LBNL-48334

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December 2001

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies, of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098, and by the U.S. Environmental Protection Agency (EPA) under IAG No. DW89938351-01.

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Abstract

Increasing the solar reflectance (albedo) of a paved surface keeps it cooler in the sun, reducing convection of heat from pavement to air and thereby decreasing the ambient air temperature. Simulations of the influence of pavement albedo on air temperature in Los Angeles predict that increasing the albedo of 1,250 km^2 of pavement by 0.25 would save cooling energy worth \$15M yr^{-1}, and reduce smog-related medical and lost-work expenses by \$76M yr^{-1}. Most sidewalks and a small fraction of roads and parking areas are paved with portland cement concrete, which can be made quite reflective through suitable choice of cement and aggregate. Variations with composition and environmental exposure of the albedos of portland cement concrete pavements were investigated through laboratory fabrication and exposure of 32 mixes of concrete.

Twenty-four mixes yielded substandard, “rough” concretes due to high, unmet aggregate water demand. The albedos of the remaining eight “smooth” concrete mixes ranged from 0.41 to 0.77 (mean 0.59). Simulated weathering, soiling, and abrasion each reduced average concrete albedo (mean decreases 0.06, 0.05, and 0.19, respectively), though some samples became slightly more reflective through weathering or soiling. Simulated rain (wetting) strongly depressed the albedos of concretes (mean decrease 0.23) until their surfaces were dried. Concrete albedo grew as the cement hydration reaction progressed (mean increase 0.08), but stabilized within six weeks of casting.

White-cement concretes were on average significantly more reflective than gray-cement concretes. The albedo of the most-reflective white-cement concrete was 0.18 to 0.39 higher than that of the most-reflective gray-cement concrete, depending on state of exposure. Concrete albedo generally correlated with cement albedo and sand albedo, and, after abrasion, with rock albedo. Cement albedo had a disproportionately strong influence on the reflectance of concrete. Efflorescence and surface carbonation whitened some gray-cement mixes.

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies, of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098, and by the U.S. Environmental Protection Agency (EPA) under IAG No. DW89938351-01. We acknowledge the support and guidance of Jeanne Briskin, Edgar Mercado, and Eva Wong of the EPA.

We also thank those who provided us with facilities, analysis, and feedback, including Prof. Paulo Monteiro, Prof. Carl L. Monismith, and Lev Stepanov, Department of Civil and Environmental Engineering, University of California at Berkeley; Dr. Melvin Pomerantz and Dr. Paul Berdahl, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory; Dr. Mack Kennedy, Dr. Marshall Parker, and Dr. Matthijs van Soest, Earth Sciences Division, Lawrence Berkeley National Laboratory; Matt McPharlin, the Granite Company; and Martha VanGeem, Construction Technology Laboratories.

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1 Introduction

Increasing the solar reflectance ("albedo") of a paved surface keeps it cooler in the sun, reducing convection of heat from pavement to air and thereby decreasing the ambient air temperature. Lower air temperatures decrease demand for cooling energy and slow the formation of urban smog. Simulations of the influence of pavement albedo on air temperature in Los Angeles predict that increasing the albedo of 1,250 km^2 of pavement by 0.25 would save cooling energy worth $15M yr^{-1}, and reduce smog-related medical and lost-work expenses by $76M yr^{-1} (Rosenfeld et al. 1998).

Most sidewalks and a small fraction of roads and parking areas are paved with portland cement concrete (hereafter, simply "concrete"). Concrete can be made quite reflective through suitable choice of cement and aggregate. Photographic land-cover analyses indicate that pavement covers 41% of the surface of the developed regions of Sacramento, CA (Akbari et al. 1999) and 31% of the surface of the developed regions of Salt Lake City, UT (Akbari and Rose 2001). Assuming that 95% of sidewalks and 5% of roads and parking areas are paved with concrete, concrete covers about 16 to 20% of the paved surface area and 6 to 7% of the total surface area in these two cities (**Table 1**).

