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Effects of composition and exposure on the solar reflectance of portland cement concrete

Ronnen Levinson*, Hashem Akbari

Heat Island Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA

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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. Lower air temperatures decrease demand for cooling energy and slow the formation of urban smog. 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. 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. Simulated weathering, soiling, and abrasion each reduced average concrete albedo, though some samples became slightly more reflective through weathering or soiling. Concrete albedo grew as the cement hydration reaction progressed, but stabilized within six weeks of casting.

Keywords: Solar reflectance; Concrete; Aggregate; Acceleration; Aging

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 1250 km^2 of pavement by 0.25 would save cooling energy worth \$15 million $year^{-1}$, and reduce smog-related medical and lost-work expenses by \$76 million $year^{-1}$ [1].

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 [2]; 31% of the surface of the developed regions of Salt Lake City, UT [3]; and 34% of the surface of the developed regions of metropolitan Chicago, IL [4]. Assuming that 95% of sidewalks and 5% of roads and parking areas are paved with concrete, concrete covers about 14% to 20% of the paved surface areas and 5% to 7% of the total surface areas in these three cities (Table 1).

Concrete is formed by curing a mixture of cement, water, fine aggregate (sand) and coarse aggregate (stone or crushed rock). Once mixed, its chemical composition and hence its appearance depend on the progress of the cement hydration reaction, the rate and products of which are well known [5,6]. 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 [7–12]. 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) [13–15]. 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 [16].

The visible reflectance of pavement is of interest to transportation engineers concerned with lane marking and

* Corresponding author. Tel.: +1-510-486-7494; fax: +1-425-955-1992.
E-mail address: rmlevinson@lbl.gov (R. Levinson).

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Table 1
Concrete-pavement land coverage in three cities

City	Land cover fraction				Coverage by concrete	
	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
Chicago, IL	16	3	14	34	14	5

Shown are pavement coverages of Sacramento, CA; Salt Lake City, UT; and Chicago, IL; 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.

artificial illumination of roads [17–19]; some measurements are available [20,21]. However, a surface's *solar* reflectance can differ from its visible reflectance because visible light (wavelengths 400–700 nm) typically accounts for only 43% of the energy in the solar spectrum (300–2500 nm). Another 52% lies in the near-infrared (700–2500 nm), and 5% in the ultraviolet (300–400 nm) [22]. 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 [23], 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 [24].

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 and Services model SSR-ER; 300–2500 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 [25], 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 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 $\rho = 0.32, 0.87$); four types of sand (S1–S4: $\rho = 0.20, 0.22, 0.27, 0.45$); and four types of rock (R1–R4: $\rho = 0.17, 0.19, 0.49, 0.55$) (Fig. 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

[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 [22].

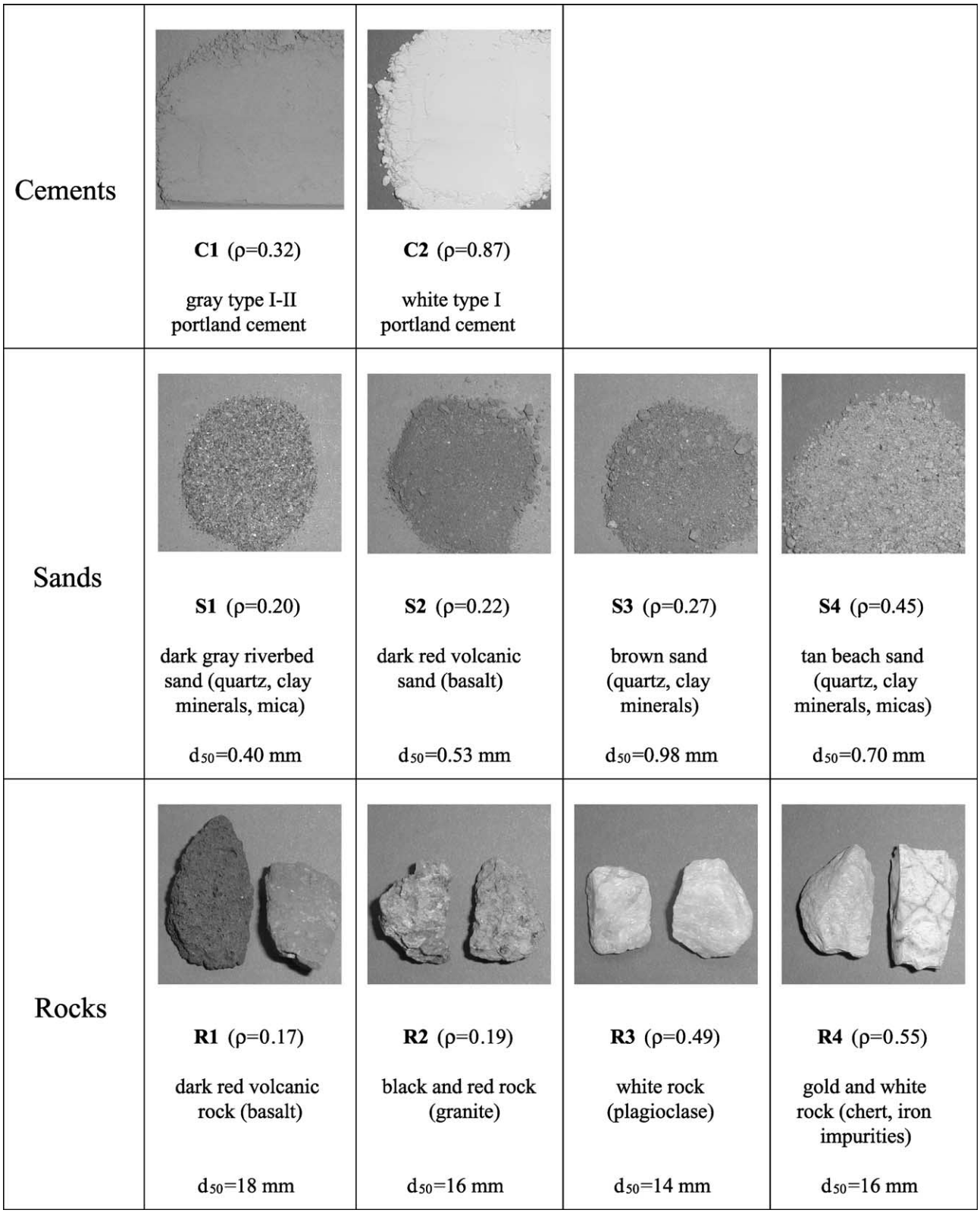


Fig. 1. Properties of concrete components. Shown are the albedo ρ, mass mean diameter d_{50}, composition and image of each of the two cements, four sands, and four rocks used to form 32 mixes of concrete.

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 [26]. For example, the white cement (C2) appears lighter than the

Table 2
Colors of some iron oxide minerals [26]

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

gray cement (C1) because it contains less hematite, an iron oxide. 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.

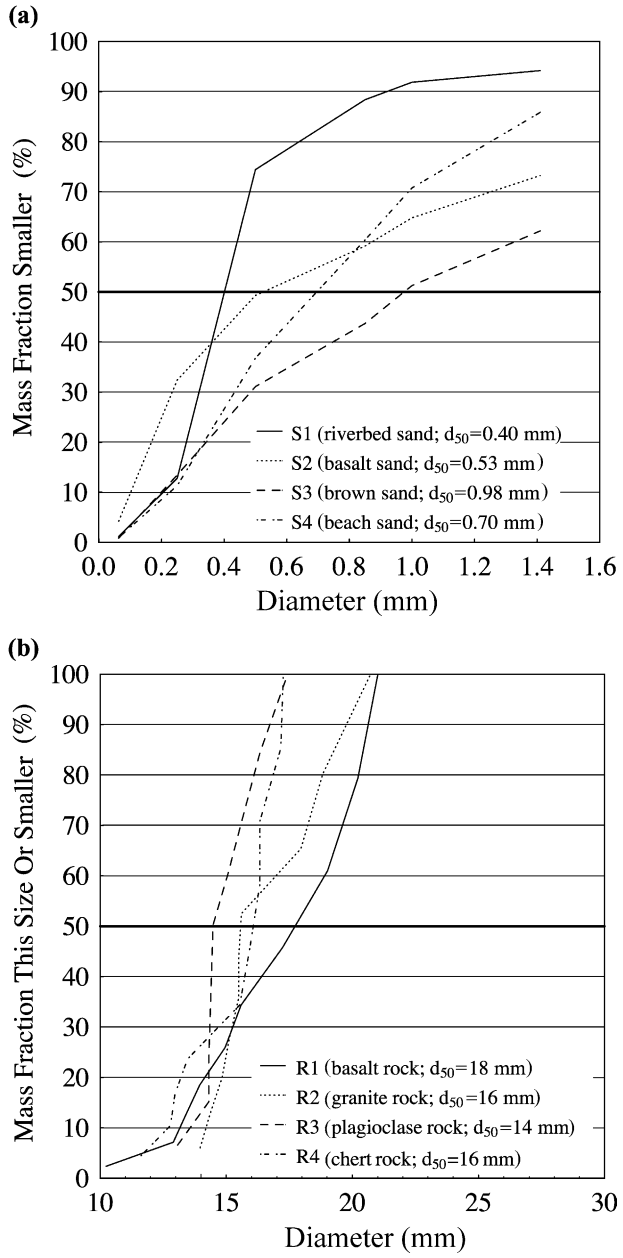


Fig. 2. Sand and rock sizes. Shown are the size distributions and mass mean diameters (d_{50}) of (a) sands S1–S4 and (b) rocks R1–R4.

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 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 (Fig. 2).

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 [27], 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 (Fig. 3).

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

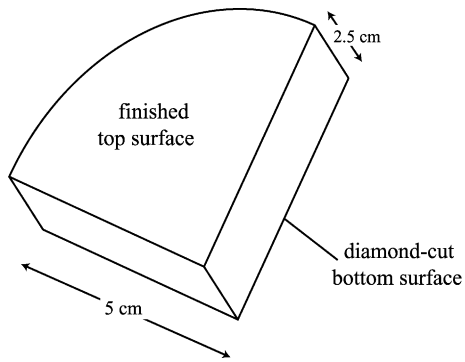


Fig. 3. Surfaces of concrete sample quarter-disk. Each sample had a finished (i.e., unformed and uncut) top surface and a cut bottom surface.

