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Solar Reflectance of Concretes for LEED Sustainable Sites Credit: Heat Island Effect

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KEYWORDS

Albedo, color, concretes, fly ash cements, hardscape, LEED Green Building Rating System, pavement, roof, solar reflectance, reflectivity, slag cements, sustainable construction, urban heat island

ABSTRACT

This report presents the results of solar reflectance testing on 135 concrete specimens from 45 concrete mixes, representing a broad range of concretes. This testing determined which combinations of concrete constituents meet the solar reflectance index requirements in the Leadership in Energy and Environmental Design for New Construction (LEED-NC) Sustainable Sites credit for reducing the heat island effect.

All concretes in this study had average solar reflectances of at least 0.30 (corresponding to an SRI of at least 29), and therefore meet the requirements of LEED-NC SS 7.1. These concretes also meet the requirements for steep-sloped roofs in LEED-NC SS 7.2. The lowest solar reflectances were from concretes composed of dark gray fly ash.

The solar reflectance of the cement had more effect on the solar reflectance of the concrete than any other constituent material. The solar reflectance of the supplementary cementitious material had the second greatest effect.

REFERENCE

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Solar Reflectance of Concretes for LEED Sustainable Sites Credit: Heat Island Effect

by Medgar L. Marceau and Martha G. VanGeem[1]

INTRODUCTION

This report presents the results of solar reflectance testing on 135 concrete specimens from 45 concrete mixes, representing a broad range of concretes. The purpose of this testing is to determine which combinations of concrete constituents will meet the solar reflectance index requirements in the LEED Sustainable Sites credit for reducing the heat island effect.

Background

A heat island is a local area of elevated temperature in a region of cooler temperatures. Heat islands usually occur in urban areas; hence they are sometimes called *urban* heat islands. Urban heat islands occur when built-up areas are warmer than the surrounding environment. Figure 1 is a schematic depiction of a heat island. Urban heat island effects are real but local, and have a negligible influence on climate change (IPCC 2007).

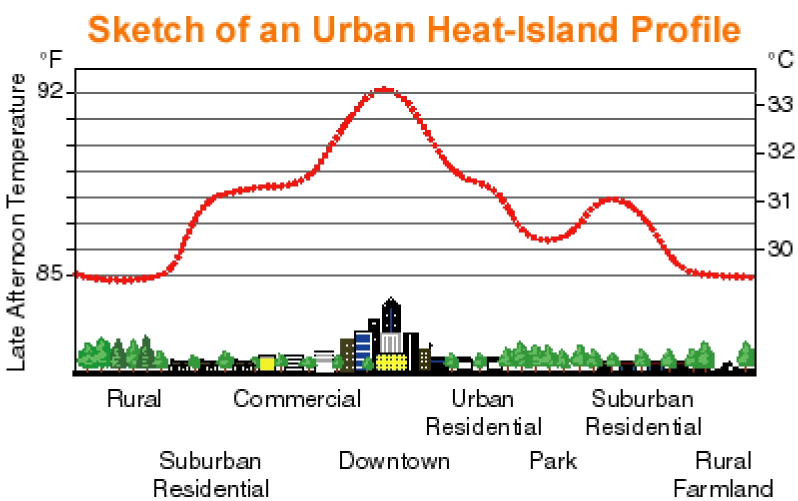

Figure 1. This schematic depiction of a heat island shows that air temperature is higher in the city center relative to the surrounding countryside. (The Urban Heat Island Group, http://eetd.lbl.gov/HeatIsland/HighTemps/, lasted visited 2007 March 30)

Heat islands occur where there is a preponderance of dark exterior building materials and a lack of vegetation. Materials with low solar reflectance (generally dark materials) absorb heat

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from the sun, and materials with higher solar reflectance (generally light-colored materials) reflect heat from the sun and do not warm the air relative to the surrounding areas as much. Evaporation of water from the surface of plants, where present, keeps them and the air around them cool.

In places that are already burdened with high temperatures, the heat island effect can make cities warmer, more uncomfortable, and occasionally more life-threatening (FEMA 2007). Temperatures greater than 24°C (75°F) increase the probability of formation of ground level ozone (commonly called smog), which exacerbates respiratory conditions such as asthma. Higher temperatures also lead to greater reliance on air conditioning, which leads to more energy use. The material properties that determine how much radiation a surface will absorb and retain are solar reflectance and emittance, respectively.

Green Buildings and LEED

The green building movement is a response to the negative environmental impacts of buildings, such as energy use, climate change, and urban heat islands. LEED is one result of this response. The Leadership in Energy and Environmental Design (LEED) Green Building Rating System is a family of voluntary rating systems for designing, constructing, operating, and certifying green buildings. LEED is administered by the U.S. Green Building Council (USGBC), a coalition of individuals and groups from across the building industry working to promote buildings that are environmentally responsible, profitable, and healthy places to live and work. This report references the solar reflectance requirements in version 2.2 of LEED for New Construction and Major Renovation (LEED-NC) (USGBC 2005a).