Concrete is formed by curing a mixture of cement, water, fine aggregate (sand) and coarse aggregate (stone or crushed rock). Its composition and hence its appearance depend on the progress of the cement hydration reaction, the rate and products of which are well known (Brunauer and Copeland 1964; Papadakis and Vayenas 1991). Color can be imparted by using naturally colored cements, by adding pigments (primarily iron oxides) to the mixture or surface, or by exposing colored aggregate (Lea 1998; Hurd 1993; Kirk-Othmer 1979; Nasvik 2000; Schierhorn 1996; Hurd 1988). Concrete surfaces can be "frosted"—that is, coated with a white film—through efflorescence (the leaching of salts, particularly calcium hydroxide, from interior to surface) and carbonation (the reaction of calcium hydroxide with atmospheric carbon dioxide to form calcium carbonate) (Kenney 1996; Hooker 1994; Newman 2000). Soiling, wetting, growth of lichen and moss, and reactions with certain aggregates (e.g., iron pyrites) are also known to change the appearance of concrete (Goode 1991).

The visible reflectance of pavement is of interest to transportation engineers concerned with lane marking and artificial illumination of roads (CIE/PIARC 1977; Homburger and Kell 1984; IES 1983); some measurements are available (Jung et al. 1984; Jackett and Fisher 1974). However, a surface's

Table 1. Concrete-pavement land coverage in two cities. *Shown are pavement coverage of Sacramento, CA and Salt Lake City, UT, and the fractions of paved surface areas and total surface areas covered with concrete. It is assumed that 95% of sidewalks and 5% of roads and parking areas are concrete.*

	Land Cover Fraction				**Coverage By Concrete**	
City	**Roads**	**Sidewalks**	**Parking Areas**	**All Pavements**	**Paved Surfaces**	**All Surfaces**
Sacramento, CA	24%	5%	12%	41%	16%	7%
Salt Lake City, UT	15%	5%	11%	31%	20%	6%

solar reflectance can differ from its visible reflectance because visible light (wavelengths 400-700 nm) accounts for only 43% of the energy in the solar spectrum (300-2,500 nm). Another 52% lies in the near-infrared (700-2,500 nm), and 5% in the ultraviolet (300-400 nm) (ASTM 1998). No studies of the influences of composition and/or exposure on the solar reflectance of concrete were found in an extensive electronic search of engineering, physics, material science, and transportation literatures.

There are no standard tests for the variation of the solar reflectance of pavement with weathering, wetting, abrasion, or soiling, though ASTM Practice G154-00ae1 ("standard practice for operating fluorescent light apparatus for UV exposure of nonmetallic materials") provides test cycles that simulate weathering by moisture and direct sunlight (ASTM 2001), and ASTM Practice E660-90 (1996) ("standard practice for accelerated polishing of aggregates or pavement surfaces using a small-wheel, circular track polishing machine") specifies a procedure for the accelerated polishing of pavement (ASTM 1999).

In this study, the variation with composition and environmental exposure of the solar reflectance of portland cement concrete pavement is investigated through laboratory fabrication and exposure of 32 mixes of concrete. The terms albedo and reflectance will be used interchangeably to denote solar reflectance.

2 Experiment

Concrete cylinders were cast from a variety of cements, sands, and rocks, and then exposed to simulated weathering, soiling, abrasion, and rain. Their albedos were measured before and after exposure over a 69-week period, and compared to those of their constituents.

2.1 Albedo Measurements

Five (or in the case of cut concrete surfaces, 10) readings of a solar-spectrum reflectometer (Devices & Services model SSR-ER; 300-2,500 nm) were averaged to measure air-mass 1.5 albedos[1] of cements, sands, rocks, and concretes. Since wetting markedly changes the reflectance of most surfaces (Twomey et al. 1986), aggregates and concretes not intentionally wetted were dried—aggregates on a hot plate, and concretes with a hot-air gun—prior to albedo measurement.

The rocks were too small to fill the 25-mm-diameter aperture of the reflectometer, and too irregularly shaped to combine to form a larger flat surface. To determine their albedos, measurements were

[1] The air-mass 1.5 albedo of a surface refers to its ability to reflect sunlight that has a spectral irradiance distribution characteristic of having traversed an atmospheric path length equal to 1.5 times the height of the earth's atmosphere. This path length corresponds to a solar altitude of 42°. An air-mass 1.5 irradiance is representative of average conditions in the contiguous United States (ASTM 1998).

made with the aperture covered by a black disk with an 8-mm-diameter hole. The albedo of each rock, ρ_r, was calculated from

$$\rho_r = \rho_b + (\rho_w - \rho_b) \times \frac{\rho'_r - \rho'_b}{\rho'_w - \rho'_b}$$

where ρ'_w, ρ'_b, and ρ'_r were the reflectances measured through the disk of a white standard, a black standard, and the rock face, respectively; and ρ_w and ρ_b were the albedos of the white and black standards, respectively.

