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.

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

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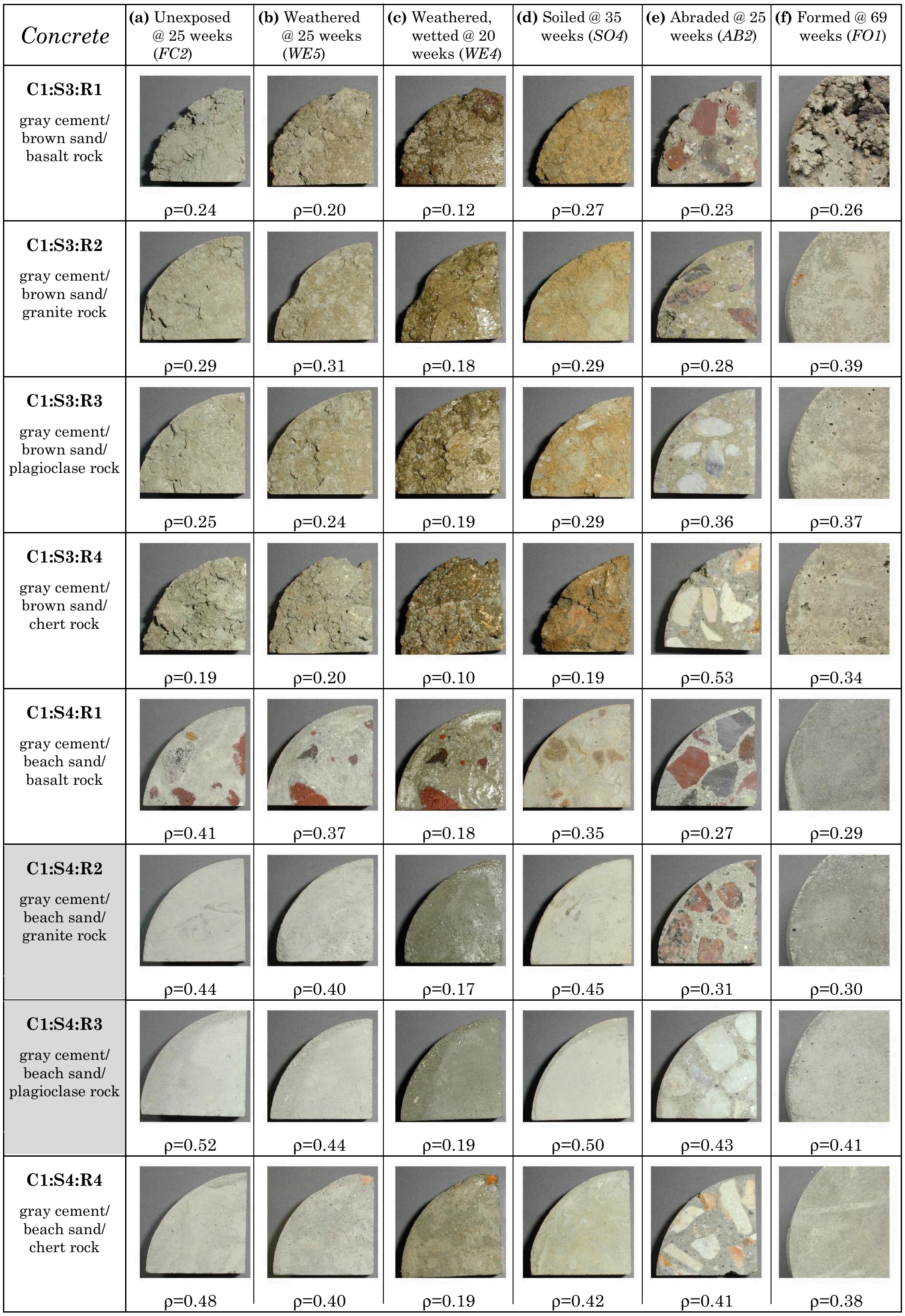
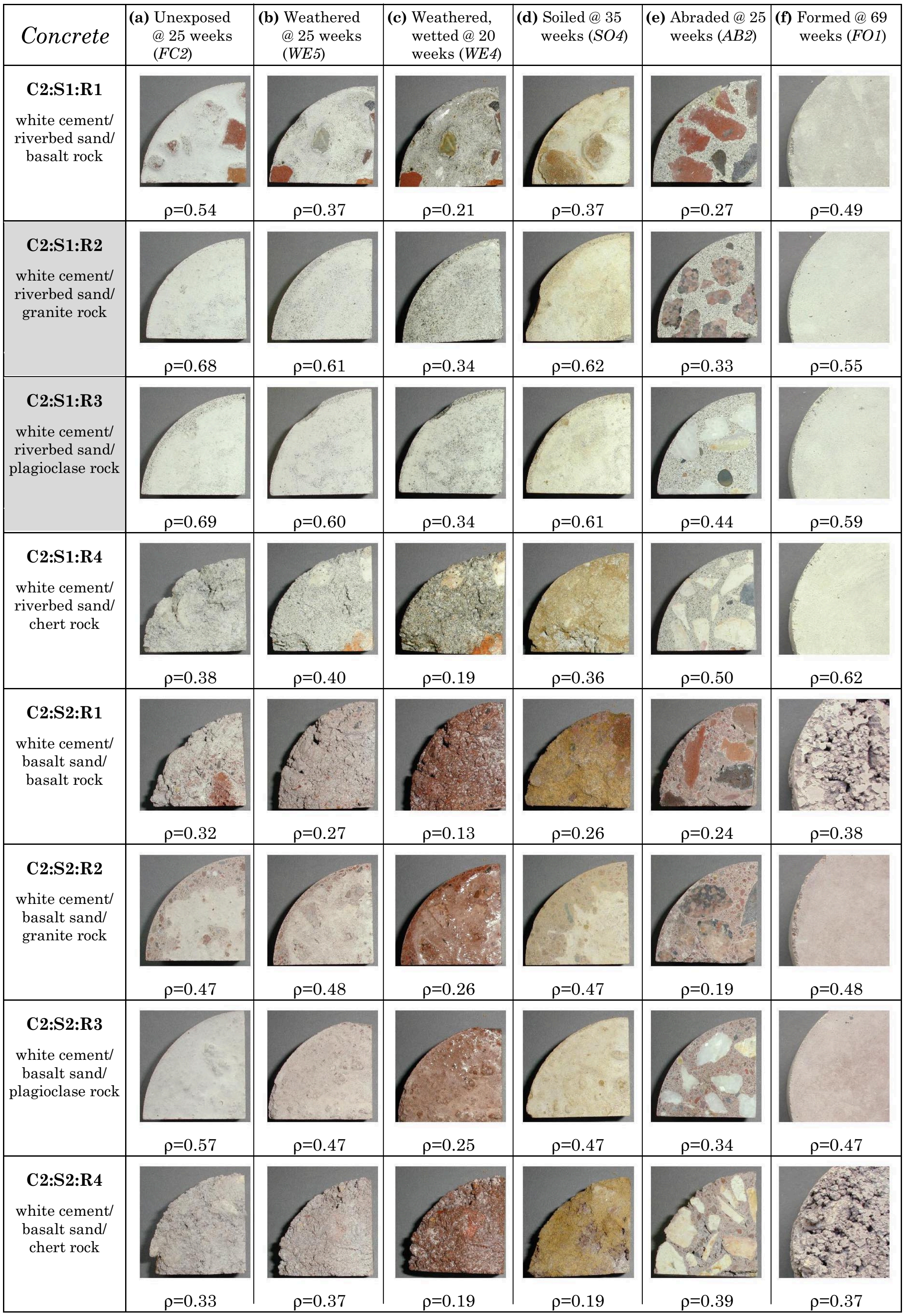
Figure 5. Properties of all mature concretes. *Images and albedos [ρ] of all 32 mixes of concrete are shown (a) unexposed, (b) weathered, (c) weathered and wetted, (d) soiled, (e) abraded, and (f) formed. Smooth concretes are shaded.*