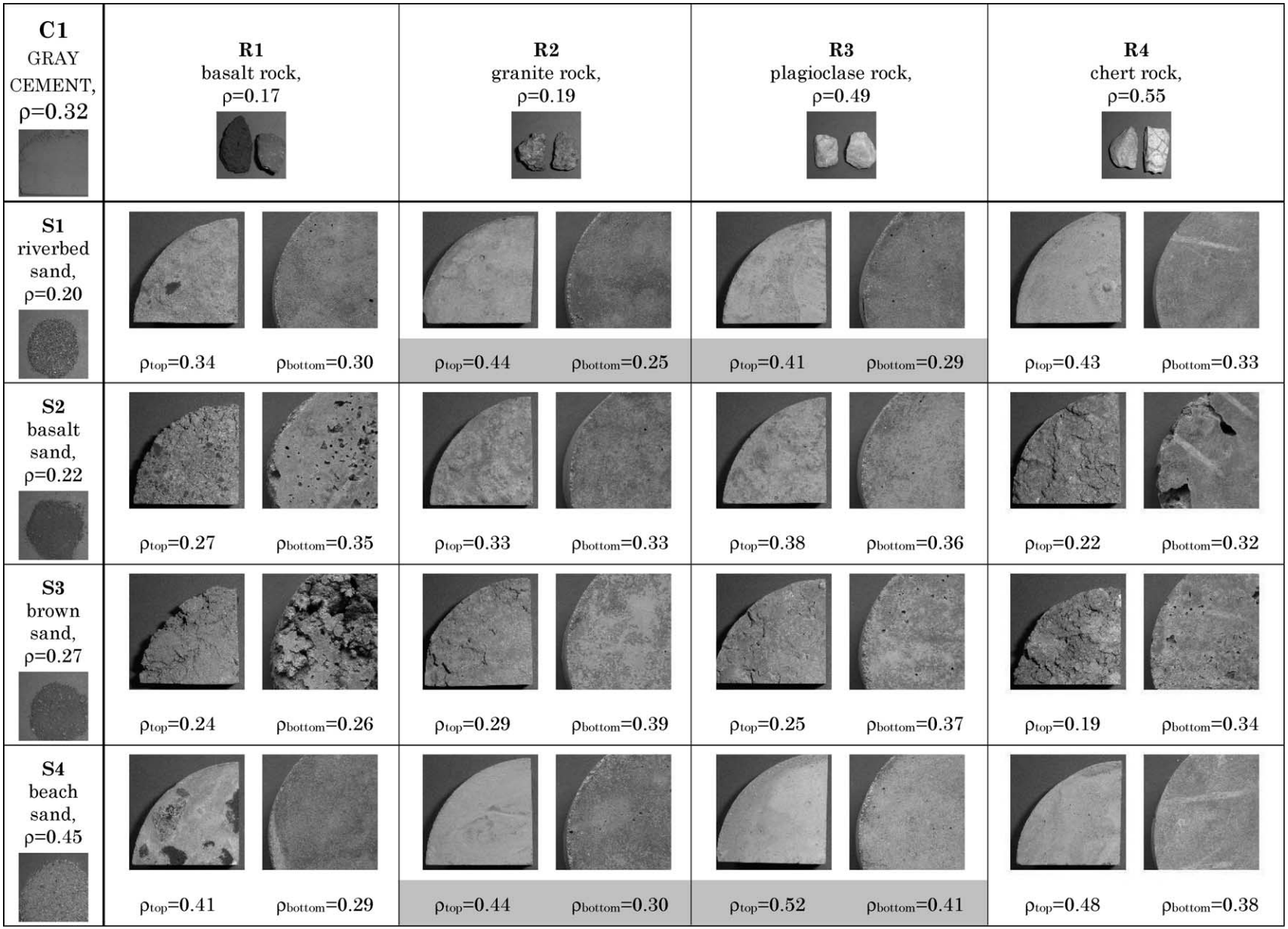


Fig. 4. Properties of mature, unexposed concretes. Shown for each of (i) the 16 gray-cement concretes and (ii) the 16 white-cement concretes are the albedo ρ and image of the top (finished) surface at 25 weeks, and the bottom (formed) surface at 69 weeks. The smooth concretes are shaded.

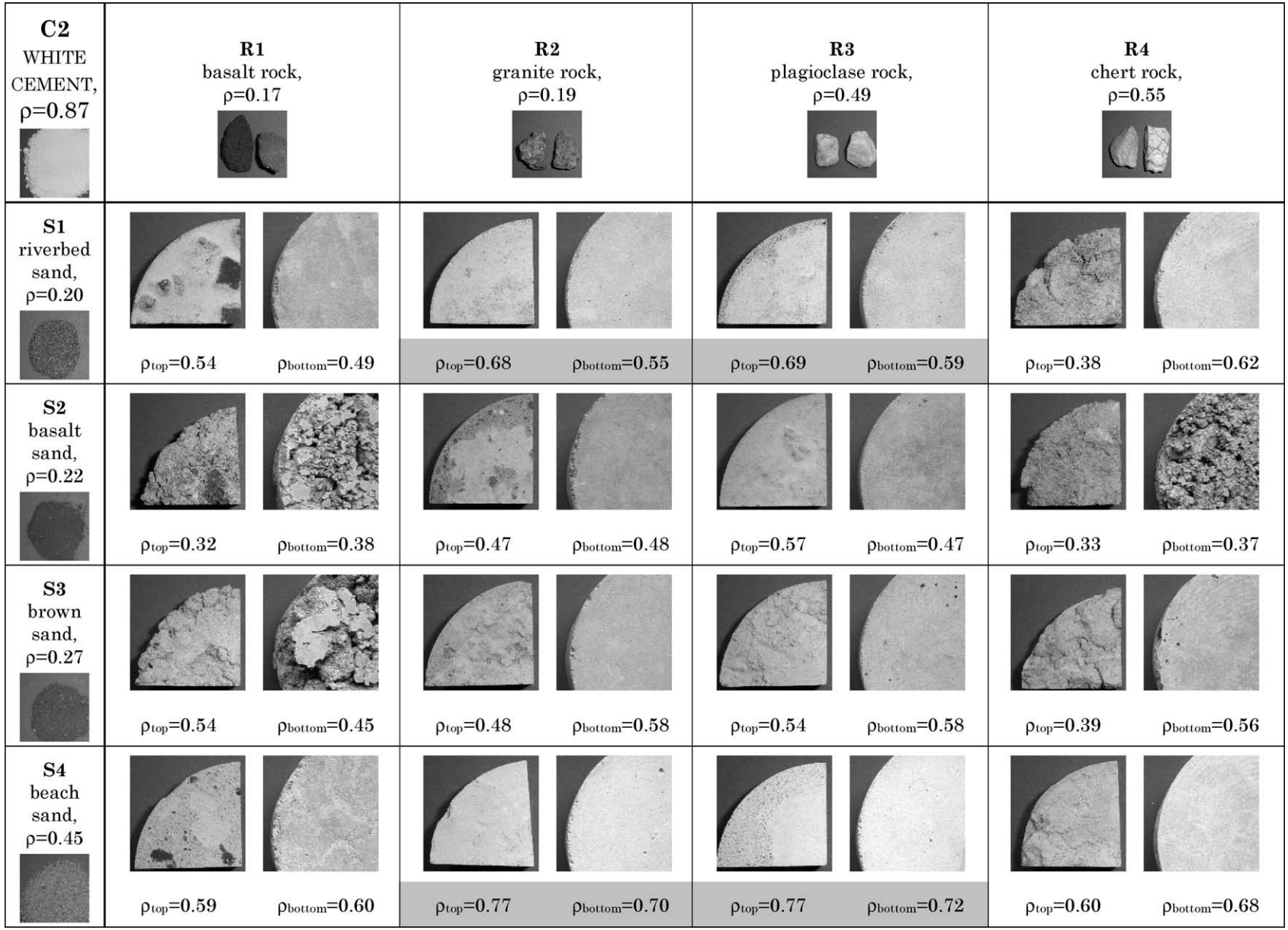


Fig. 4 (*continued*).