Some concretes had rough surfaces that allowed light to escape from the reflectometer-surface interface, yielding erroneously low measurements. The magnitude of this error is unknown.

2.2 Cement, Sand, and Rock Properties

Thirty-two mixes of concrete were cast from two types of cement (C1, C2: albedo ρ=0.32, 0.87); four types of sand (S1…S4: ρ=0.20, 0.22, 0.27, 0.45); and four types of rock (R1…R4: ρ=0.17, 0.19, 0.49, 0.55) (**Figure 1**). Components were chosen for their varied colors and reflectances, and are numbered in order of increasing albedo.

One of the sands (S2, basalt) is naturally dark red in color. The other three sands (S1, a dark gray riverbed sand; S3, a brown sand; and S4, a tan beach sand) were observed to contain primarily transparent or white materials: quartz, clay minerals, and, in the cases of S1 and S4, mica. This suggests that these sands contain other mineral colorants. Red, brown, and black iron-oxide impurities (**Table 2**) are common because oxygen (O) and iron (Fe) constitute about 46% and 6%, respectively, of the mass of the Earth's crust (Lide 1990). For example, the white cement (C2) appears lighter than the gray cement (C1) because it contains less hematite, an iron oxide (**Table 3**). The four rocks (R1, dark red basalt; R2, black and red granite; R3, white plagioclase; and R4, gold and white chert with iron impurities) were dusty.

Table 2. Colors of some iron-oxide minerals.

name	formula	color
hematite	Fe_2O_3	red-brown to black
magnetite	Fe_3O_4	black or red-black
goethite	$FeO(OH)$	brown or blackish
wuestite	FeO	black

Sand particle size distributions were measured with a six-sieve cascade [U.S. standard mesh numbers 14 (1.41 mm), 18 (1.00 mm), 20 (0.850 mm), 35 (0.500 mm), 60 (0.250 mm), and 230 (0.063 mm)]. Rock size distributions were determined by measuring the mass m_i of each of 10 randomly selected samples, and measuring the volume of water V displaced by all 10 samples. The diameter of each sample, d_i, was approximated by

$$d_i = (m_i V / M)^{1/3}$$

where M is the total mass of the 10 samples. Sand mass-mean diameters ranged from 0.40 to 0.98 mm, while rock mass-mean diameters ranged from 14 to 18 mm (**Figure 2**).

Cements	 **C1** (ρ=0.32) gray type I-II portland cement	 **C2** (ρ=0.87) white type I portland cement		
Sands	 **S1** (ρ=0.20) dark gray riverbed sand (quartz, clay minerals, mica) d_{50}=0.40 mm	 **S2** (ρ=0.22) dark red volcanic sand (basalt) d_{50}=0.53 mm	 **S3** (ρ=0.27) brown sand (quartz, clay minerals) d_{50}=0.98 mm	 **S4** (ρ=0.45) tan beach sand (quartz, clay minerals, micas) d_{50}=0.70 mm
Rocks	 **R1** (ρ=0.17) dark red volcanic rock (basalt) d_{50}=18 mm	 **R2** (ρ=0.19) black and red rock (granite) d_{50}=16 mm	 **R3** (ρ=0.49) white rock (plagioclase) d_{50}=14 mm	 **R4** (ρ=0.55) gold and white rock (chert, iron impurities) d_{50}=16 mm

Figure 1. Properties of concrete components. *Shown are the albedo ρ, mass-mean diameter d_{50}, composition and image of each of the two cements, four sands, and four rocks used to form 32 mixes of concrete.*