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

(ii of iv)

Figure 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)
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

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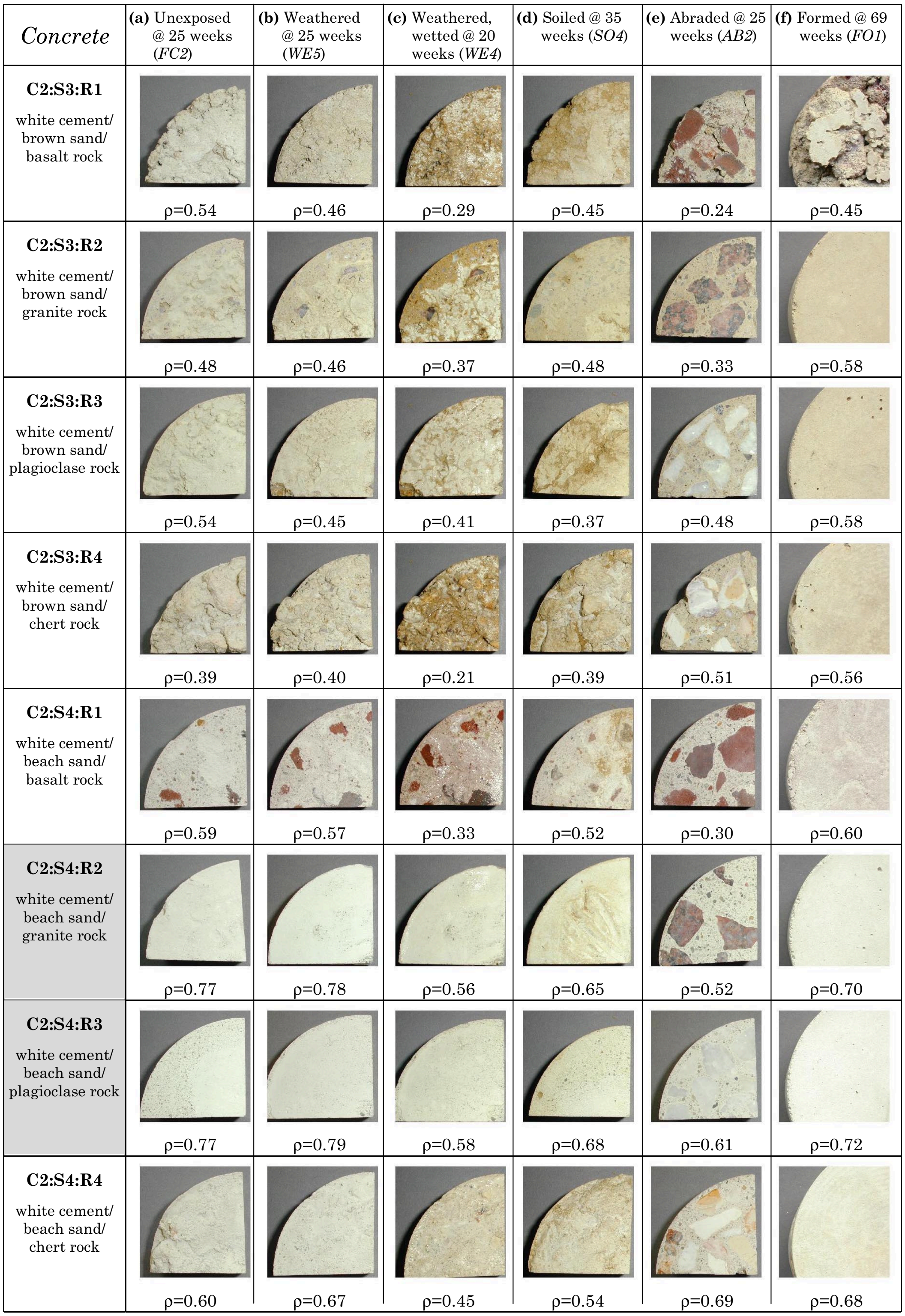
Figure 5. Properties of all mature concretes. *Images and albedos [ρ] of all 32 mixes of concrete are shown (a) unexposed, (b) weathered, (c) weathered and wetted, (d) soiled, (e) abraded, and (f) formed. Smooth concretes are shaded.*



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*)
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

(iv of iv)

Figure 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.*

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 six than at week one (measurement *FC1* vs. measurement *WE1:* smooth-mix change δ_s=0.08, χ_s=0.13; all-mix change δ_a=0.12, χ_a=0.15) (**Figure 7**). However, the albedos of unexposed concretes stabilized within six weeks of casting, increasing only slightly from weeks six to 25 (*FC2* vs. *FC1*: δ_s=0.01, χ_s=0.02; δ_a=0.01, χ_a=0.03) (**Figure 8**), and even less from weeks 25 to 35 (*FC3* vs. *FC2*: δ_s=0.00, χ_s=0.01; δ_a=0.00, χ_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 (**Appendix A**).