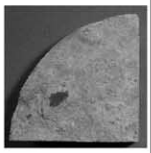
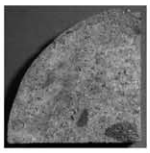
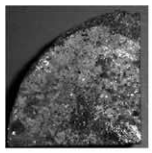
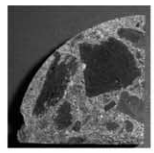
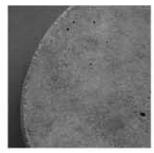
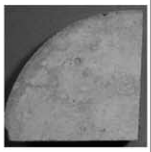
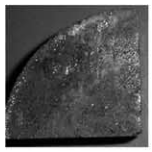
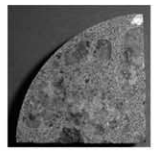
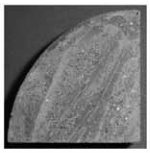
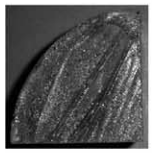
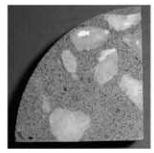
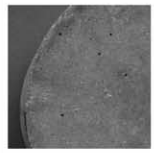
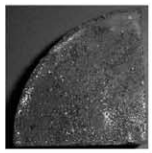
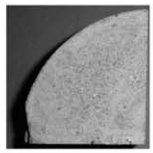
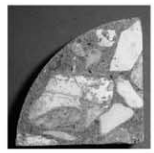
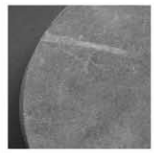
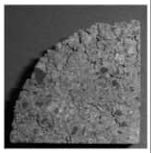
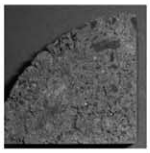
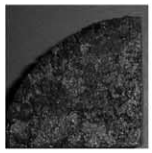
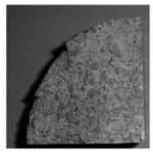
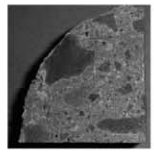
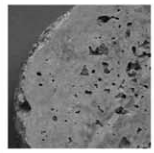
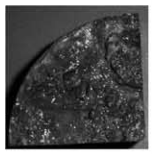
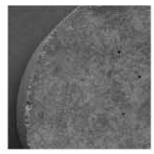
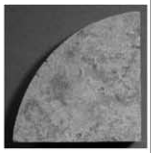
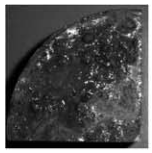
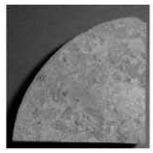
Concrete	**(a)** Unexposed @ 25 weeks (*FC2*)	**(b)** Weathered @ 25 weeks (*WE5*)	**(c)** Weathered, wetted @ 20 weeks (*WE4*)	**(d)** Soiled @ 35 weeks (*SO4*)	**(e)** Abraded @ 25 weeks (*AB2*)	**(f)** Formed @ 69 weeks (*FO1*)
C1:S1:R1 gray cement/ riverbed sand/ basalt rock	 ρ=0.34	 ρ=0.27	 ρ=0.18	 ρ=0.38	 ρ=0.13	 ρ=0.30
C1:S1:R2 gray cement/ riverbed sand/ granite rock	 ρ=0.44	 ρ=0.34	 ρ=0.14	 ρ=0.43	 ρ=0.24	 ρ=0.25
C1:S1:R3 gray cement/ riverbed sand/ plagioclase rock	 ρ=0.41	 ρ=0.30	 ρ=0.13	 ρ=0.36	 ρ=0.31	 ρ=0.29
C1:S1:R4 gray cement/ riverbed sand/ chert rock	 ρ=0.43	 ρ=0.36	 ρ=0.22	 ρ=0.41	 ρ=0.55	 ρ=0.33
C1:S2:R1 gray cement/ basalt sand/ granite rock	 ρ=0.27	 ρ=0.23	 ρ=0.14	 ρ=0.27	 ρ=0.25	 ρ=0.35
C1:S2:R2 gray cement/ basalt sand/ granite rock	 ρ=0.33	 ρ=0.25	 ρ=0.12	 ρ=0.33	 ρ=0.24	 ρ=0.33
C1:S2:R3 gray cement/ basalt sand/ plagioclase rock	 ρ=0.38	 ρ=0.30	 ρ=0.15	 ρ=0.36	ρ=0.33	ρ=0.36
C1:S2:R4 gray cement/ basalt sand/ chert rock	ρ=0.22	ρ=0.23	ρ=0.11	ρ=0.26	ρ=0.41	ρ=0.32

Fig. 5. Properties of all mature concretes. Images and albedos ρ of all 32 mixes of concrete are shown (a) unexposed, (b) weathered, (c) weathered and wetted, (d) soiled, (e) abraded, and (f) formed. Smooth concretes are shaded.

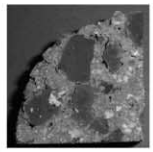
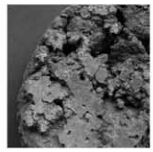
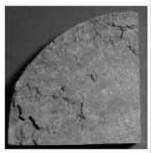
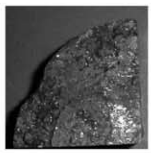
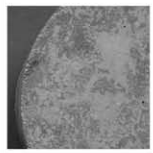
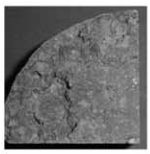
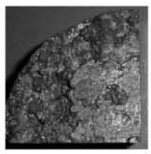
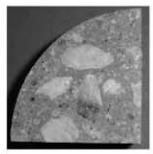
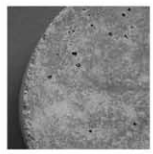
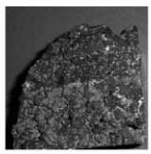
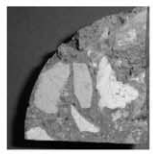
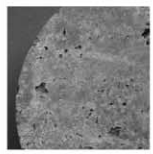
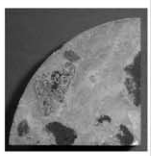
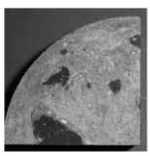
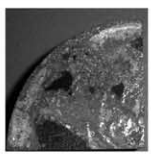
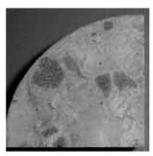
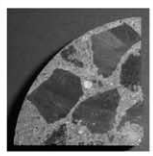
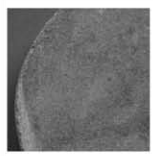
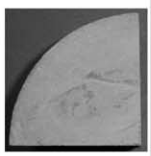
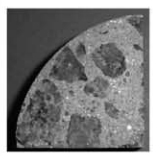
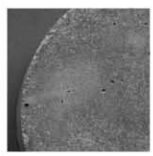
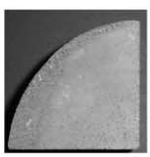
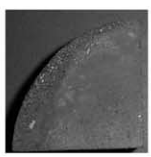
Concrete	**(a)** Unexposed @ 25 weeks (*FC2*)	**(b)** Weathered @ 25 weeks (*WE5*)	**(c)** Weathered, wetted @ 20 weeks (*WE4*)	**(d)** Soiled @ 35 weeks (*SO4*)	**(e)** Abraded @ 25 weeks (*AB2*)	**(f)** Formed @ 69 weeks (*FO1*)
C1:S3:R1 gray cement/ brown sand/ basalt rock	 ρ=0.24	 ρ=0.20	 ρ=0.12	 ρ=0.27	 ρ=0.23	 ρ=0.26
C1:S3:R2 gray cement/ brown sand/ granite rock	 ρ=0.29	 ρ=0.31	 ρ=0.18	 ρ=0.29	 ρ=0.28	 ρ=0.39
C1:S3:R3 gray cement/ brown sand/ plagioclase rock	 ρ=0.25	 ρ=0.24	 ρ=0.19	 ρ=0.29	 ρ=0.36	 ρ=0.37
C1:S3:R4 gray cement/ brown sand/ chert rock	 ρ=0.19	 ρ=0.20	 ρ=0.10	 ρ=0.19	 ρ=0.53	 ρ=0.34
C1:S4:R1 gray cement/ beach sand/ basalt rock	 ρ=0.41	 ρ=0.37	 ρ=0.18	 ρ=0.35	 ρ=0.27	 ρ=0.29
C1:S4:R2 gray cement/ beach sand/ granite rock	 ρ=0.44	 ρ=0.40	 ρ=0.17	 ρ=0.45	 ρ=0.31	 ρ=0.30
C1:S4:R3 gray cement/ beach sand/ plagioclase rock	 ρ=0.52	 ρ=0.44	 ρ=0.19	 ρ=0.50	ρ=0.43	ρ=0.41
C1:S4:R4 gray cement/ beach sand/ chert rock	ρ=0.48	ρ=0.40	ρ=0.19	ρ=0.42	ρ=0.41	ρ=0.38

Fig. 5 (*continued*).

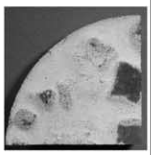
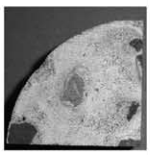
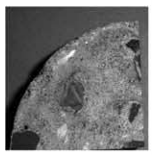
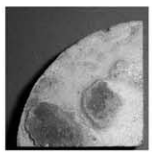
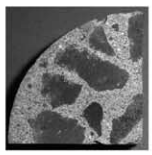
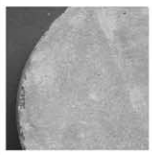
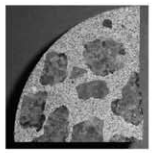
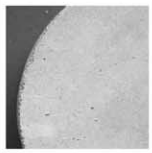
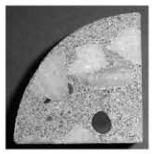
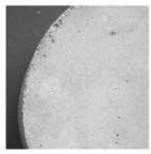
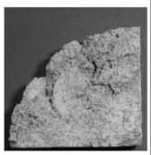
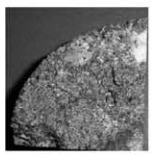
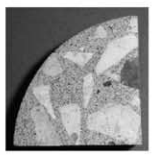
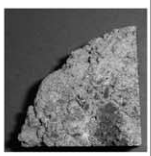
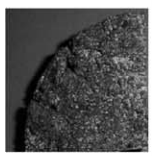
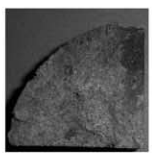
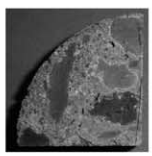
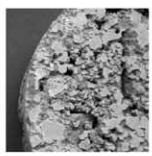
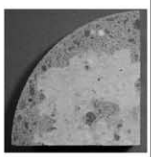
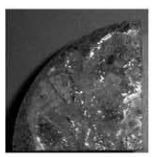
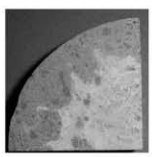
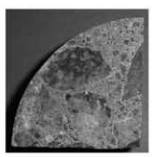
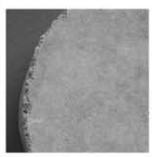
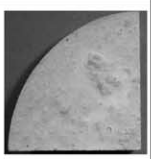
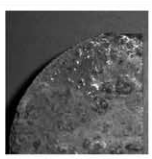
Concrete	**(a)** Unexposed @ 25 weeks (*FC2*)	**(b)** Weathered @ 25 weeks (*WE5*)	**(c)** Weathered, wetted @ 20 weeks (*WE4*)	**(d)** Soiled @ 35 weeks (*SO4*)	**(e)** Abraded @ 25 weeks (*AB2*)	**(f)** Formed @ 69 weeks (*FO1*)
C2:S1:R1 white cement/ riverbed sand/ basalt rock	 ρ=0.54	 ρ=0.37	 ρ=0.21	 ρ=0.37	 ρ=0.27	 ρ=0.49
C2:S1:R2 white cement/ riverbed sand/ granite rock	 ρ=0.68	 ρ=0.61	 ρ=0.34	 ρ=0.62	 ρ=0.33	 ρ=0.55
C2:S1:R3 white cement/ riverbed sand/ plagioclase rock	 ρ=0.69	 ρ=0.60	 ρ=0.34	 ρ=0.61	 ρ=0.44	 ρ=0.59
C2:S1:R4 white cement/ riverbed sand/ chert rock	 ρ=0.38	 ρ=0.40	 ρ=0.19	 ρ=0.36	 ρ=0.50	 ρ=0.62
C2:S2:R1 white cement/ basalt sand/ basalt rock	 ρ=0.32	 ρ=0.27	 ρ=0.13	 ρ=0.26	 ρ=0.24	 ρ=0.38
C2:S2:R2 white cement/ basalt sand/ granite rock	 ρ=0.47	 ρ=0.48	 ρ=0.26	 ρ=0.47	 ρ=0.19	 ρ=0.48
C2:S2:R3 white cement/ basalt sand/ plagioclase rock	 ρ=0.57	 ρ=0.47	 ρ=0.25	 ρ=0.47	ρ=0.34	ρ=0.47
C2:S2:R4 white cement/ basalt sand/ chert rock	ρ=0.33	ρ=0.37	ρ=0.19	ρ=0.19	ρ=0.39	ρ=0.37