LEED-NC has gained widespread acceptance across the US. Many states and municipalities require that new public and publicly funded buildings meet the LEED-NC requirements for certification. Many owners and architects are also seeking LEED-NC ratings for privately funded buildings. LEED is rapidly gaining mainstream acceptance and architects are using products that help them obtain LEED points easily.

The LEED rating systems are point-based systems. Points are awarded for meeting certain requirements, such as energy conservation. The LEED-NC Sustainable Sites (SS) Credit 7 Heat Island Effect provides up to 2 points for reducing the heat island effect. One point can be obtained for using paving material with a solar reflectance index (SRI) of at least 29 for a minimum of 50% of the site hardscape (including roads, sidewalks, courtyards, and parking lots) (Credit 7.1). Another point is available for using low-sloped roofing with an SRI of at least 78 or steep-sloped roofing with an SRI of at least 29 for a minimum of 75% of the roof surface (Credit 7.2). Currently, to qualify for these points samples of the paving and roofing materials must be tested according to specified test procedures.

LEED is transforming the marketplace because architects increasingly specify materials that qualify for LEED points. As of August 2006, 62% of LEED project qualified for Credit 7.1 (the 23rd most commonly achieved point) and 53% qualified for Credit 7.2 (the 31st most commonly achieved point) (Steiner 2007).

TERMINOLOGY

Terms that related to solar energy conversion are defined in this section. These terms refer to measures of electromagnetic flux, which is the amount of electromagnetic radiation (including visible light) in a given place at a given time.

Reflectance

Reflectance is defined as the ratio of the reflected flux to the incident flux, and *reflectivity* is the reflectance of a microscopically homogeneous sample with a clean optically smooth surface and of thickness sufficient to be a completely opaque (ASTM E 772). Reflectivity is a property of a material, and reflectance is a surface property.

Solar Reflectance

For urban heat islands, we are interested in terrestrial flux, that is, the sun's energy that reaches the earth's surface after it has been filtered by the atmosphere (shown in Figure 2). About 3% of the total terrestrial flux is ultraviolet, 47% is visible light, and the remaining 50% is infrared (ASHRAE 2005).

Solar reflectance of opaque materials is a surface property. Solar reflectance is measured on a scale of 0 to 1: from not reflective (0) to 100% reflective (1.0). Generally, materials that appear to be light-colored in the visible spectrum have high solar reflectance and those that appear dark-colored have low solar reflectance. However, color is not always a reliable indicator of solar reflectance because color only represents 47% of the energy in the solar spectrum.

The spectral solar reflectance is the total reflectance (diffuse and specular) as a function of wavelength, across the solar spectrum (wavelengths of 0.3 to 2.5 µm). It is used to compute the overall solar reflectance, using a standard solar spectrum as a weighting function. It also contains the information in the visual range (0.4 to 0.7 µm) which is sufficient to compute the color coordinates for color matching with other materials (LBNL 2001)

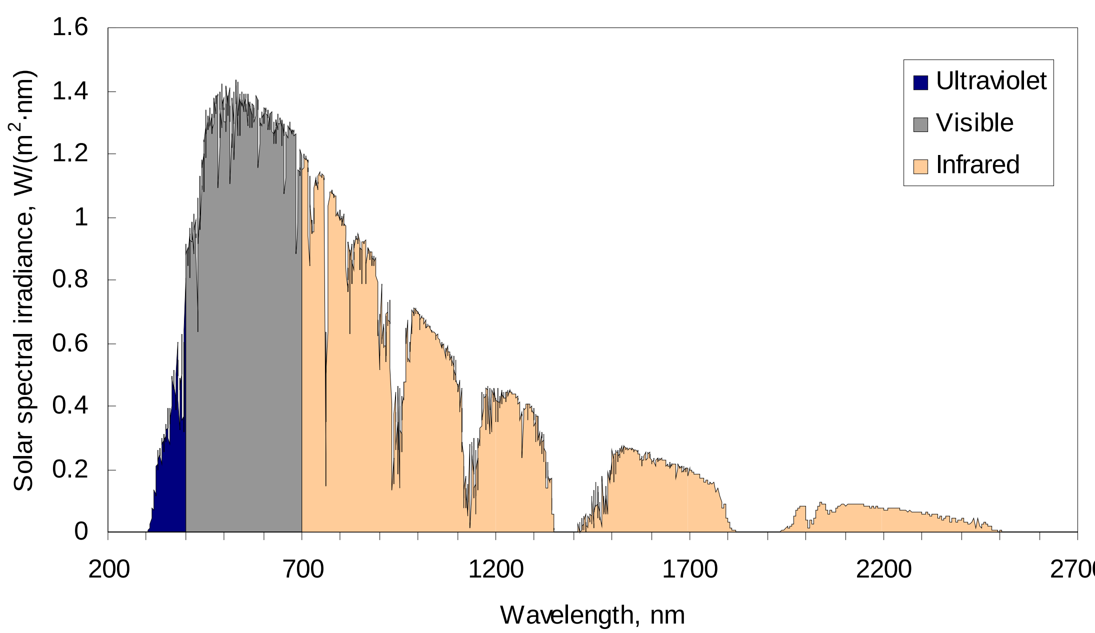


Figure 2. The terrestrial solar spectral irradiance is the sun's energy that reaches the earth after being filtered by the earth's atmosphere (ASTM G 173).