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 **Figure 9** and **Figure 10**, respectively.

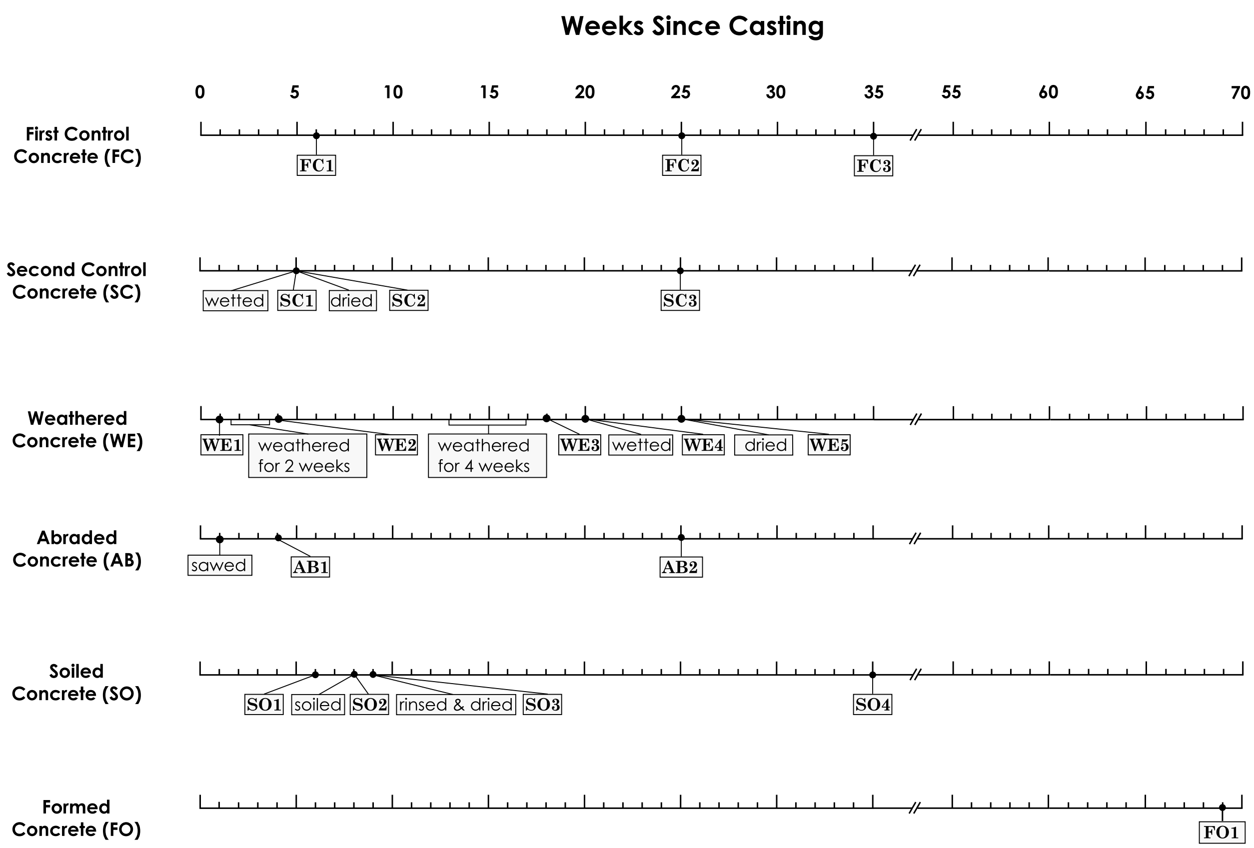


Figure 6. Experiment timeline. *Shown are the exposure and reflectance-measurement histories of six concrete-surface sets. Labels of the form* **AB1** *denote albedo measurements.*

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 (**Figure 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 more reflective 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.

Weathering. On average, weathered concretes were somewhat less reflective than unexposed concretes (*WE5* vs. *FC2*: δ_s=-0.06, χ_s=0.07; δ_a=-0.04, χ_a=0.07) (**Figure 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).

Soiling. On average, soiled (and rinsed and dried) concretes were also somewhat less reflective than unexposed concretes (*SO4* vs. *FC2*: δ_s=-0.05, χ_s=0.07; δ_a=-0.04, χ_a=0.07) (**Figure 11b**). This process had little effect on the mean albedo of gray-cement concretes, but appreciably lowered that of white-

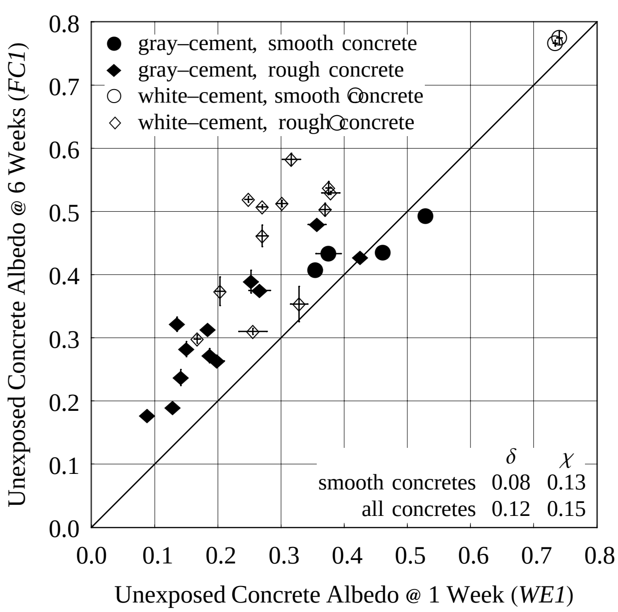


Figure 7. Concrete albedo growth. *The albedos of most unexposed concretes increased from week one to week six. δ and χ are mean and root-mean-square differences in albedo; the diagonal line marks equality.*