Fig. 5 (*continued*).

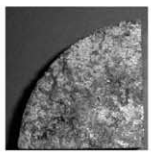
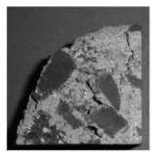
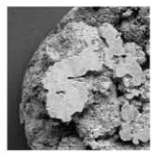
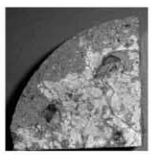
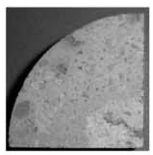
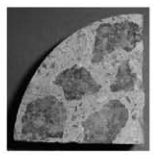
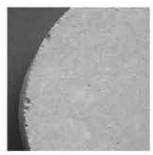
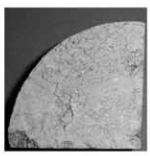
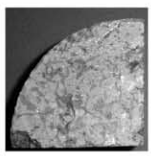
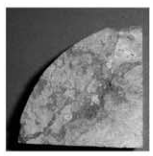
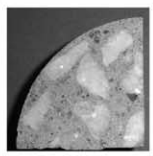
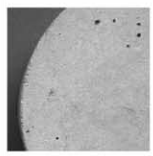
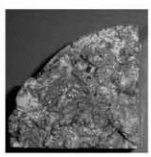
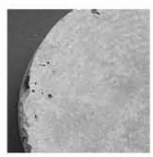
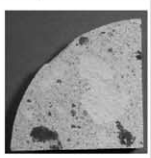
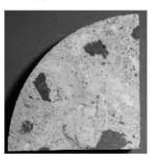
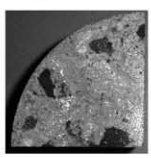
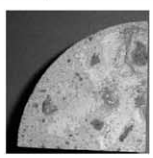
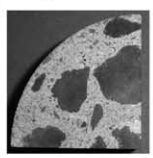
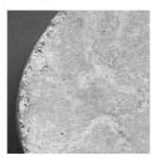
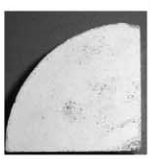
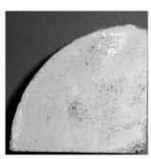
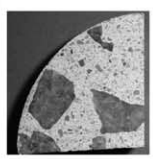
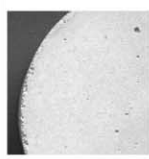
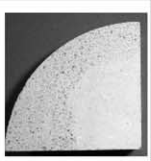
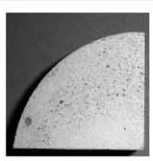
Concrete	**(a)** Unexposed @ 25 weeks (*FC2*)	**(b)** Weathered @ 25 weeks (*WE5*)	**(c)** Weathered, wetted @ 20 weeks (*WE4*)	**(d)** Soiled @ 35 weeks (*SO4*)	**(e)** Abraded @ 25 weeks (*AB2*)	**(f)** Formed @ 69 weeks (*FO1*)
C2:S3:R1 white cement/ brown sand/ basalt rock	 ρ=0.54	 ρ=0.46	 ρ=0.29	 ρ=0.45	 ρ=0.24	 ρ=0.45
C2:S3:R2 white cement/ brown sand/ granite rock	 ρ=0.48	 ρ=0.46	 ρ=0.37	 ρ=0.48	 ρ=0.33	 ρ=0.58
C2:S3:R3 white cement/ brown sand/ plagioclase rock	 ρ=0.54	 ρ=0.45	 ρ=0.41	 ρ=0.37	 ρ=0.48	 ρ=0.58
C2:S3:R4 white cement/ brown sand/ chert rock	 ρ=0.39	 ρ=0.40	 ρ=0.21	 ρ=0.39	 ρ=0.51	 ρ=0.56
C2:S4:R1 white cement/ beach sand/ basalt rock	 ρ=0.59	 ρ=0.57	 ρ=0.33	 ρ=0.52	 ρ=0.30	 ρ=0.60
C2:S4:R2 white cement/ beach sand/ granite rock	 ρ=0.77	 ρ=0.78	 ρ=0.56	 ρ=0.65	 ρ=0.52	 ρ=0.70
C2:S4:R3 white cement/ beach sand/ plagioclase rock	 ρ=0.77	 ρ=0.79	 ρ=0.58	 ρ=0.68	ρ=0.61	ρ=0.72
C2:S4:R4 white cement/ beach sand/ chert rock	ρ=0.60	ρ=0.67	ρ=0.45	ρ=0.54	ρ=0.69	ρ=0.68

Fig. 5 (*continued*).

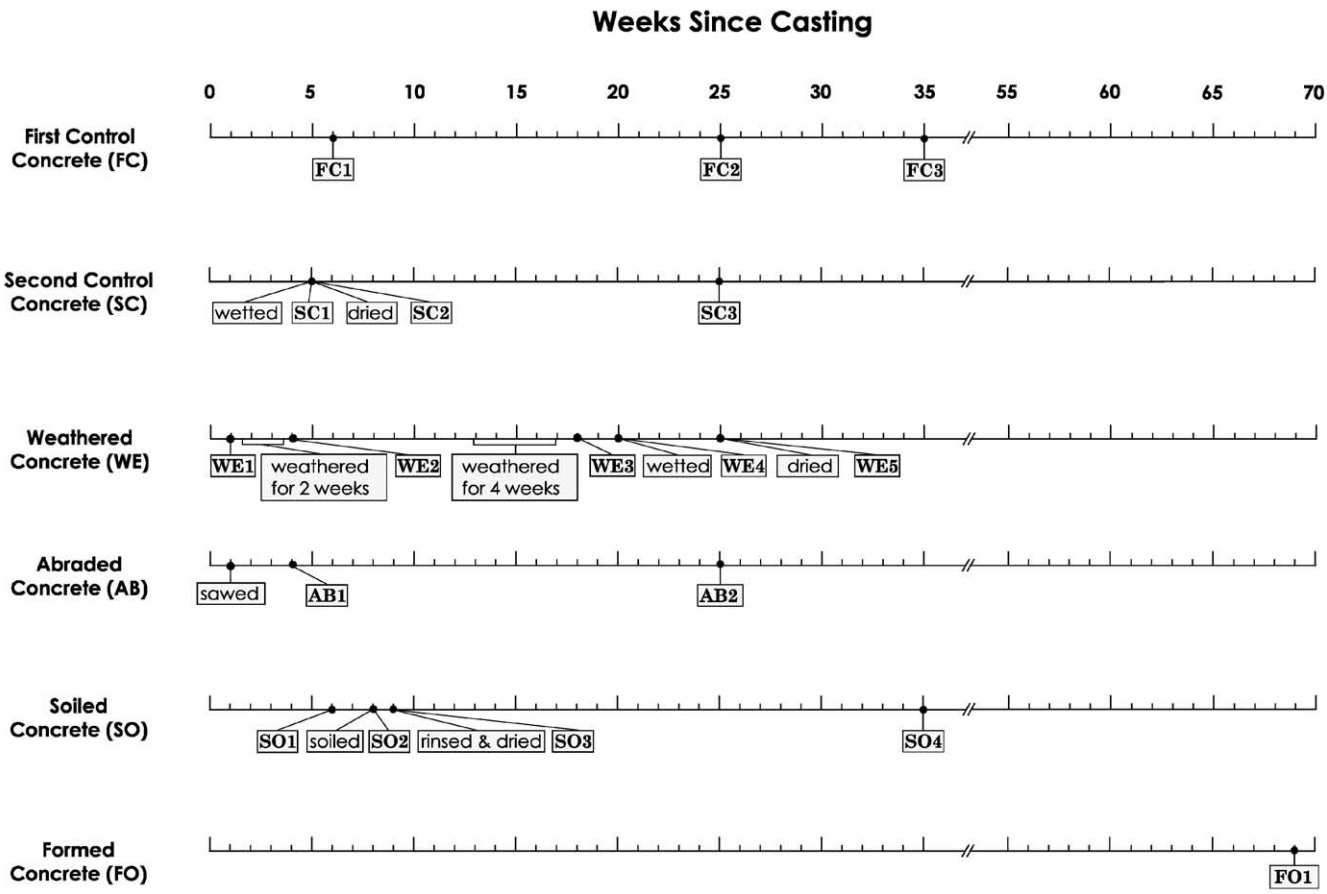


Fig. 6. Experiment timeline. Shown are the exposure and reflectance-measurement histories of six concrete-surface sets. Labels of the form AB1 denote albedo measurements.