Albedo

Some researchers often use the term albedo and solar reflectance interchangeably, but in the context of LEED, the correct terminology is solar reflectance.

Emittance

Emittance for a sample at a given temperature is the ratio of the radiant flux emitted by the sample to that emitted by a blackbody radiator at the same temperature, under the same spectral and geometric conditions of measurement (ASTM E 772). A blackbody radiator is a hypothetical object that completely absorbs all incident radiant energy, independent of wavelength and direction (ASTM E 772). Emittance can be thought of as a measure of how well a surface emits (or lets go) heat. It is a value between 0 and 1. Highly polished aluminum has an emittance less than 0.1, and a black non-metallic surface has an emittance greater then 0.9. However, most non-metallic opaque materials at temperatures encountered in the built environment have an emittance between 0.85 and 0.95 (ASHRAE 2005). Emissivity is a property of a material, and emittance is a surface property.

Solar Reflectance Index

Solar reflectance Index (SRI) is a composite measure that accounts for a surface's solar reflectance and emittance. Reflectance and emittance are so-called radiometric properties. These are properties that vary with the direction of incident or exitant radiation flux, or both, and with the relative spectral distribution of the incident flux and the spectral response of the detector for the exitant flux. For reflectance, the direction and geometric extent of both the incident beam and exitant beam must be specified. For emittance, only the exitant beam need be specified. (ASTM E 772). The calculation procedure for solar reflectance index is described in ASTM E 1980, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low Slope Opaque Surfaces*.

Nonmetallic opaque building materials such as masonry, concrete, and wood have an emittance of 0.90 (ASHRAE 2005). Using ASTM E 1980 and an emittance of 0.90, concrete needs to have a solar reflectance of at least 0.28 to meet the LEED-NC SS 7.1 requirement of an SRI of at least 29. Concrete needs to have a solar reflectance of at least 0.64 to meet the LEED-NC SS 7.2 requirement of an SRI of at least 78 for low-sloped roofs and at least 0.28 to meet the LEED-NC SS 7.2 requirements of an SRI of at least 29 for steep-sloped roofs. The LEED-NC *Reference Guide* provides a default value for concrete emittance of 0.9 (USGBC 2005a). The same source provides default solar reflectance values for "new typical gray concrete" of 0.35 and "new typical white concrete" of 0.70. The default SRI values for the new gray and new white concrete are 35 and 86, respectively.

PREVIOUS RESEARCH

A test program to determine factors affecting solar reflectance of concrete was carried out at Ernest Orlando Lawrence Berkeley National Laboratory (LBNL) (Levinson and Akbari 2001). The LBNL test program studied the following factors: fine aggregate color, coarse aggregate color, cement color, wetting, soiling, abrasion, and age. Unfortunately, the specimens did not represent real-world flatwork due to how they were fabricated and finished. The specimens were made in 4×4-in. cylindrical molds. The concrete cylinders were moist cured for 7 days, removed from their molds, and cut longitudinally into four 3-in. discs. Each disc was considered one specimen and subjected to various treatments.

No allowance was made for the different absorptions and moisture contents of the aggregates in each concrete. As such, all concrete had the same mix proportions regardless of the physical properties of the mix constituents. The result was an irregular surface on some specimens due to not enough water in the concrete mix. Conventionally, each concrete mix ought to have been designed to account for particular properties of the constituents (Kosmatka and others 2002). However, the results of the LBNL study are still useful. They show that:

1. Concrete reflectance increases as cement hydration progresses but stabilizes within six weeks of casting. The average increase is 0.08 over a six-week period.
2. Simulated weathering, soiling, and abrasion each reduce the average reflectance of concretes by 0.06, 0.05, and 0.19, respectively.

PRESENT RESEARCH

The present research builds on these results because in addition to testing commonly available concrete constituent materials, the test specimens were proportioned, mixed, fabricated, and finished like typical exterior flatwork (such as roads, sidewalks, and parking lots).

OBJECTIVE

The objective of this project is to demonstrate that concretes made from a range of constituents have a solar reflectance of at least 0.30 and an SRI of at least 29. This is the criteria for LEED-NC Sustainable Sites Credit 7.1 Heat Island Effect: Non-Roof. Further, analysis of variance is used to determine the effects of concrete constituents on concrete solar reflectance.