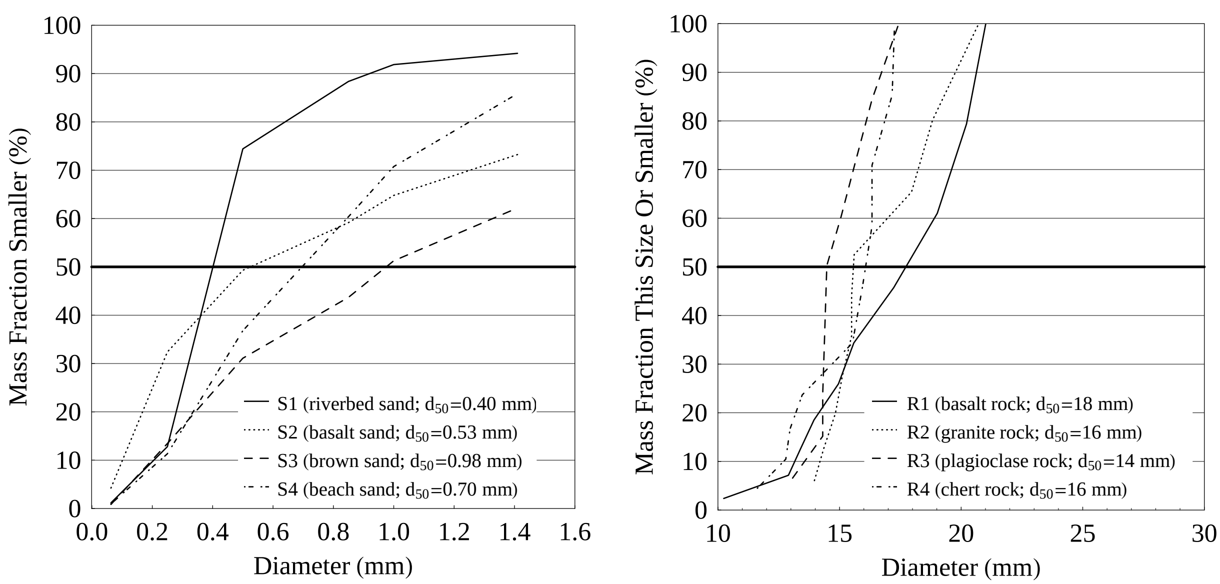
Table 3. Cement compositions. *Shown are manufacturer-reported chemical mass fractions of the gray and white cements. The gray cement is colored primarily by hematite (Fe_2O_3).*

Cement	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)
gray type I-II (C1)	21.9	4.3	3.5	63.6	1.9	2.5
white type I (C2)	22.7	5.1	0.2	67.5	0.8	2.7

2.3 Concrete Fabrication

Cement, sand, rock, and water were hand mixed in medium-strength-concrete mass proportions of 1/2.3/2.8/0.6 (Mehta 1993), and poured into 100-mm-high, 100-mm-diameter cylindrical plastic molds. The wet concrete was rodded, vibrated, and troweled to uniformly distribute aggregate, remove air bubbles, and level the "finished" upper surface. The molds were sealed at time t=0 and their contents hardened overnight, after which the concrete cylinders were removed from their molds to cure for five days in a saturated-air environment.

A 25-mm-thick disk was sliced from the top of each concrete cylinder with a water-cooled, diamond-tipped blade. The disks were quartered to provide quadruplicate, 32-member sample sets designated I…IV. Each concrete quarter-disk had a finished (i.e., unformed and uncut) upper surface and a smooth, diamond-cut lower surface (**Figure 3**).



(a) **(b)**

Figure 2. Sand and rock sizes. *Shown are the size distributions and mass-mean diameters [d_{50}] of (a) sands S1…S4 and (b) rocks R1…R4.*

Concrete strengths were not measured, but mixes incorporating sand S2 (basalt), sand S3 (quartz, clay minerals), rock R1 (basalt), or rock R4 (chert, iron impurities) had finished surfaces that tended to crumble easily, show rock, and/or be rough. These 24 substandard mixes will be labeled "rough," while the remaining eight mixes, which appeared solid and smooth, will be labeled "smooth." Air voids were sometimes observed at the formed bottom surfaces of the rough concrete cylinders (**Figure 4**).