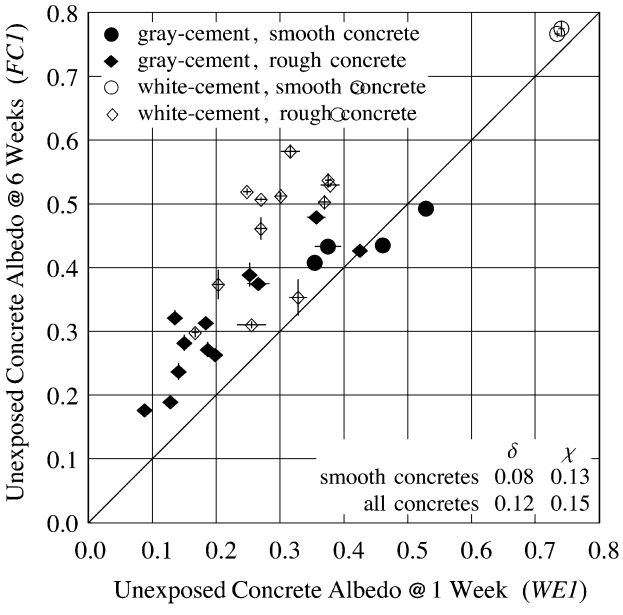


Fig. 7. Concrete albedo growth. The albedos of most unexposed concretes increased from Week 1 to Week 6. δ and χ are mean and root mean square differences in albedo; the diagonal line marks equality.

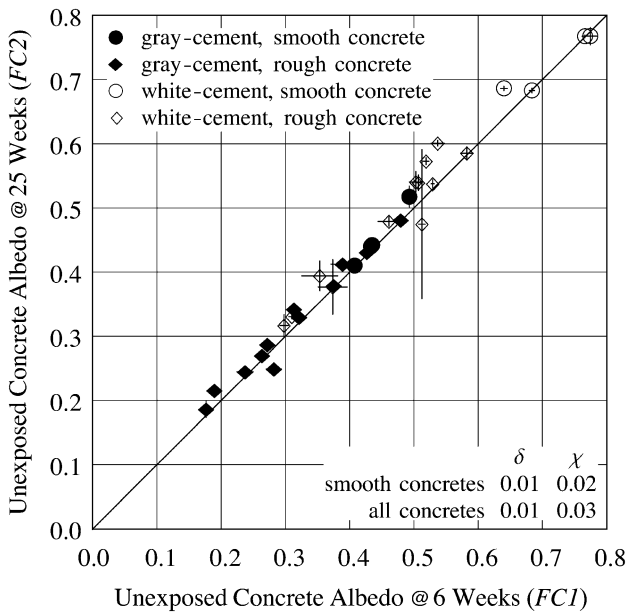


Fig. 8. Concrete albedo stabilization. The albedos of unexposed concretes increased very slowly after Week 6.

sometimes observed at the formed bottom surfaces of the rough concrete cylinders (Fig. 4).

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, and to develop unique cement, water, and aggregate proportions for each aggregate combination.

2.4. Exposure simulations

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

2.4.1. 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.

2.4.2. Formed surfaces

The formed bottom of each cylinder (“formed” surface FO) was kept dry and unexposed.

2.4.3. Weathered surfaces

The finished surface of quarter-disk III (“weathered” surface WE) was exposed to 12-h cycles of deionized water spray, condensation, and intense ultraviolet light for 6 weeks to simulate the effects of dew and sunlight (ASTM Practice G154-00ae01, Cycle 7: UVA 340 nm, 1.35 W m^{-2} nm^{-1}; 8-h UV light at 60 °C, 10 min spray, 3.75 h condensation at 50 °C, 5 min spray [23]). 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 [28]. Following exposure, the albedo of surface WE was measured both wet and dry.

2.4.4. 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

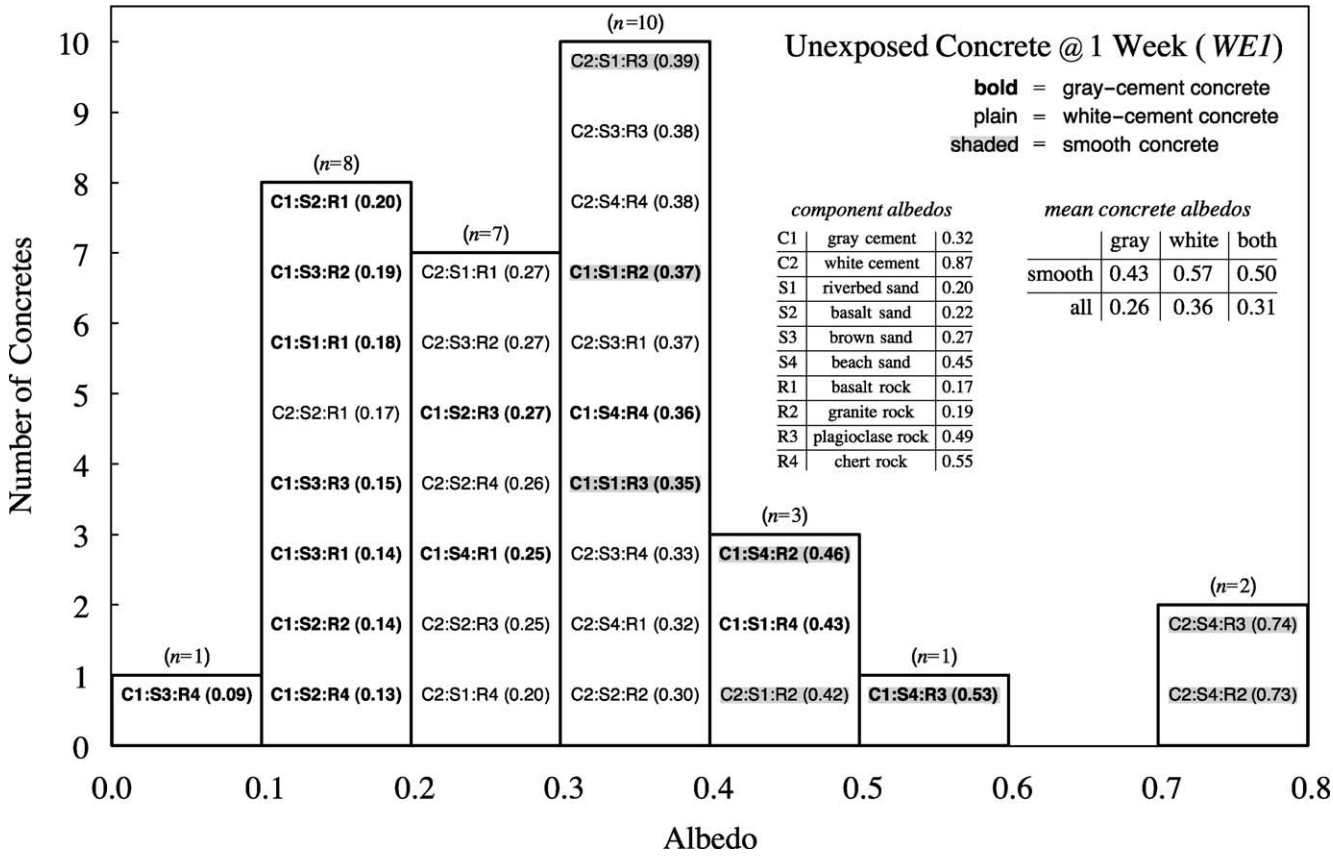


Fig. 9. Albedos of immature, unexposed concretes. While white-cement, immature concretes were generally more reflective than gray-cement, immature concretes, the mean white-gray albedo difference was not large (0.14 for smooth mixes, and 0.10 for all mixes).

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.

2.4.5. 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 Fig. 5. Concrete albedos were measured at various times over a 69-week postcasting period chronicled in Fig. 6. The *n*th measurement of the albedo of surface XY is denoted XY*n*; 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 reflectances of the rough concretes were 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.

3.1. Concrete albedo vs. time

Isolating the influence of exposure on albedo was complicated by the tendencies of most concretes to become more reflective as they cured. Nearly all unexposed concretes were significantly more reflective at Week 6 than at Week 1 (measurement FC1 vs. measurement WE1: smooth-mix change $\delta_s = 0.08$, $\chi_s = 0.13$; all-mix change $\delta_a = 0.12$, $\chi_a = 0.15$) (Fig. 7). However, the albedos of unexposed concretes