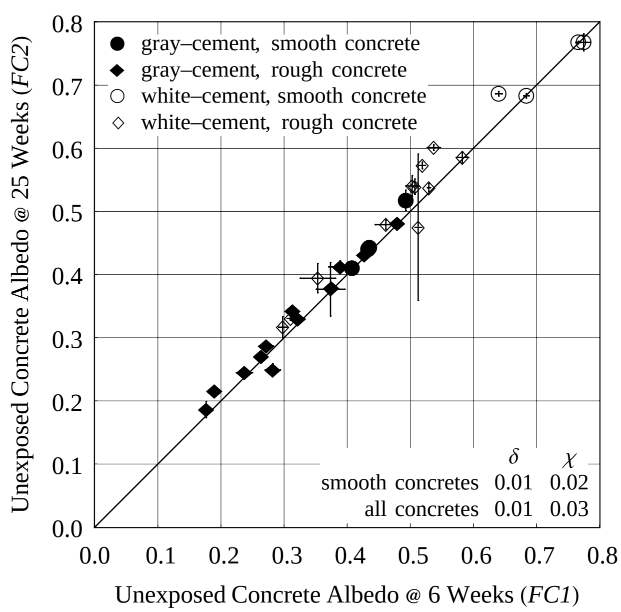


Figure 8. Concrete albedo stabilization. *The albedos of unexposed concretes increased very slowly after week six.*

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*: δ_s=0.03, χ_s=0.03; δ_a=0.02, χ_a=0.04) (**Figure 12**).

Abrasion. The abraded concretes were on average noticeably less reflective than the unexposed concretes (*AB2* vs. *FC2*: δ_s=-0.19, χ_s=0.21; δ_a=-0.08, χ_a=0.18) (**Figure 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 surface.

Wetting. Wetting made most of the weathered surfaces significantly less reflective (*WE4* vs. *WE5*: δ_s=-0.23, χ_s=0.23; δ_a=-0.17, χ_a=0.18) (**Figure 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.

Cement. The albedo of unexposed, smooth concrete increased with cement albedo for all four combinations of sand and rock (**Figure 13a**); the same was true after weathering, soiling, and abrasion (**Appendix B**). The four most-reflective, unexposed, smooth concretes (ρ=0.68 to 0.77) were made with white cement; the four least-reflective, unexposed, smooth concretes (ρ=0.44 to 0.52) were made with gray cement (**Figure 10**).

Sand. The albedo of unexposed, smooth concrete increased with sand albedo for three out of four combinations of cement and rock (**Figure 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 (**Appendix B**).

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 (**Figure 13c**). The same was true after weathering, soiling, and abrasion (**Appendix B**). As expected, the albedo of abraded, smooth concrete correlated with rock albedo for all four combinations (**Figure 13d**).

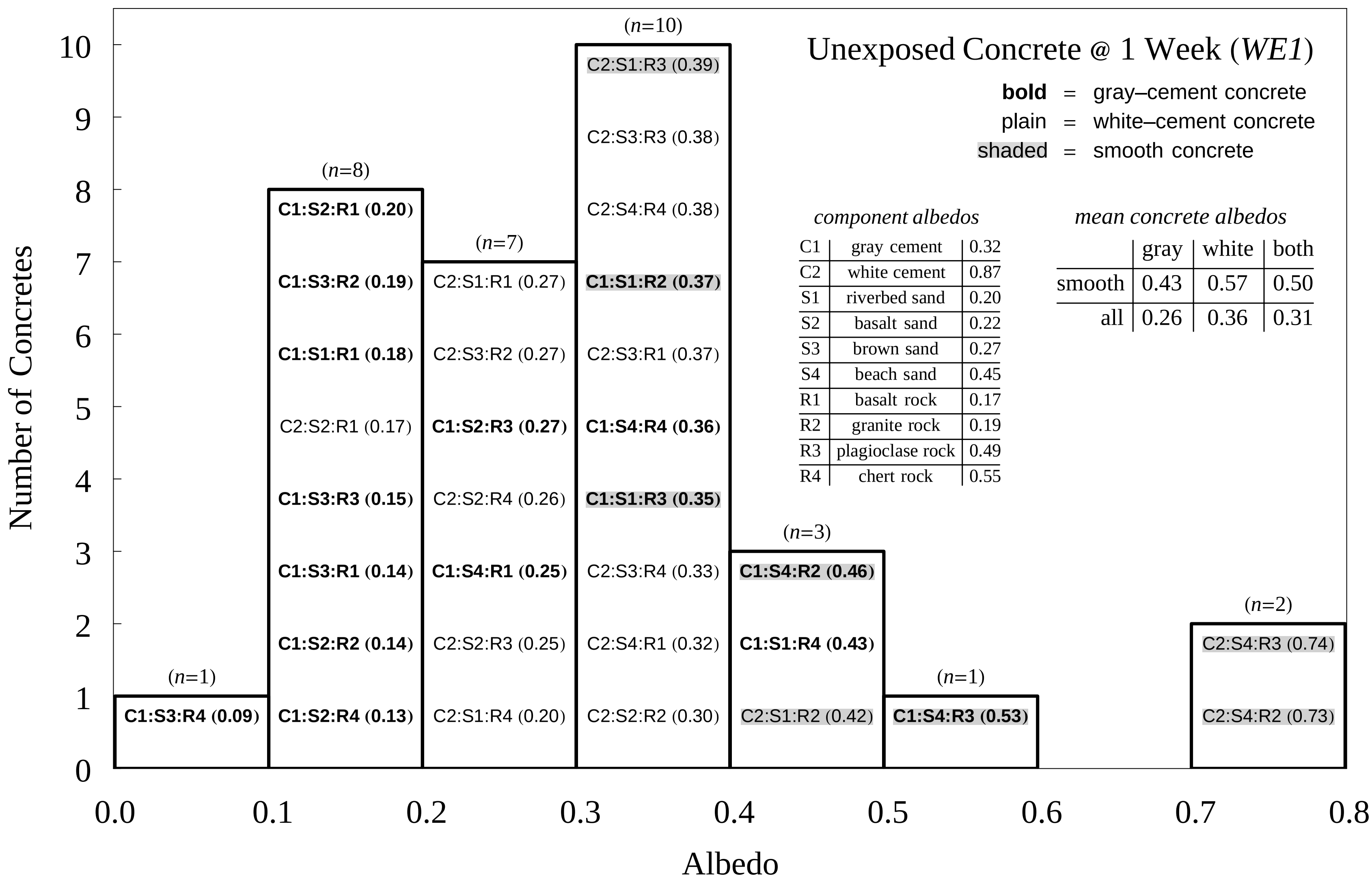


Figure 9. Albedos of immature, unexposed concretes*. While white-cement, immature concretes were generally more reflective than gray-cement, immature concretes, the mean white-gray albedo difference was not large (0.14 for smooth mixes, and 0.10 for all mixes).*