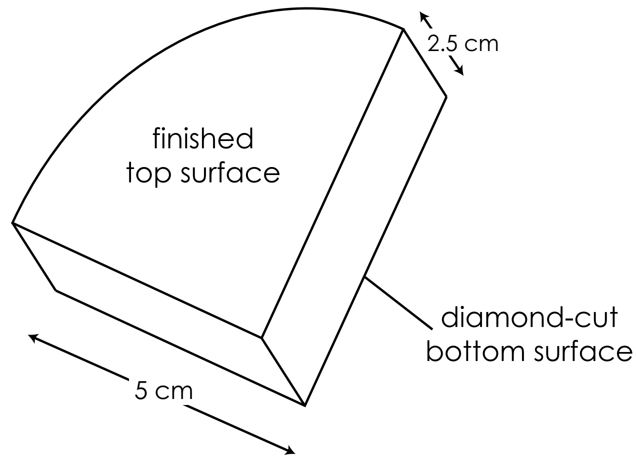


Figure 3. Surfaces of concrete sample quarter-disk. *Each sample had a finished (i.e., uncut and unmolded) top surface and a cut bottom surface.*

High, unmet aggregate water demand (reducing the amount of water available to react with cement, and thereby hindering the formation of cement paste) was likely responsible for the substandard nature of the rough mixes. Attempts to create better-finished concretes by adding more water to these mixes yielded test cylinders that disintegrated when removed from their molds. Proper practice would have been to wash and thereby saturate all aggregates before casting the concretes.