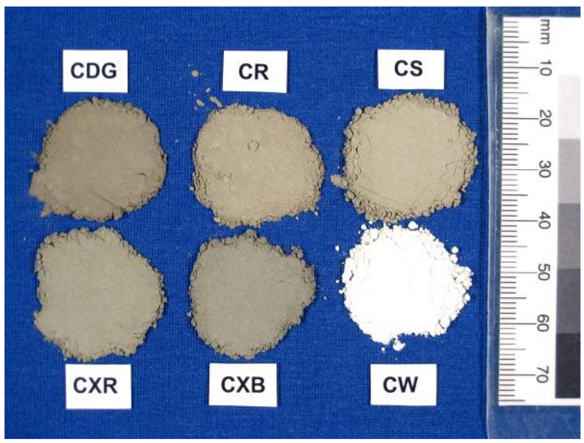
METHODOLOGY

The methodology consists of selecting representative samples of concrete constituents, measuring the solar reflectance of the constituents, making concrete specimens, and measuring the solar reflectance of the specimens.

Selection of Concrete Constituents

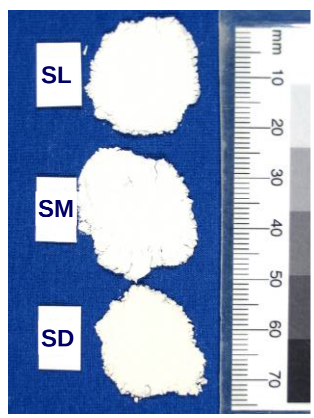
From hundreds of samples of concrete constituents that are sent to our laboratories from all over the US for various testing, we chose concrete constituents, based on color, that represent the variety of materials used to make concrete in the US. The initial choice was based on color because we could find no data, neither from manufacturers nor in the literature, on the solar reflectance of concrete constituents. We further narrowed the choice to materials that are actually used to make concrete. The final sample consists of six portland cements, six fly ashes, three slag cements, four fine aggregates, and two coarse aggregates. Figure 3 shows the cementitious materials and Figure 4 shows the aggregates. We had originally intended to select 10 cements and 10 sands, but as we began looking at available materials we realized there was not much variation in color. Except for white portland cement, portland cements are about the same shade of gray. The color of individual particles of fine aggregate varies, but fine aggregate used in concrete is usually erosion sediment consisting of granite, quartz, feldspar, etc., and the overall color is a medium buff color. Occasionally, the fine fraction of crushed aggregate is used to make concrete. This is usually limestone which, after washing, tends to be light gray.

Abbreviated Names. A system of abbreviated names is used in this report to make it easier to present and discuss the results. Each concrete constituent has a two- to three-letter abbreviation. Cements start with the letter C and subsequent letters refer to the relative color or source. For example, “CDG” is dark gray cement and “CXB” is cement from a plant described as “XB” to ensure confidentiality. Fly ashes start with the letter F and subsequent letters refer the relative color. For example, “FDG” is dark gray fly ash and “FYB” is a yellowish buff fly ash. Slag cements start with the letter S and the second letter refers to the relative color. Throughout this report, slag cement refers to ground, granulated blast furnace slag. For example, “SD” is dark slag cement. Fine aggregates start with the letter A and the second letter refers to the relative color or source. For example, “AE” is Eau Claire sand and “AB” is black sand. Coarse aggregates start with the letter C and the second letter refers to the type. For example, “CP” is pea gravel and “CL” is coarse aggregate from crushed limestone. See Table 1 for complete descriptions.



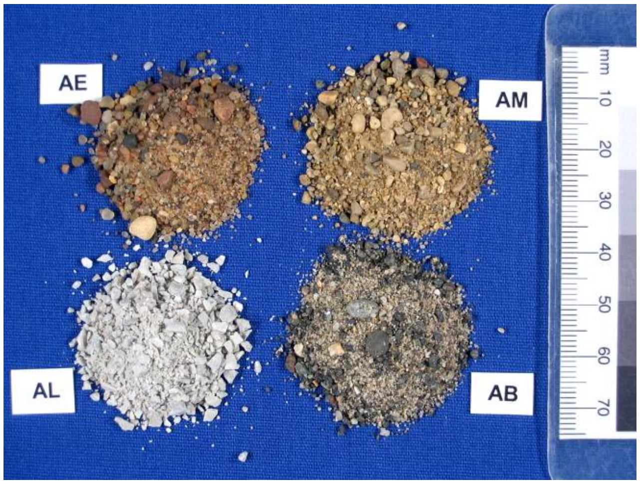
Portland cements (C)

Fly ashes (F)