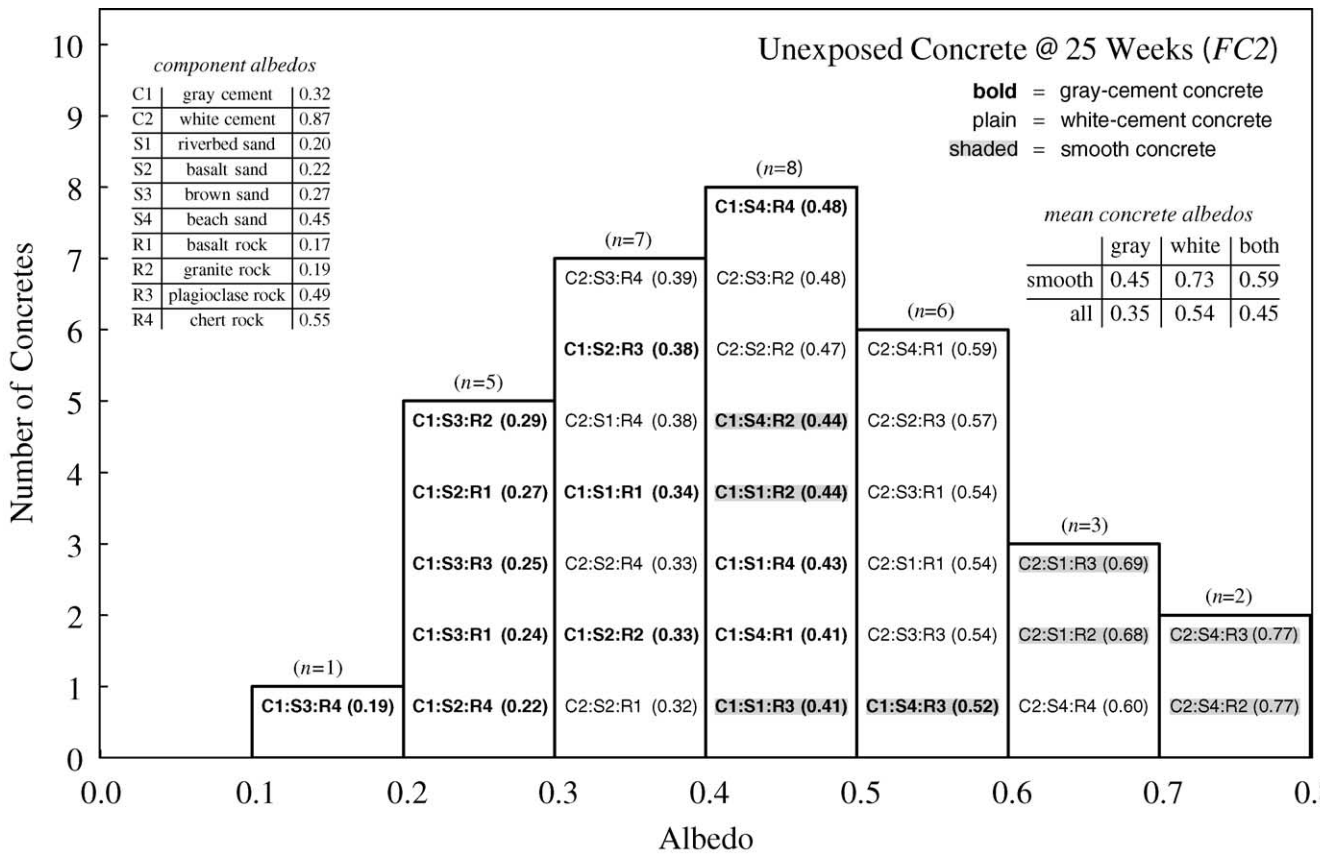


Fig. 10. Albedos of mature, unexposed concretes. Mature, white-cement concretes were generally more reflective than mature, gray-cement concretes, and the mean white–gray difference (0.28 for smooth mixes, and 0.19 for all mixes) was about twice that of immature concretes.

stabilized within 6 weeks of casting, increasing only slightly from Weeks 6 to 25 (FC2 vs. FC1: $\delta_s = 0.01$, $\chi_s = 0.02$; $\delta_a = 0.01$, $\chi_a = 0.03$) (Fig. 8), and even less from Weeks 25 to 35 (FC3 vs. FC2: $\delta_s = 0.00$, $\chi_s = 0.01$; $\delta_a = 0.00$, $\chi_a = 0.02$). Concretes whose albedos have stabilized will be denoted "mature". The rate of albedo growth in immature concretes varied from set to set, and was influenced by changes to water content induced by surface wetting and drying [29].

The reflectance difference between white-cement concretes and gray-cement concretes widened as concretes matured because the albedos of white-cement concretes increased more than did those of gray-cement concretes. The albedo distributions of immature and mature unexposed concretes are shown in Fig. 9 and Fig. 10, respectively.

3.2. Concrete albedo vs. exposure

The mature albedos of the unexposed control concretes (FC2) ranged from 0.41 to 0.77 (mean 0.59) for smooth mixes, and from 0.19 to 0.77 (mean 0.45) for all mixes

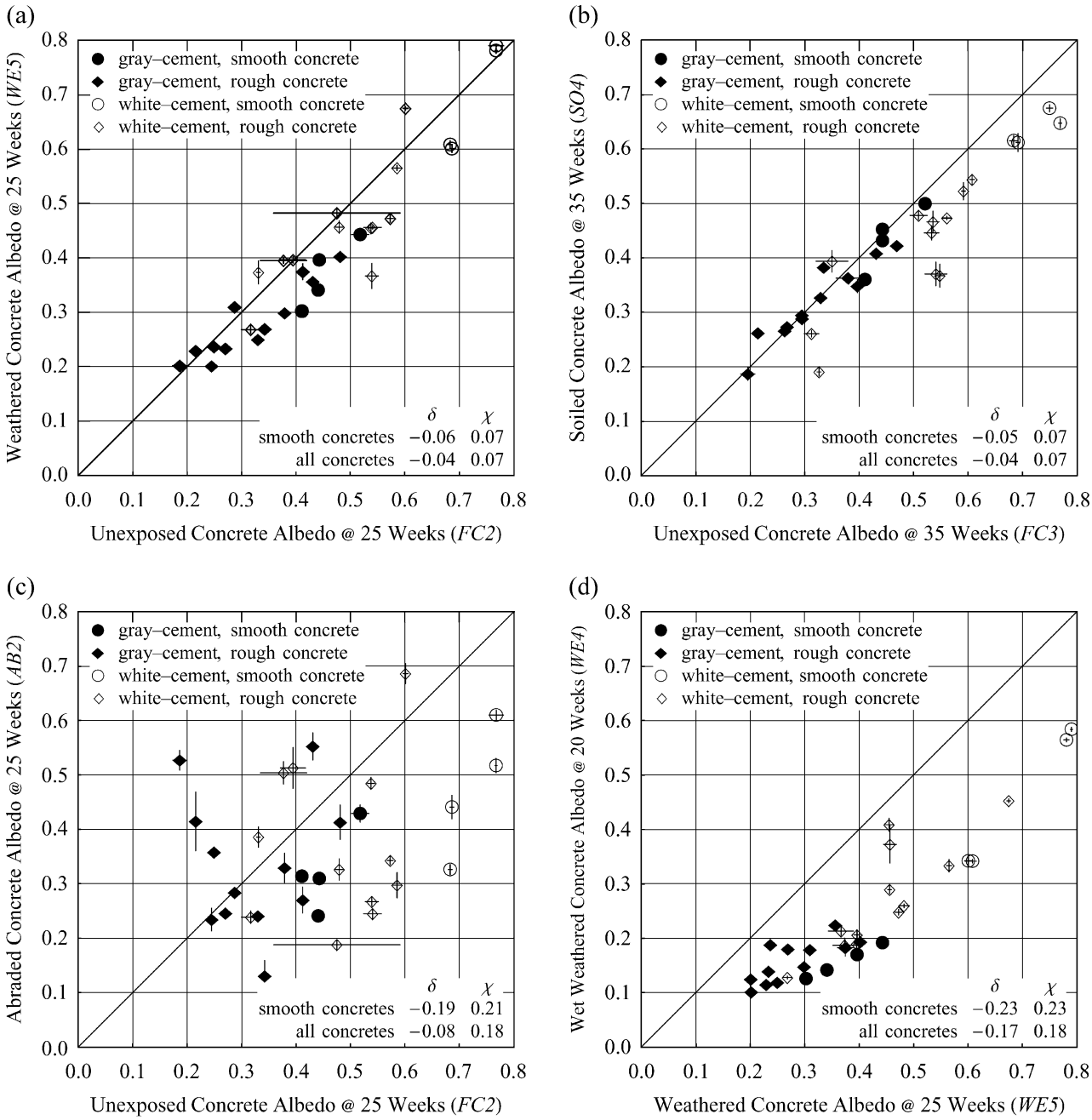


Fig. 11. Mature concrete albedo vs. exposure. Exposure to (a) weathering, (b) soiling, and (c) abrasion moderately reduced mean albedos, while (d) wetting made all concretes less reflective. Note that charts (a) through (c) each compare two different sample sets (e.g., soiled set SO vs. first-control set FC), while chart (d) compares two different states of the same sample set (weathered set WE).

(Fig. 10). All exposure processes reduced the mean albedo of the set of smooth mixes, and that of the set of all mixes. However, the reflectances of some mixes were slightly increased by weathering or soiling, and some rough mixes were made more reflective by abrasion. Before exposure, the albedos of the white-cement concretes were on average appreciably higher than those of their corresponding gray-cement concretes ($\delta_{s,w-g}=0.27$; $\delta_{a,w-g}=0.19$). Two exposure processes (soiling and abrasion) lowered the albedos of white-cement concretes more than those of gray-cement concretes, reducing the mean white–gray difference, while a third process (weathering) slightly increased the gap.

3.2.1. Weathering

On average, weathered concretes were somewhat less reflective than unexposed concretes (WE5 vs. FC2: $\delta_s=-0.06$, $\chi_s=0.07$; $\delta_a=-0.04$, $\chi_a=0.07$) (Fig. 11a). Weathering tended to reduce the reflectances of gray-cement concretes more than it did those of white-cement concretes, slightly widening the mean white–gray difference ($\delta_{s,w-g}=0.32$; $\delta_{a,w-g}=0.21$).

3.2.2. Soiling

On average, soiled (and rinsed and dried) concretes were also somewhat less reflective than unexposed concretes (SO4 vs. FC2: $\delta_s=-0.05$, $\chi_s=0.07$; $\delta_a=-0.04$, $\chi_a=0.07$) (Fig. 11b). This process had little effect on the mean albedo of gray-cement concretes, but appreciably lowered that of white-cement concretes, narrowing the mean white–gray difference ($\delta_{s,w-g}=0.19$; $\delta_{a,w-g}=0.12$). Rinsing and drying only slightly increased the mean albedo of the soiled surfaces (SO3 vs. SO2: $\delta_s=0.03$, $\chi_s=0.03$; $\delta_a=0.02$, $\chi_a=0.04$) (Fig. 12).

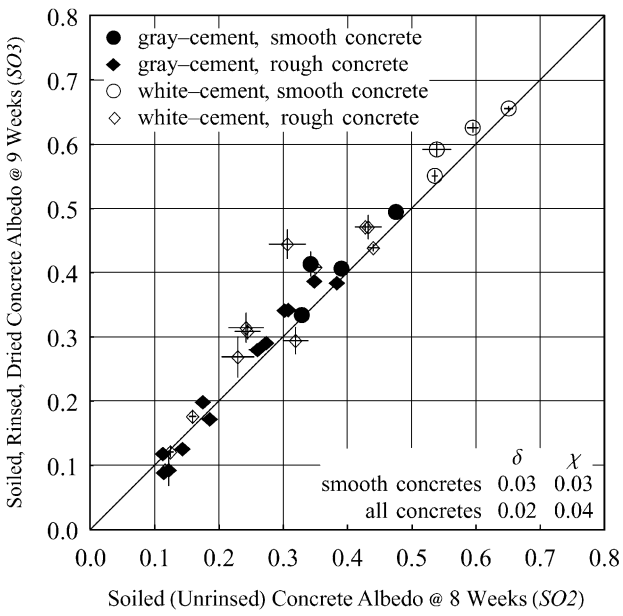


Fig. 12. Rinsing soiled concretes. Rinsing and drying made soiled surfaces slightly more reflective (SO3 vs. SO2).