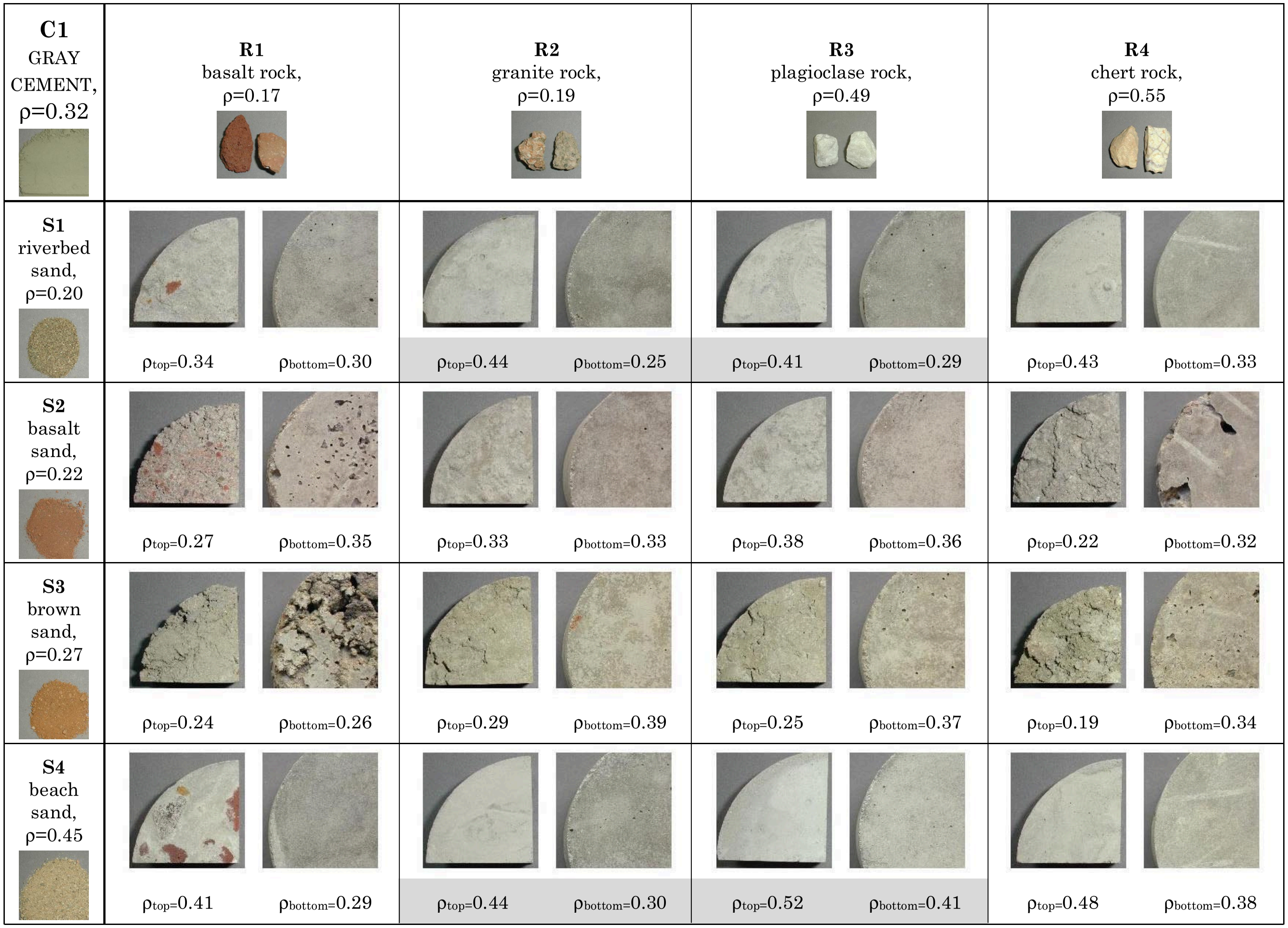
2.4 Exposure Simulations

Each variety of concrete was subjected to the following simulations of pavement exposure processes.

Control Surfaces. The finished surfaces of quarter-disks I and II ("first-control" surface *FC* and "second-control" surface *SC*) were not exposed to processes expected to permanently change surface properties. Surface *FC* was kept dry, while the albedo of surface *SC* was measured both wet and dry to gauge the extent to which rain reduces concrete reflectance.

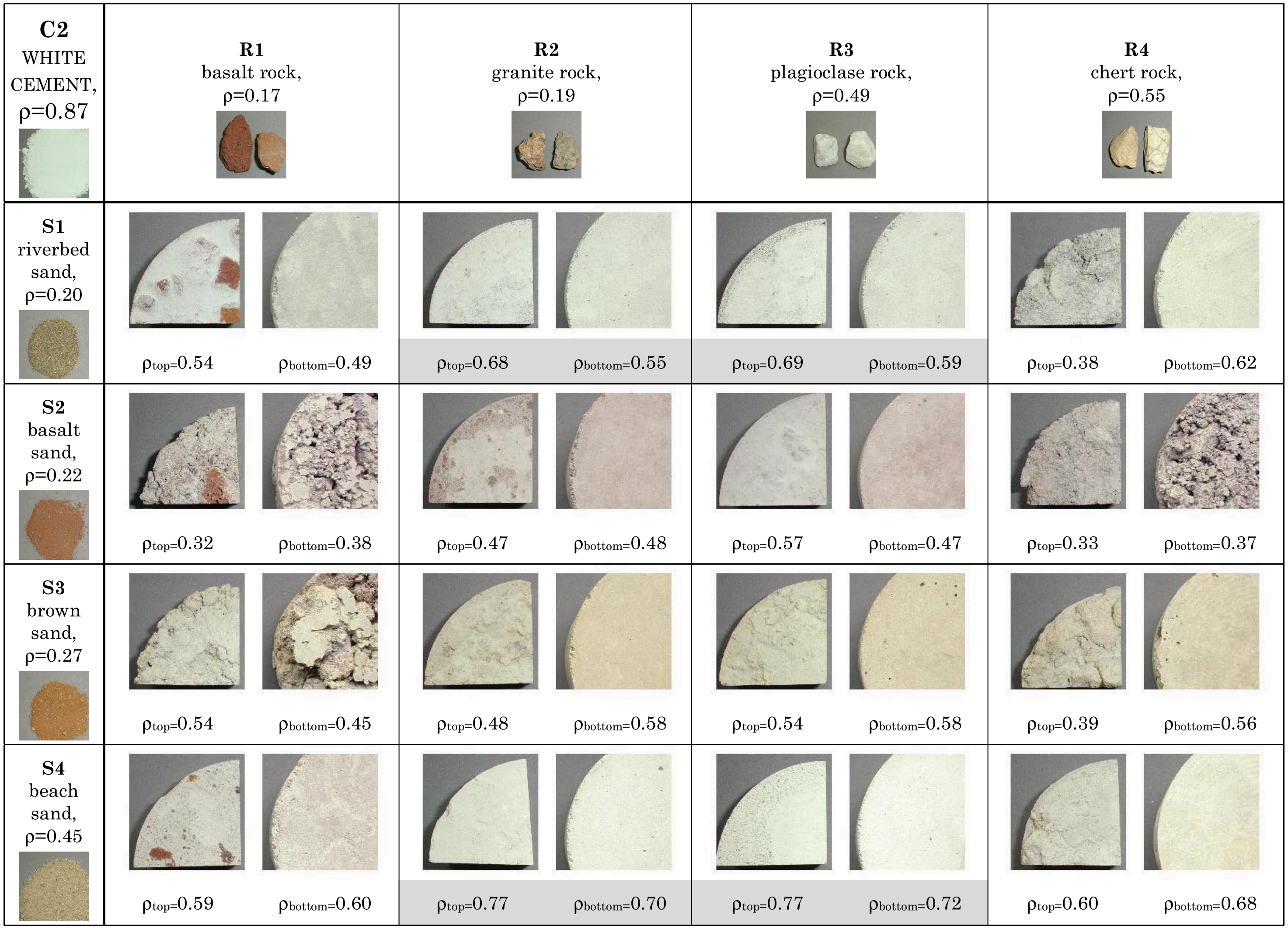
Formed Surfaces. The formed bottom of each cylinder ("formed" surface *FO*) was kept dry and unexposed.