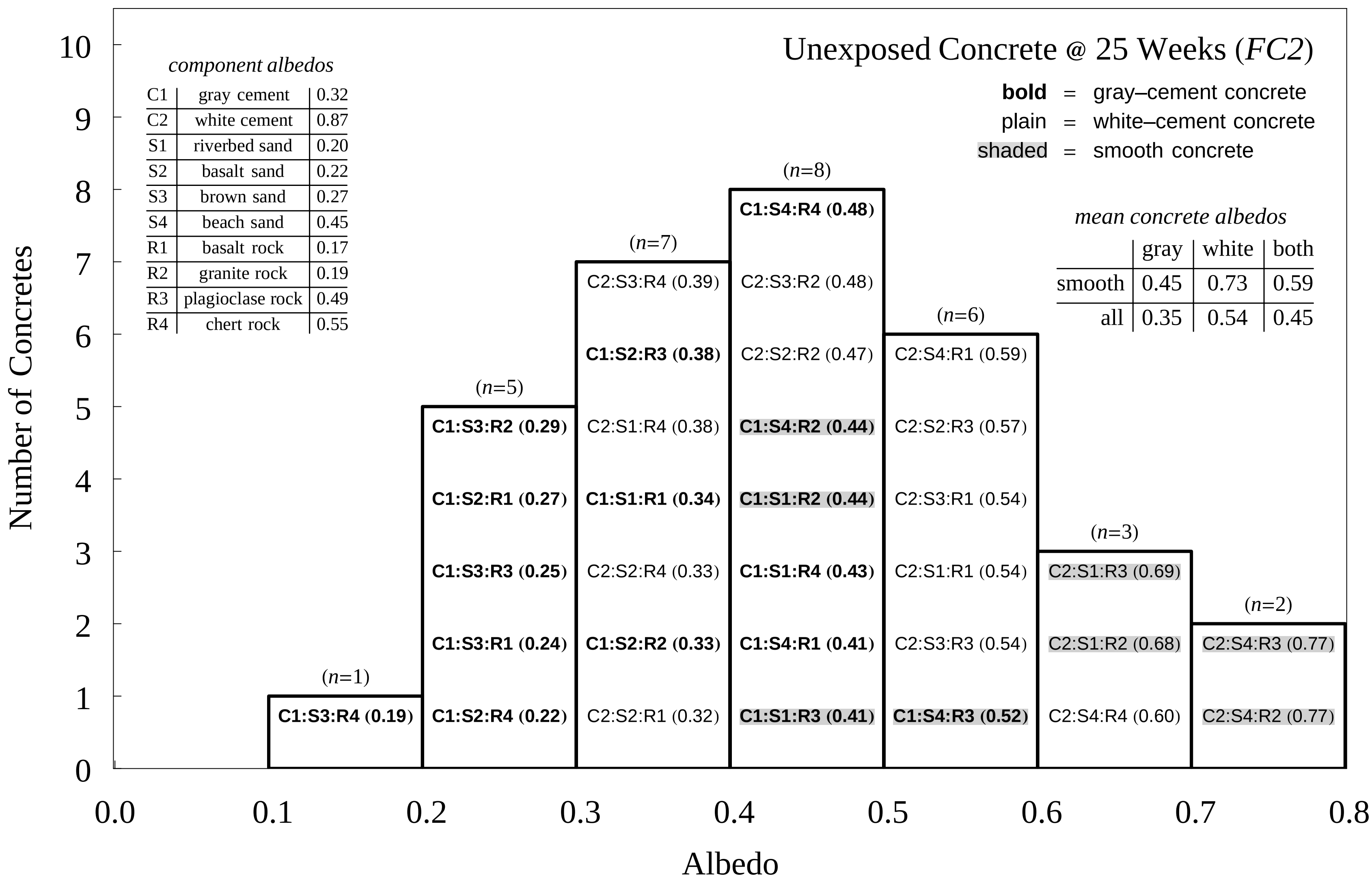


Figure 10. Albedos of mature, unexposed concretes. *Mature, white-cement concretes were generally more reflective than mature, gray-cement concretes, and the mean white-gray difference (0.28 for smooth mixes, and 0.19 for all mixes) was about twice that of immature concretes.*