3.2.3. Abrasion

The abraded concretes were on average noticeably less reflective than the unexposed concretes (AB2 vs. FC2: $\delta_s=-0.19$, $\chi_s=0.21$; $\delta_a=-0.08$, $\chi_a=0.18$) (Fig. 11c). Abrasion lowered the mean albedo of white-cement concretes much more than it did that of gray-cement concretes, shrinking the mean white–gray difference ($\delta_{s,w-g}=0.15$; $\delta_{a,w-g}=0.07$). Some rough concretes became more reflective, probably because their abraded surfaces were much flatter than their finished surfaces.

3.2.4. Wetting

Wetting made most of the weathered surfaces significantly less reflective (WE4 vs. WE5: $\delta_s=-0.23$, $\chi_s=0.23$; $\delta_a=-0.17$, $\chi_a=0.18$) (Fig. 11d), and slightly changed the mean white–gray difference, increasing it for the set of smooth concretes and decreasing it for the set of all concretes ($\delta_{s,w-g}=0.30$; $\delta_{a,w-g}=0.16$).

3.3. Concrete albedo vs. composition

The mature albedos of unexposed and abraded concretes were generally bounded by the albedos of their least and most reflective components, with a few exceptions attributable to frosting.

3.3.1. Cement

The albedo of unexposed, smooth concrete increased with cement albedo for all four combinations of sand and rock (Fig. 13a); the same was true after weathering, soiling, and abrasion [29]. The four most reflective, unexposed, smooth concretes ($\rho=0.68$ to 0.77) were made with white cement; the four least reflective, unexposed, smooth concretes ($\rho=0.44$ to 0.52) were made with gray cement (Fig. 10).

3.3.2. Sand

The albedo of unexposed, smooth concrete increased with sand albedo for three out of four combinations of cement and rock (Fig. 13b). In the exceptional case, the concrete made with the less reflective sand was frosted. After weathering, soiling, and abrasion, smooth concrete albedo correlated with sand albedo for all four combinations of cement and rock [29].

3.3.3. Rock

The albedo of unexposed, smooth concrete did not vary appreciably with rock albedo for two combinations of cement and sand; increased with rock albedo for a third combination; and decreased with rock albedo for a fourth combination (Fig. 13c). The same was true after weathering, soiling, and abrasion [29]. As expected, the albedo of abraded, smooth concrete correlated with rock albedo for all four combinations (Fig. 13d).

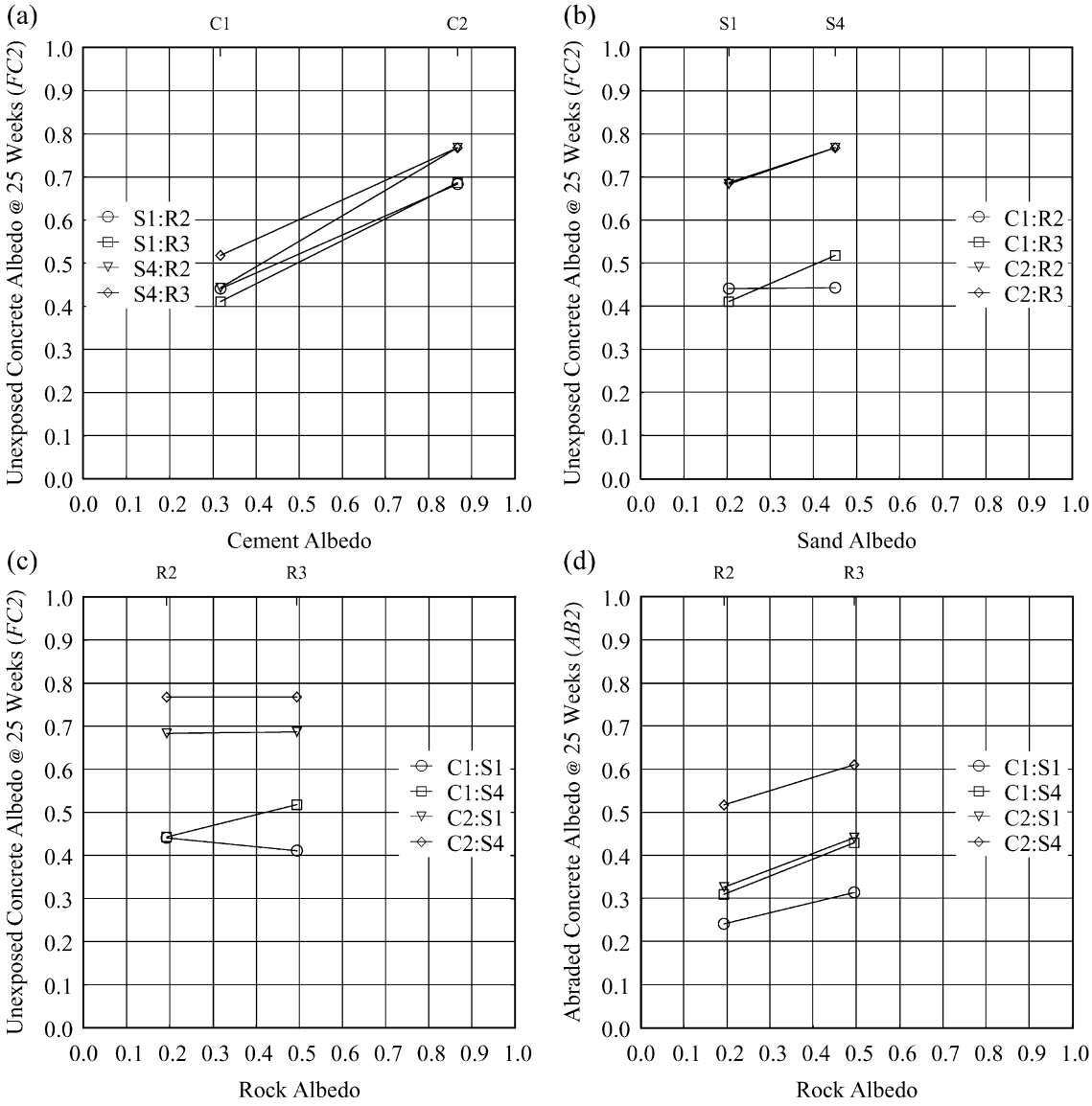


Fig. 13. Mature, smooth concrete albedo vs. composition. The albedo of unexposed, mature, smooth concrete correlated with (a) cement albedo and (b) sand albedo, but not (c) rock albedo. However, the albedo of (d) abraded, mature, smooth concrete correlated with rock albedo. Lines connecting data points should not be used for interpolation.

3.3.4. Relative influences

Concrete albedo ρ_{concrete} was regressed to cement albedo ρ_c and sand albedo ρ_s for the unexposed, weathered, and soiled smooth concretes; and also to rock albedo ρ_r for the abraded smooth concretes. (The variation of smooth concrete albedo with rock albedo was statistically significant only after abrasion.) That is, smooth concrete albedo was modeled by

$$\rho_{\text{concrete}} = k_c\rho_c + k_s\rho_s + k_r\rho_r + k_0$$

where cement, sand, and rock albedo correlation estimates k_c, k_s, and k_r each measure the influence on concrete albedo of component albedo; and constant term k_0 measures the net influence on concrete albedo of all other factors, such as cement hydration, frosting, weathering, and/or soiling. Rock albedo correlation estimate k_r was set to zero for unabraded concretes.

Cement albedo had nearly twice the influence of sand albedo on the reflectance of unexposed smooth concrete, even though each concrete mix contained more than twice as much sand as cement. After weathering or soiling, the influence of sand albedo was comparable to that of cement albedo. After abrasion, the influence of rock albedo was comparable to that of cement albedo, but only about half that of sand albedo (Table 3). It was disproportionately low, since each mix contained more

Table 3
Correlation of smooth-concrete albedo to component albedo

State	k_c	k_s	k_r	k_0	Adjusted R^2	Regression model
Unexposed	0.50 (0.03)	0.28 (0.08)		0.20 (0.03)	0.97	$\rho_{concrete} = k_c\rho_c + k_s\rho_s + k_0$
Weathered	0.59 (0.04)	0.57 (0.09)		0.00 (0.04)	0.97	
Soiled	0.37 (0.04)	0.26 (0.09)		0.24 (0.04)	0.93	
Abraded	0.27 (0.04)	0.55 (0.10)	0.33 (0.08)	− 0.06 (0.05)	0.99	$\rho_{concrete} = k_c\rho_c + k_s\rho_s + k_r\rho_r + k_0$

Cement, sand, and rock albedo correlation estimates k_c, k_s, and k_r and their standard errors (in parentheses) are shown for unexposed, weathered, soiled, and abraded smooth concretes. The k_0 term accounts for all other factors. Results should not be used predictively because the number of samples is small ($n = 8$).

rock than sand or cement (2.8/2.3/1 by mass). These results should not be used predictively since the sample size $n = 8$ is small.

4. Discussion

While the scope of this study was limited to a small number of materials and simulated exposure processes, the results suggest trends in the dependence of concrete albedo on composition, exposure, and chemistry, and provide insight into the fabrication of high-reflectance concrete.

4.1. Trends in the variation of concrete albedo

Several important trends emerged from the variations of concrete albedo with aging, exposure, and composition.

4.1.1. Aging

Unexposed concretes generally became more reflective in the early stages of curing, stabilizing by Week 6 (and possibly earlier, since the albedos of unexposed concretes were not measured between Weeks 1 and 6). Wetting and drying the concretes affected the hydration process and hence the rate of albedo change.