Weathered Surfaces. The finished surface of quarter-disk III ("weathered" surface *WE*) was exposed to 12-hour cycles of deionized water spray, condensation, and intense ultraviolet light for six weeks to simulate the effects of dew and sunlight [ASTM Practice G154-00ae01, cycle seven: UVA 340 nm, 1.35 W m^{-2} nm^{-1}; 8 hr UV light @ 60°C, 10 min spray, 3.75 hr condensation @ 50°C, 5 min spray (ASTM 2001)]. For brevity, this combined UV, water-spray, and condensation exposure will be denoted weathering. The weathering acceleration factor for this test is unknown, but factors of 2 to 35 have been reported for exposure of polymers to similar, but not identical, cycles (Fedor and Brennan 1996). Following exposure, the albedo of surface *WE* was measured both wet and dry.



(i of ii)

Figure 4. Properties of mature, unexposed concretes. *Shown for each of (i) the 16 gray-cement concretes and (ii) the 16 white-cement concretes are the albedo ρ and image of the top [finished] surface at 25 weeks, and the bottom [formed] surface at 69 weeks. The smooth concretes are shaded.*



(ii of ii)

Figure 4. Properties of mature, unexposed concretes. *Shown for each of (i) the 16 gray-cement concretes and (ii) the 16 white-cement concretes are the albedo ρ and image of the top [finished] surface at 25 weeks, and the bottom [formed] surface at 69 weeks. The smooth concretes are shaded.*

Soiled Surfaces. Pavements can be soiled by agents including dirt, oil, rubber, and carbon. Soiling was simulated by dipping the finished surface of quarter-disk IV ("soiled" surface *SO*) in clean motor oil, rubbing the oiled surface in sand S3, and dislodging loose sand with paper toweling. This simulation did not include soiling by rubber or carbon. Surface *SO* was later rinsed and dried to simulate cleaning by rain. Surfaces that were soiled, rinsed, and dried will be labeled "soiled" for brevity.

Abraded Surfaces. Tire abrasion can wear down pavement, exposing rock as mortar is dislodged. A diamond-blade cut at a depth comparable to the diameter of the rock exposes about as much rock as can be revealed by any abrasion process. Thus, the cut surface of quarter-disk II ("abraded" surface *AB*, 25 mm below the finished surface) simulated extreme abrasion. Surface *AB* was otherwise unexposed.

Unexposed and exposed surfaces of all 32 mixes of concrete are shown in **Figure 5**. Concrete albedos were measured at various times over a 69-week post-casting period chronicled in **Figure 6**. The n^{th} measurement of the albedo of surface *XY* is denoted *XYn*; e.g., *AB1* denotes the first measurement of the reflectance of abraded concrete surface *AB.*

3 Results

Aging, exposure, and composition influenced concrete albedo. The effects of aging and exposure on the full set of all 32 concrete mixes were similar to their effects on the subset of eight smooth concrete mixes. The effects of composition on concrete albedo will be presented only for the smooth concretes, since the reflectance of the rough concretes was influenced more by improper casting than by component properties.

Changes to the albedos of a set of surfaces can be characterized by the mean change δ, which indicates on average whether the albedos are increasing or decreasing, and by the root-mean-square change χ, which measures the average magnitude of the changes. If χ is zero, no albedos have changed. If δ is zero but χ is finite, increases and decreases have cancelled on average. The subscript "s" will be used to denote properties of the set of eight smooth mixes, and the subscript "a" to denote the set of all 32 mixes.