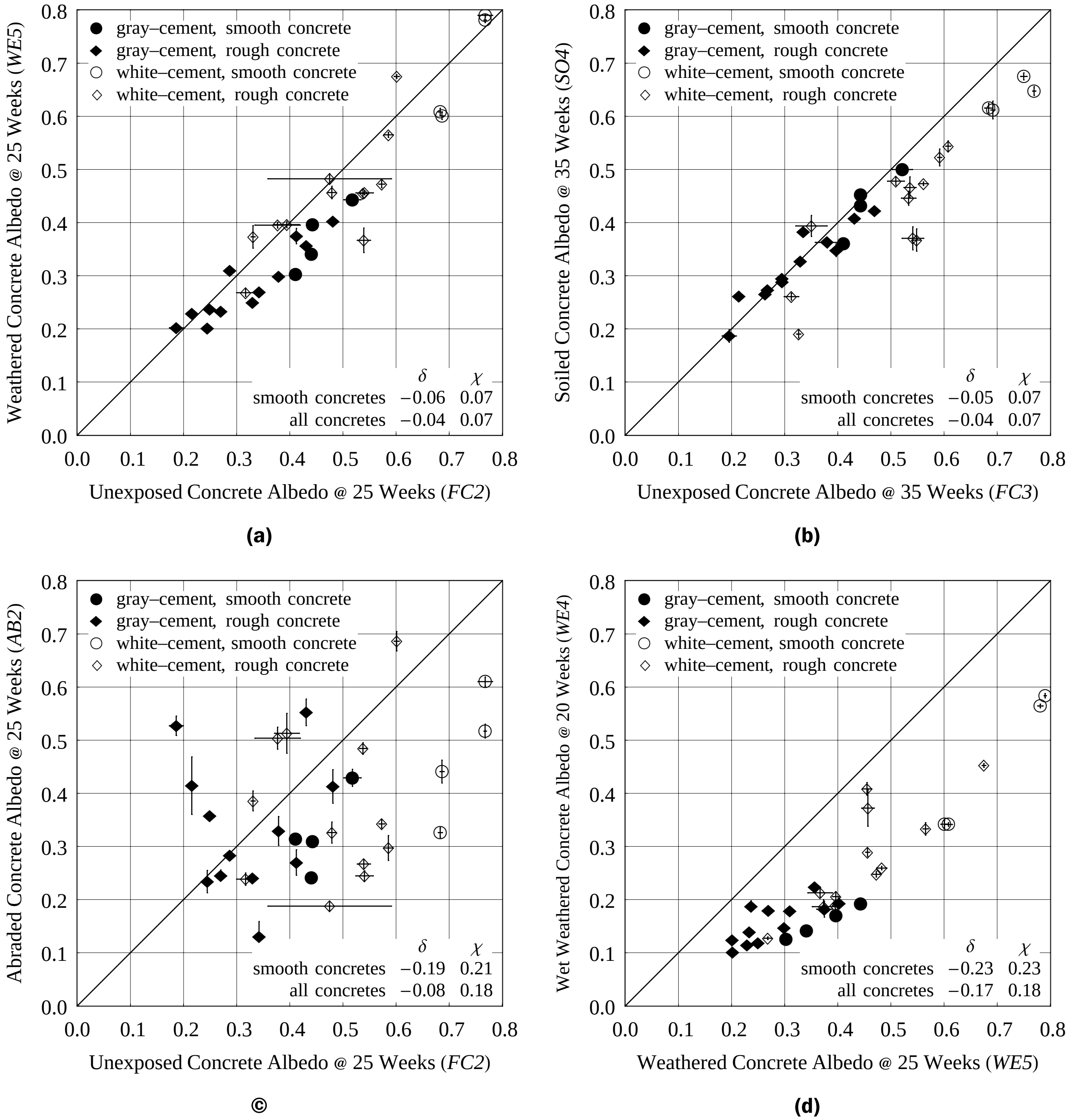


Figure 11. Mature concrete albedo vs. exposure. *Exposure to (a) weathering, (b) soiling, and (c) abrasion moderately reduced mean albedos, while (d) wetting made all concretes less reflective. Note that charts (a) through (c) each compare two different sample sets (e.g., soiled set* SO *vs. first-control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

Table 4. Correlation of smooth-concrete albedo to component albedo. *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).*

state	k_c	k_s	k_r	k_0	**adj.** 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	$\rho_{concrete} = k_c\ \rho_c + k_s\ \rho_s + k_r\ \rho_r + k_0$

Relative Influences. Concrete albedo $\rho_{concrete}$ was regressed to cement albedo ρ_c and sand albedo ρ_s for the unexposed, weathered, and soiled smooth concretes; and also to that of 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

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

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 4**). It was disproportionately low, since each mix contained more 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.

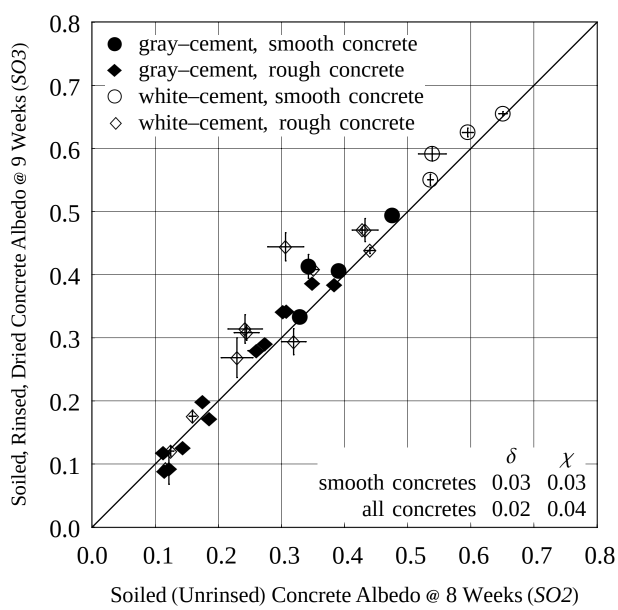


Figure 12. Rinsing soiled concretes. *Rinsing and drying made soiled surfaces slightly more reflective (SO3 vs. SO2).*

