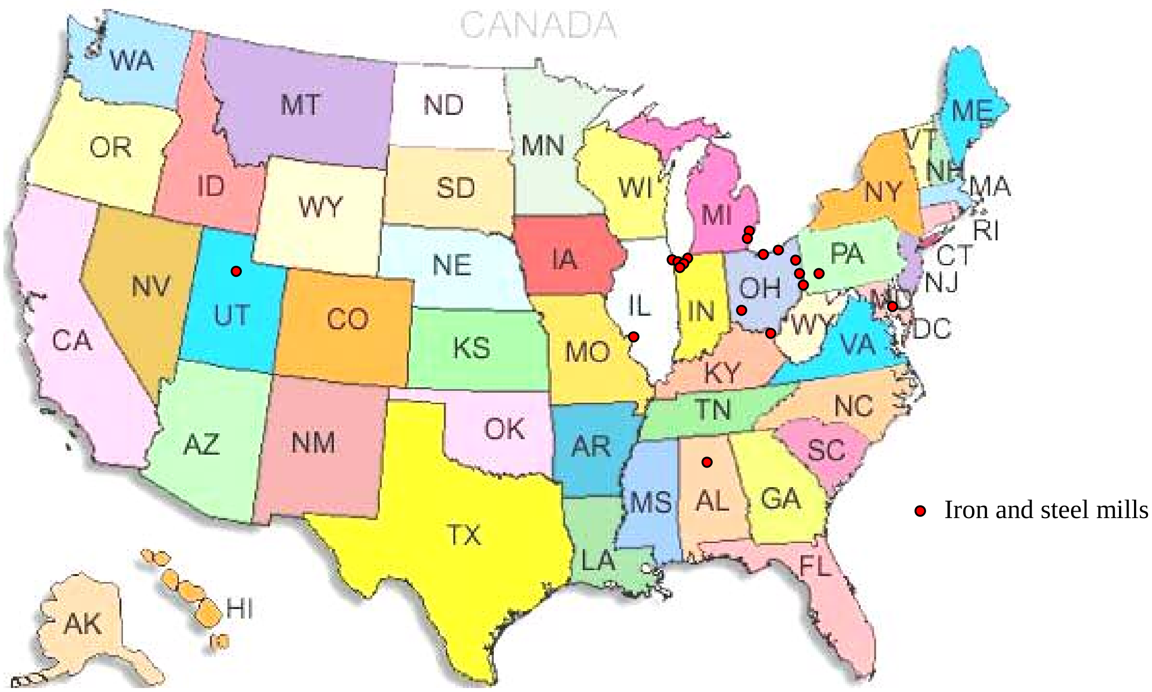


FIGURE 4 Slag production sources in the U.S. (based on data from (*41)*)