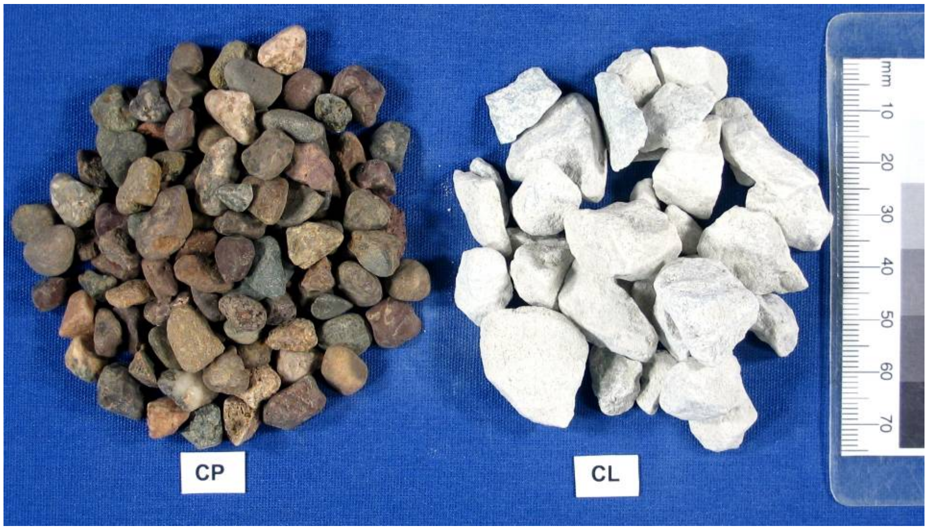


Slag cements (S)

Figure 3. Cementitious materials, the abbreviated names are explained in the text and in Table 1.



Fine aggregates (A)



Coarse aggregates (C)

Figure 4. Fine and coarse aggregates, the abbreviated names are explained in the text and in Table 1.

Measuring Solar Reflectance

Solar reflectance was measured with a solar spectrum reflectometer (SSR) from Devices and Services Company using the procedure in ASTM C 1549. This method is acceptable for meeting the requirements of LEED-NC SS 7.1 and 7.2. The solar spectrum reflectometer requires zero-offset adjustment and calibration before measurements can be taken. A blackbody cavity, with a solar reflectance of zero, is used to adjust the zero offset. A white standard reference material, with a solar reflectance of 0.801 is use for calibration. The apparatus is shown in Figure 5. Powders and aggregate were measured using a modification to ASTM C 1549 as described in the next two sections.

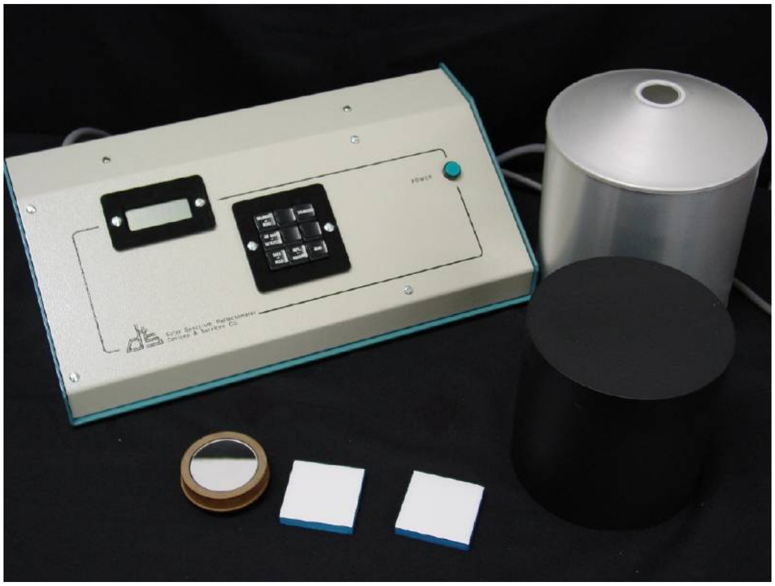


Figure 5. The Devices and Services Company solar spectrum reflectometer model SSR-ER is shown with the measurement head (upper right), black body cavity (lower right), and three calibration standards (a round mirror, and two square white ceramic tiles).

Measuring Powder

The solar reflectance of powders (portland cement, fly ash, and slag cement) is measured according to ASTM C 1549 with the following modification: After zeroing, the SSR is calibrated with a white standard reference material (a diffuse ceramic tile) covered with a glass microscope slide. A glass microscope slide is used because it has high transmittance and low reflectance. Approximately 4 cm^3 (¼ cu in.) of powder is placed on a 50×75-mm (2×3-in.) microscope slide. Using the edge of a second microscope slide and a chopping motion, any lumps in the powder are broken up. Figure 6 shows the set-up. The second slide is place flat on top of the powder and pressure is applied to the slide to flatten the powder into a 5-cm (2-in.) diameter disc. The resulting sample, sandwiched between the two microscope slides, is opaque. The solar reflectance of the sample is measured through the glass slide. For each powder, this procedure is repeated with two additional samples of powder.

The effect of the glass slide on measured solar reflectance is eliminated because the SSR is calibrated with the glass slide over the standard reference material. This was confirmed by measuring the solar reflectance of the standard with the slide in place. The measured value was the same as the published value.