4.1.2. Exposure

Weathering, abrasion, and soiling each reduced the albedo of most concrete mixes, while wetting made all less reflective. However, since the first three processes were simulated arbitrarily, they do not necessarily represent real-world pavement exposures. Weathering narrowly increased and abrasion and soiling each slightly decreased the mean albedo difference between white-cement and gray-cement concretes.

4.1.3. Composition

The reflectance of smooth concrete generally correlated with cement albedo, sand albedo, and, after abrasion, with rock albedo. However, concrete reflectance did not increase with sand reflectance when the concrete made with the less reflective sand was frosted. Also, the influence of component albedo on smooth concrete albedo was not proportional to component mass fraction.

4.2. Reflectance as an indicator of cement and concrete chemistry

Calcium hydroxide [$Ca(OH)_2$] produced in the cement hydration process constitutes about 25% of the mass of a fully hydrated cement [5]. This white compound can be carried to the surface by non-chemically bound water in wet concrete (“primary efflorescence”), or leached to the surface by the penetration of rainwater into dry concrete (“secondary efflorescence”). Reaction with atmospheric carbon dioxide (“carbonation”) can convert the water-soluble calcium hydroxide to white calcium carbonate [$CaCO_3$] within months. Calcium carbonate is insoluble, but can gradually react with carbon dioxide and water to form white, water-soluble calcium bicarbonate [$Ca(HCO_3)_2$]. This process can take years [13]. Hence, the “frost” on a concrete surface can begin as effloresced calcium hydroxide, convert to calcium carbonate, and slowly become soluble calcium bicarbonate. Frosting can largely disappear within a few years in climates characterized by frequent alternation of rain and sunshine [30].

Cement hydration, efflorescence, and carbonation were all observed to influence concrete reflectance. First, concrete albedo increased significantly within 6 weeks of casting, and then stabilized, which is consistent with the hydration reaction time constant of 20 days reported in Ref. [6]. Second, white efflorescence appeared on some of the gray-cement concrete surfaces within a week of casting. Third, the reflectances of concretes aged 18 to 35 weeks did not change appreciably when wetted and dried. That rinsing did not change reflectance suggests that the white surface films had been converted to insoluble calcium carbonate.

4.3. Making high-albedo concrete: white cement vs. gray cement

It is difficult to make general statements about the costs of the sands and rocks used in this study, because the price of aggregate depends strongly on the distance that it must be transported. For example, a beach sand may cost more inland than near the coast. However, white cement is typically twice as expensive as gray cement. If one’s goal is to economically cast high-albedo concrete, it is interesting to compare the albedos of highly reflective gray-cement and white-cement mixes. In this experiment, the most reflective gray-cement and white-cement concretes (C1:S4:R3 and

C2:S4:R3, both smooth) were formed with beach sand S4 ($\rho = 0.45$) and plagioclase rock R3 ($\rho = 0.49$). Their mature, unexposed albedos were 0.52 and 0.77, respectively ($\delta_{w-g} = 0.25$). After exposure, the albedo of the high-reflectance gray-cement concrete ranged from 0.19 to 0.50, and that of the high-reflectance white-cement concrete ranged from 0.58 to 0.79. The white-cement concrete was always significantly more reflective than the gray-cement concrete ($\delta_{w-g} = 0.18$ to 0.39).

The effects of weathering, soiling, and abrasion were measured separately. An approximate way to predict albedo after exposure to two or more of these processes is to assume that reflectance changes combine geometrically. For example, if the unexposed, weathered, and abraded albedos of a concrete are ρ_0, ρ_1, and ρ_2, respectively, we compute its albedo after both weathering and abrasion as $\rho_0 \times r_1 \times r_2$, where $r_1 \equiv \rho_1/\rho_0$ and $r_2 \equiv \rho_2/\rho_0$ (Fig. 14). Geometric combination of the effects of abrasion, soiling, and weathering yields $r_{AB} \times r_{SO} \times r_{WE}$ values of 68% for the most reflective gray-cement concrete, and 72% for the most reflective white-cement concrete. In other words, exposure to these three processes would reduce the albedo of each concrete to about 70% of its unexposed value, and the highest albedo white-cement concrete would still be appreciably more reflective than the highest albedo gray-cement concrete ($\delta_{w-g} = 0.20$).

It may be erroneously assumed that one way to increase the reflectance of gray-cement concretes is to promote efflorescence and carbonation through choice of aggregate. In this experiment, some concretes made with sands S1 (riverbed sand) and S4 (beach sand) were frosted. However, this whitening may not be uniform or permanent, because even insoluble films of calcium carbonate can gradually wash away after conversion to calcium bicarbonate, or be removed by abrasion. Patchily frosted surfaces may also be considered unattractive.

4.4. The road to cool pavements

This laboratory study examined small (and in some cases, improperly cast) concrete samples that were made from limited and arbitrarily chosen varieties of cement, sand, and rock. These were then subjected to improvised simulations of weathering, soiling, and abrasion. The next technical step toward developing practical high-reflectance concrete pavements might entail working with the concrete industry to (a) find locally available, structurally proven, high-albedo aggregates; (b) use promising concretes to pave

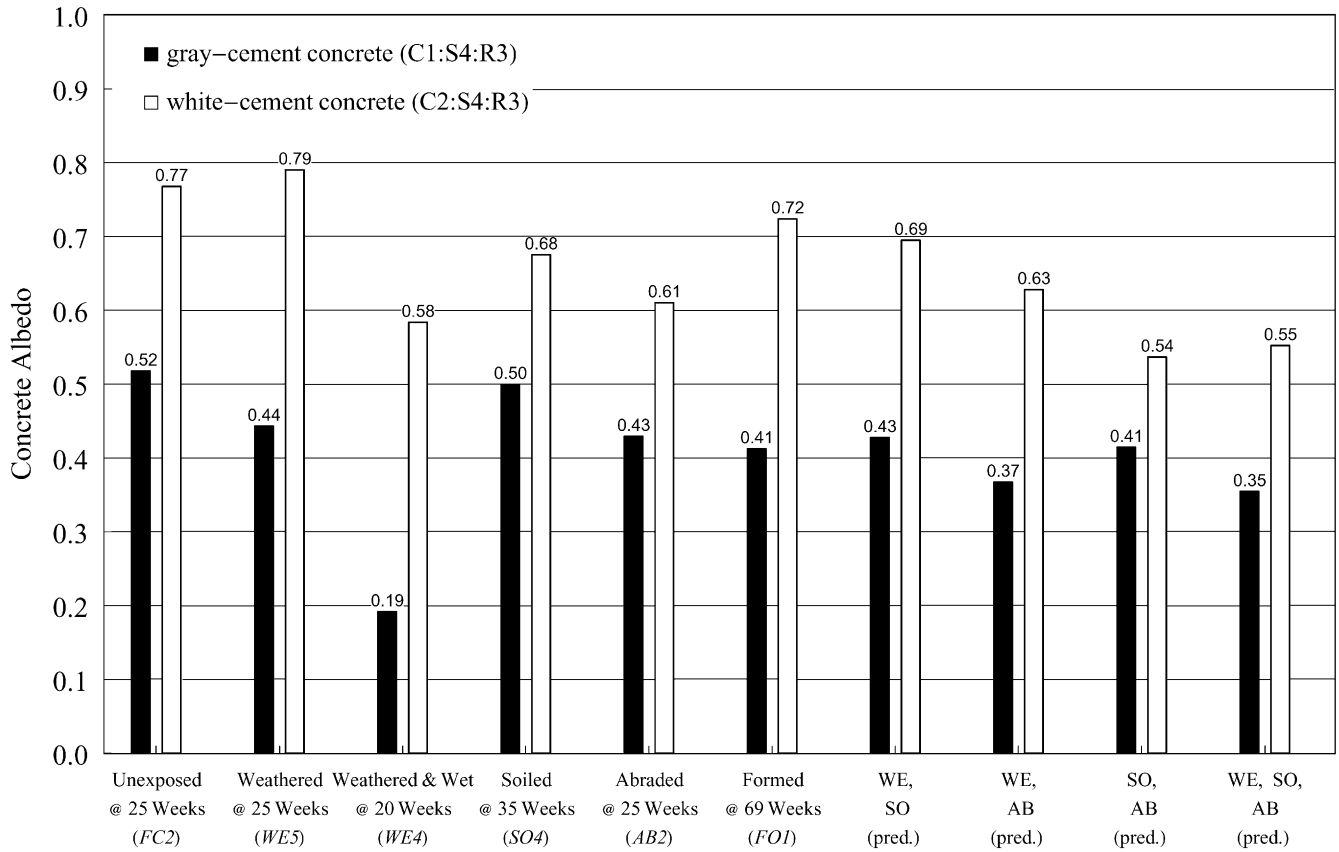


Fig. 14. Measured and predicted mature albedos of the most reflective white-cement and gray-cement smooth concretes. Shown from left to right are reflectances measured in six states (unexposed, weathered, weathered and wet, soiled, abraded, and formed), and reflectances predicted for four geometrically combined exposures (weathered and soiled, weathered and abraded, soiled and abraded, and weathered and soiled and abraded).

segments of actual roads and parking lots; and (c) measure the real-world optical and mechanical performances of these pavements over time. This would help identify cost-effective and mechanically sound varieties of concrete from which to fashion reflective pavements. Some concrete mixes could include fly ash and/or ground granulated blast furnace slag, which are coal-combustion by-products that are used to replace or supplement cement and aggregate.

5. Conclusions

Concrete albedo grew as the cement hydration reaction progressed (mean increase 0.08), but stabilized within six weeks of casting. The mature albedos of the eight properly made, "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. Exposure similarly affected the albedos of the improperly made, "rough" concretes.

White-cement smooth concretes were on average significantly more reflective than gray-cement smooth concretes. The albedo of the most reflective white-cement smooth concrete was 0.18 to 0.39 higher than that of the most reflective gray-cement smooth concrete, depending on state of exposure. Smooth 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 smooth concrete. Efflorescence and surface carbonation whitened some gray-cement concretes.

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