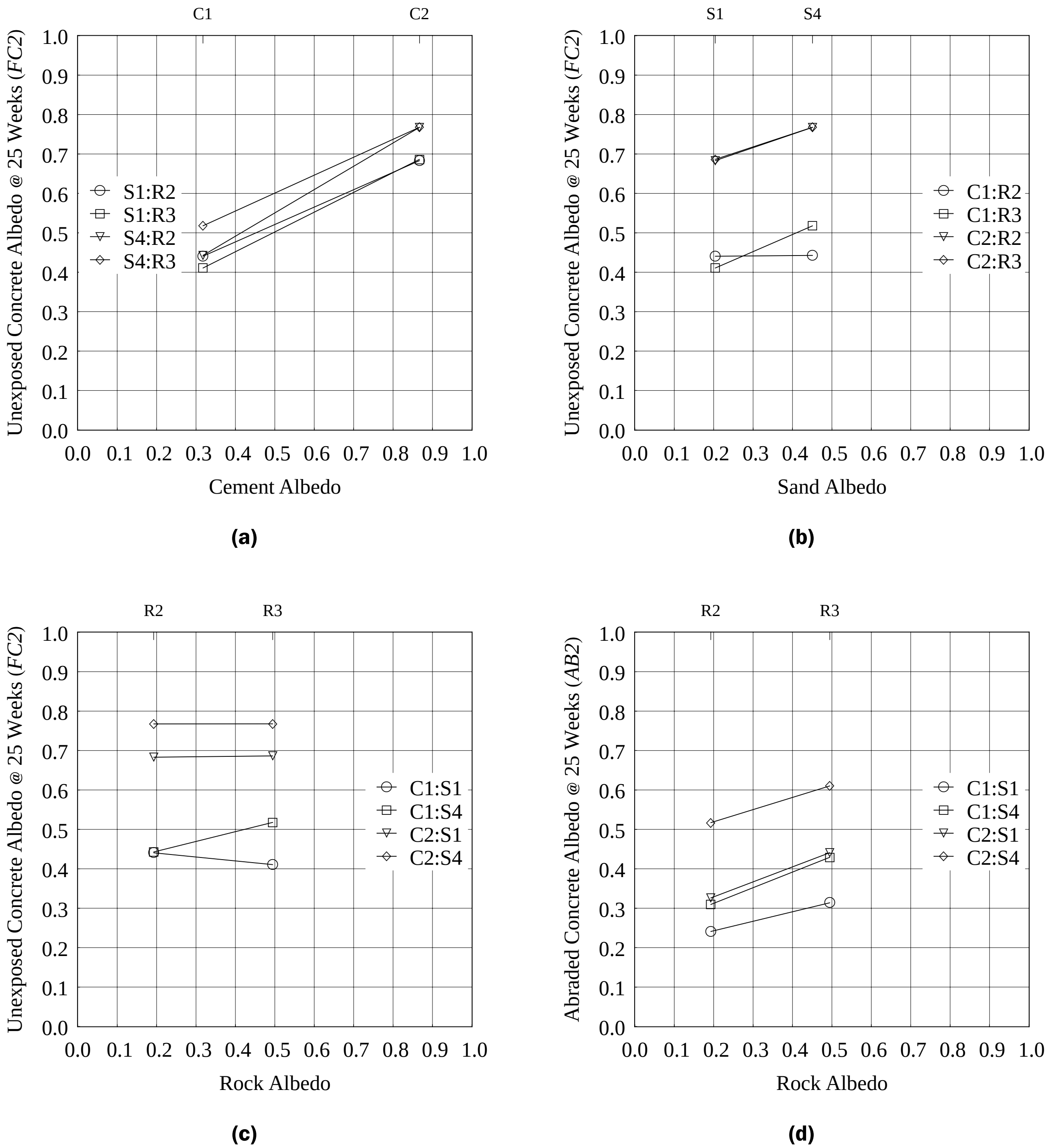


Figure 13. Mature, smooth concrete albedo vs. composition. *The albedo of unexposed, mature, smooth concrete correlated with (a) cement albedo and (b) sand albedo, but not (c) rock albedo. However, the albedo of (d) abraded, mature, smooth concrete correlated with rock albedo. Lines connecting data points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

4 Discussion

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

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

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.

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 each component's mass fraction.

4.1 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 (Brunauer and Copeland 1964). 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 (Kenney 1996). 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 (Bayer Corporation 1997).

Cement hydration, efflorescence, and carbonation were all observed to influence concrete reflectance. First, concrete albedo increased significantly within six weeks of casting, and then stabilized, which is consistent with the hydration-reaction time constant of 20 days reported by Papadakis and Vayenas (1991). 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.

4.2 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 (both smooth) were formed with beach sand S4 (ρ=0.45) and plagioclase rock R3 (ρ=0.49). Their mature, unexposed albedos were 0.52 and 0.77, respectively (δ_{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 (δ_{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 $r_2 \equiv \rho_2 / \rho_0$ (**Figure 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 (**Table 5**). 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 (δ_{w-g}=0.20).

Table 5. Combining exposure-induced albedo changes*. Shown from left to right for each concrete are its unexposed albedo ρ_0; the measured ratios r_{WE}, r_{SO}, and r_{AB} of exposed albedo to unexposed albedo after weathering, soiling, and abrasion, respectively; and predicted ratios for combined exposures.*

	ρ_0	r_{WE}	r_{SO}	r_{AB}	$r_{WE} \times r_{SO}$	$r_{WE} \times r_{AB}$	$r_{AB} \times r_{SO}$	$r_{AB} \times r_{SO} \times r_{WE}$
most-reflective gray-cement concrete **C1:S4:R3**	0.52	86%	97%	83%	83%	71%	80%	**68%**
most-reflective white-cement concrete **C2:S4:R3**	0.77	103%	88%	79%	90%	82%	70%	**72%**