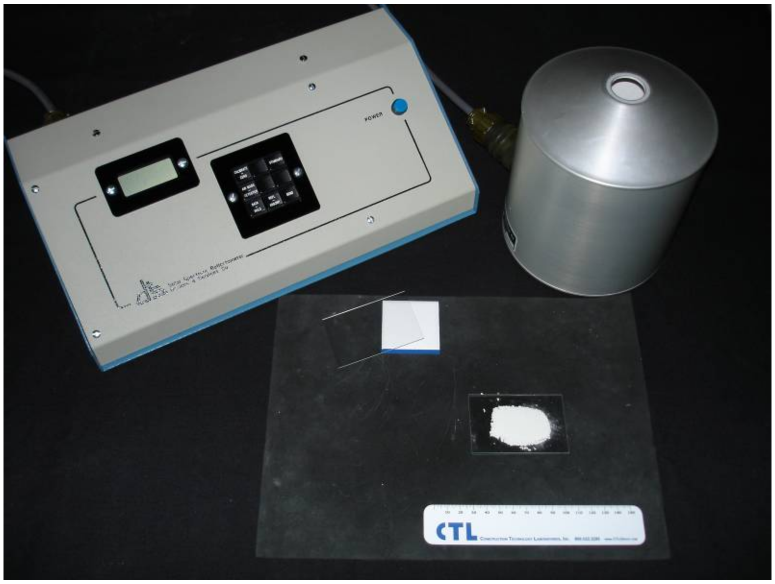


Figure 6. The solar reflectance of a sample of slag cement (white powder on microscope slide near ruler) is measured between two microscope slides (the second slide is lying across the white ceramic tile).

Measuring Aggregates

The solar reflectance of fine aggregates is measured according to ASTM C 1549 with the following modification. After zeroing, transparent low density polyethylene film (GLAD Cling Wrap) is stretched over the measurement port of the reflectance measurement head and the SSR is calibrated with a white standard reference (a diffuse ceramic tile). About 50 cm^3 (3 cu in.) of fine aggregate is placed in a 25-mm (1-in.) deep by 60-mm diameter (2¼-in.) Petri dish. The solar reflectance of the sample is measured with the polyethylene film stretched over the measurement port. This procedure is used to keep sand out of the reflectance measurement head which could mar the highly reflective interior coating. For each type of fine aggregate, this procedure is repeated with two additional samples of fine aggregate.

The effect of the polyethylene film on measured solar reflectance is eliminated because the SSR is calibrated with the film over the measurement port. This was confirmed by measuring the solar reflectance of the standard with the film in place. The measured value was same as the published value.

Coarse aggregate particles are too small to completely cover the measurement port and too big to measure in the same way as fine aggregate. Therefore, it is assumed that the solar reflectance of coarse aggregate is the same as fine aggregate from the same source. For example, the solar reflectance of manufactured sand from crushed limestone is the same as the solar reflectance of coarse aggregate from crushed limestone. Since solar reflectance of opaque materials is a surface property, this is not a critical assumption because coarse aggregate in quality concrete is not usually exposed. The results below will show that coarse aggregate reflectance has no affect on concrete reflectance.

Solar Reflectance of Concrete Constituents

Table 1 and Figure 7 show the measured solar reflectance of the dry concrete mix constituents. The color intensity modifiers were assigned before solar reflectance was measured, so they do not correlate exactly, for example, light gray fly ash (FLG) has a lower solar reflectance than medium gray fly ash (FMG).

Table 1. Solar Reflectance of Concrete Mix Constituents

Material	Description	Abbreviated name	Solar reflectance*
Cement	Plant XB	CXB	0.36
	Dark gray	CDG	0.38
	Plant XR	CXR	0.40
	Plant R	CR	0.44
	Plant S	CS	0.47
	White	CW	0.87
Fly ash	Dark gray	FDG	0.28
	Light gray	FLG	0.36
	Medium gray	FMG	0.40
	Pale buff	FPB	0.44
	Yellow buff	FYB	0.46
	Very light gray	FVLG	0.55
Slag cement	Dark	SD	0.71
	Medium	SM	0.75
	Light	SL	0.75
Fine aggregate	Black	AB	0.22
	Eau Claire	AE	0.27
	McHenry	AM	0.30
	Limestone	AL	0.42
Coarse aggregate	Eau Claire	CP	0.27
	Limestone	CL	0.42

*Solar reflectance of dry concrete mix constituents, in powder or granular state, was measured with a solar spectrum reflectometer using a modification to ASTM C 1549.

Mix Proportioning

Rather than fabricate and measure concrete specimens for every combination of cement, cementitious material, fine aggregate, and coarse aggregate, we chose to use a phased approach. The goal was to determine whether the darkest (actually, the lowest solar reflectance) combination of constituent materials would meet the requirement of a solar reflectance of at least 0.30 for the resulting concrete. While all materials were tested, we focused on concrete mixes with the darkest combinations of materials. We performed the work in three phases so that we could learn from previous phases what constituent materials and combinations produced the lowest solar reflectances and needed more thorough examination. The results of the three phases have been combined for this report. Table 2 presents the resulting 45 mix proportions for concrete flat-work exposed to exterior conditions.

The replacement levels for fly ash (25%) and slag cement (45%) were chosen because they are commonly used replacements levels for cement. The selected concrete constituents were proportioned to yield a mix suitable for use in exterior flat work. The target properties are as follows: 10-cm (4-in.) slump, 4% air content, 0.47 water-cementitious ratio, and 0.4 cementitious to fine aggregate volume ratio.

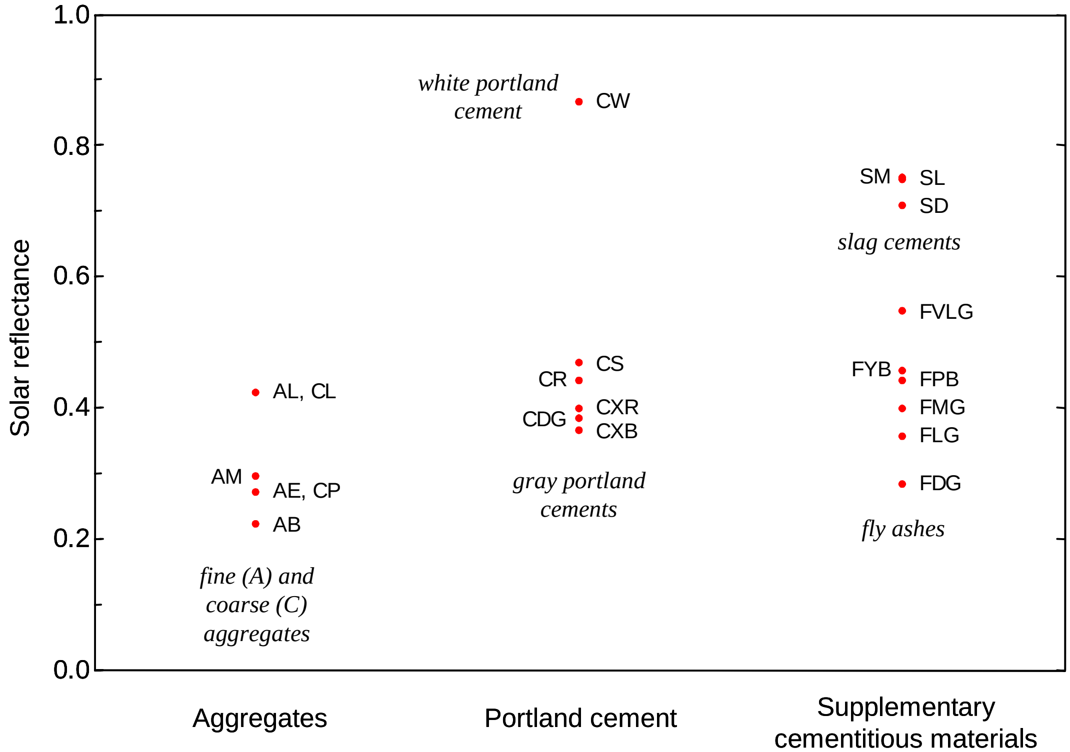


Figure 7. Solar reflectance of dry concrete mix constituents, in powder or granular state, was measured with a solar spectrum reflectometer using a modification to ASTM C 1549.

Mix Abbreviated Names. The concretes are referred to as "C…-A…-C…-F…-S…", where the first "C…" is cement, "A…" is fine aggregate, the second "C…" is coarse aggregate, "F…" is fly ash, and "S…" is slag cement. The ellipses above are place-holders for the relative color or source of the constituent. These ellipses are completed in the tables and figures. The relative color and the source of the constituent are also called the factor level in the analysis. If no fly ash or slag cement is used in the mix, the tables and figures show only an ellipsis. For example, "CW-AE-CP-...-SD" is a mix containing white cement, Eau Clair fine aggregate, pea gravel, no fly ash, and dark slag cement.

Mix and Specimen Numbering. If a concrete mix is repeated, the mix abbreviated name is also numbered. The first number after the mix name refers to the mix number. For example, "CDG-AE-CP-FDG-… 1" is the first mix made with dark gray cement, Eau Claire fine aggregate, Eau Claire coarse aggregate, dark gray fly ash, and no slag cement; and "CDG-AE-CP-FDG-… 2" is the second such mix. Each specimen is also numbered from one to three. For example, "CDG-AE-CP-FDG-… 2 01" is specimen number one from the second mix of "CDG-AR-CP-FDG-…". Three specimens were made from each concrete mix.