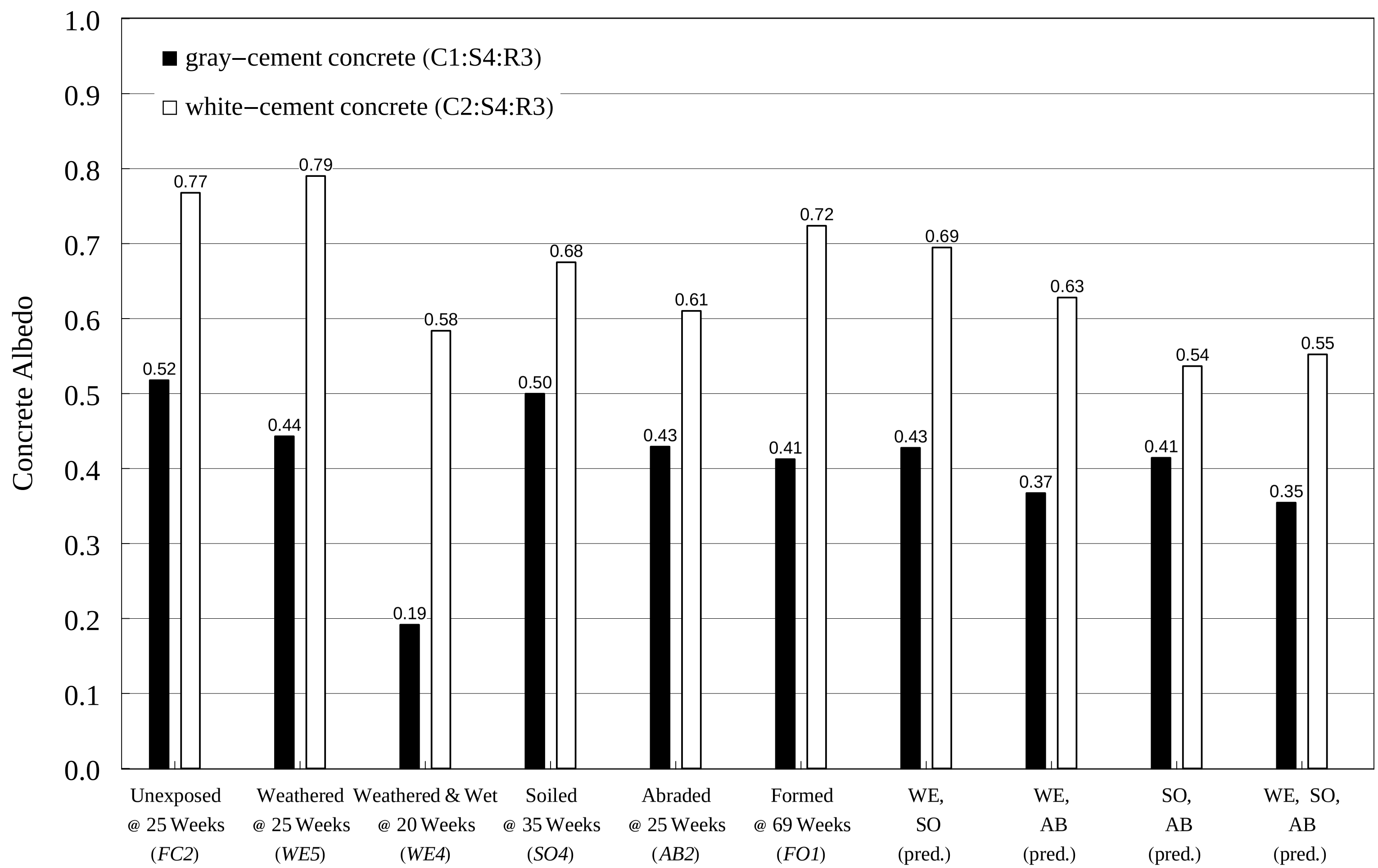


Figure 14. Measured and predicted mature albedos of the most-reflective white-cement and gray-cement smooth concretes*. Shown from left to right are reflectances measured in six states (unexposed, weathered, weathered and wet, soiled, abraded, and formed), and reflectances predicted for four geometrically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

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 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 can also be considered unattractive.

4.3 Future Research

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 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 byproducts that are used to replace or supplement cement and aggregate, respectively. Ideally, pavement consumers such as municipalities and developers would participate in future research by specifying preferences for pavement properties (e.g., color and durability) and providing road and parking areas for pavement testing.

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.

References

Akbari, H. and L.S. Rose. 2001. "Characterizing the fabric of the urban environment: a case study of Salt Lake City, Utah." Berkeley, CA; Lawrence Berkeley National Laboratory Report LBNL-47851.

Akbari, H., L.S. Rose, and H. Taha. 1999. "Characterizing the fabric of the urban environment: a case study of Sacramento, California." Berkeley, CA; Lawrence Berkeley National Laboratory Report LBNL-44688.

ASTM. 1998. "Table G159-98: standard tables for references solar spectral irradiance at air mass 1.5: direct normal and hemispherical for a 37° tilted surface." Annual Book of ASTM Standards, Vol. 14.04. Philadelphia, PA; American Society for Testing and Materials.

ASTM. 1999. "Practice E660-90 (1996): standard practice for accelerated polishing of aggregates or pavement surfaces using a small-wheel, circular track polishing machine." Annual Book of ASTM Standards, Vol. 04.03. Philadelphia, PA; American Society for Testing and Materials.

ASTM. 2001. "Practice G154-00ae1: standard practice for operating fluorescent light apparatus for UV exposure of nonmetallic materials." Annual Book of ASTM Standards, Vol. 14.04. Philadelphia, PA; American Society for Testing and Materials.

Bayer Corporation. 1997. "Efflorescence. A temporary problem." Pittsburgh, PA; Bayer Corporation, Industrial Chemicals Division.

Brunauer, S. and L.E. Copeland. 1964. "The chemistry of concrete." Scientific American, Vol. 210, No. 4, pp. 80-92.

CIE/PIARC. 1977. *Road Surfaces and Lighting*. Paris; International Commission on Illumination (CIE) and Permanent International Association of Road Congresses (PIARC).

Fedor, G.R. and P.J. Brennan. 1996. "Correlation between natural weathering and fluorescent UV exposures: UVA-340 lamp test results." Durability Testing of Non-Metallic Materials, ASTM STP 1294, Robert J. Herling, Ed. Philadelphia; American Society for Testing and Materials.

Goode, C.D. 1991. "Weathering of concrete." Concrete Construction (January).

Homburger, W.S. and J.H. Kell. 1984. *Fundamentals of Traffic Engineering, 11th Ed*. Berkeley, CA; Institute of Transportation Studies, University of California.

Hooker, K.A. 1994. "Reducing efflorescence potential." Masonry Construction (February).

Hurd, M.K. 1988. “Aggregates bring lifetime color to concrete.” Concrete Construction (June).

Hurd, M.K. 1993. “Tips for coloring concrete.” Concrete Construction (May).

IES. 1983. *American National Standard Practice for Roadway Lighting*. New York; Illuminating Engineering Society of North America.

Jackett, M.J. and A.J. Fisher. 1974. “The light reflecting properties of asphaltic concrete road surfaces.” ARRB Proceedings, Vol. 7, Part 5, pp. 287-306.

Jung, W., A. Kazakov, and A.I. Titishov. 1984. “Road surface reflectance measurements in Ontario.” Transportation Research Record, Issue 996, pp. 24-37.

Kenney, A.R. 1996. “Avoiding efflorescence in architectural precast concrete.” Concrete Producer (July).

Kirk-Othmer. 1979. *Encyclopedia of Chemical Technology, 3rd Ed*. Vol. 5, pp. 163-192. New York; J. Wiley.

Lea, F.M. 1998. *Chemistry of Cement and Concrete, 4th Ed*. London; Arnold.

Lide, D.R. 1990. *CRC Handbook of Chemistry and Physics, 71st Ed*. Boca Raton, FL; CRC Press.

Mehta, P.K. and P.J.M. Monteiro. 1993. *Concrete: Structure, Properties, and Materials, 2nd Ed*. Englewood Cliffs, NJ; Prentice Hall.

Nasvik, J. 2000. “Decorative concrete.” Concrete Construction (December).

Newman, H.B. 2000. “Everything efflorescent.” Masonry Construction (September).

Papadakis, V.G. and C.G. Vayenas. 1991. “Experimental investigation and mathematical modeling of the concrete carbonation problem.” Chemical Engineering Science, Vol. 46, No. 5/6, pp. 1333-1338.

Rosenfeld, A.H., H. Akbari, J.J. Romm, and M. Pomerantz. 1998. “Cool communities: strategies for heat island mitigation and smog reduction.” Energy & Buildings, Vol. 28, pp. 51-62.

Schierhorn, C. 1996. “Ensuring mortar color consistency.” Masonry Construction (January).

Twomey, S.A., C.F. Bohren, and J.L. Mergenthaler. 1986. “Reflectance and albedo differences between wet and dry surfaces.” Applied Optics, Vol. 25, No. 3, pp. 431-437.