Table 2. Concretes Mix Proportioning

Mix abbreviated name	Mix proportioning, lb/cu yd (unless noted otherwise)						w/c§	c/s**
	Cement	SCM*	SSD† aggregate		Water	AE‡ agent, ml/cu yd		
			Fine	Coarse				
CDG-AE-CP-...-...	565	0	1245	1896	225	108	0.40	0.45
CDG-AE-CP-...-SD	261	213	1242	1892	228	108	0.48	0.38
CDG-AE-CP-...-SL	261	213	1242	1892	228	108	0.48	0.38
CDG-AE-CP-FDG-…	381	127	1228	1869	244	81	0.48	0.41
CDG-AM-CP-FDG-...	381	127	1246	1869	244	81	0.48	0.41
CR-AB-CP-...-...	565	0	1258	1895	294	108	0.52	0.45
CR-AE-CP-...-...	565	0	1245	1896	225	108	0.40	0.45
CR-AE-CP-FDG-...	381	127	1228	1869	244	108	0.48	0.41
CR-AM-CL-FDG-...	381	127	1246	1876	252	122	0.50	0.41
CR-AM-CP-FDG-...	381	127	1242	1869	244	108	0.48	0.41
CS-AB-CP-...-...	565	0	1258	1895	299	108	0.53	0.45
CS-AB-CP-...-SD	261	213	1256	1892	272	108	0.57	0.38
CS-AB-CP-...-SL	261	213	1256	1892	228	108	0.48	0.38
CS-AB-CP-FDG-...	381	127	1242	1869	276	108	0.54	0.41
CS-AB-CP-FPB-...	381	127	1242	1869	244	81	0.48	0.41
CS-AE-CL-...-...	565	0	1245	1903	247	108	0.44	0.45
CS-AE-CL-...-SD	261	213	1242	1899	295	108	0.62	0.38
CS-AE-CL-FDG-...	381	127	1228	1876	252	108	0.50	0.41
CS-AE-CP-...-...	565	0	1245	1896	225	108	0.40	0.45
CS-AE-CP-...-SD	261	213	1242	1892	228	108	0.48	0.38
CS-AE-CP-...-SL	261	213	1242	1892	228	117	0.48	0.38
CS-AE-CP-...-SM	261	213	1242	1892	228	81	0.48	0.38
CS-AE-CP-FDG-...	381	127	1228	1869	244	117	0.48	0.41
CS-AE-CP-FLG-...	381	127	1228	1869	244	81	0.48	0.41
CS-AE-CP-FMG-...	381	127	1228	1869	244	108	0.48	0.41
CS-AE-CP-FPB-...	381	127	1228	1869	244	81	0.48	0.41
CS-AE-CP-FVLG-...	381	127	1228	1869	244	95	0.48	0.41
CS-AE-CP-FYB-...	381	127	1228	1869	244	81	0.48	0.41
CS-AL-CP-...-...	565	0	1224	1822	271	108	0.48	0.46
CS-AL-CP-...-SD	261	213	1271	1892	289	108	0.61	0.37
CS-AL-CP-...-SL	261	213	1271	1892	282	108	0.59	0.37
CS-AL-CP-FDG-...	381	127	1255	1869	244	108	0.48	0.40
CS-AL-CP-FPB-...-	381	127	1255	1869	244	81	0.48	0.40
CS-AM-CL-...-...	565	0	1260	1903	274	108	0.48	0.45
CS-AM-CP-...-...	565	0	1258	1895	226	117	0.40	0.45
CS-AM-CP-FDG-...	381	127	1242	1869	244	117	0.48	0.41
CW-AB-CP-...-...	565	0	1254	1888	301	108	0.53	0.45
CW-AE-CP-...-...	565	0	1240	1888	259	108	0.46	0.46
CW-AL-CL-FDG-...	381	127	1228	1876	257	108	0.51	0.41
CW-AL-CP-...-...	565	0	1219	1815	271	108	0.48	0.46
CW-AL-CP-...-SL	261	213	1271	1892	252	108	0.53	0.37
CXB-AE-CP-...-...	565	0	1244	1895	226	108	0.40	0.45
CXB-AE-CP-FDG-...	381	127	1228	1869	244	81	0.48	0.41
CXR-AE-CP...-...	565	0	1244	1895	249	108	0.44	0.45
CXR-AE-CP-FDG-...	381	127	1228	1869	244	81	0.48	0.41

*SCM is supplementary cementitious material: in this case, either fly ash or slag cement.
†SSD is saturated surface dry.
‡AE is air entraining.
§w/c is water to cementitious ratio.
**c/s is cementitious to fine aggregate ratio.

Specimens. Three specimens measuring 300×300×25 mm (12×12×1 in) were made from each mix. The constituent materials were mixed in a ½-cubic foot pan mixer shown in Figure 8. The properties of the fresh concrete are shown in Table 3. The specimens were given a light broom finish, moist cured for 7 days, and placed in a temperature- and humidity-controlled room at a nominal 73°F and 50% relative humidity to dry for 60 days. Previous research has shown that solar reflectance of concrete remains approximately constant after six weeks from casting (Levinson and Akbari 2001). The solar reflectance of the surface of each specimen was measured in three arbitrarily chosen locations, for a total of nine measurements of solar reflectance per concrete mix. Photographs of the specimens after testing are shown in Appendix A. The photographs are arranged alphabetically by mix abbreviated name. Each row of photographs shows the three specimens. Appendix B shows close-up photographs of each specimen. The photographs are also arranged alphabetically with the three specimens from each mix in the same row.

Figure 8. Concrete is mixed in a ½-cubic foot pan mixer.

Repeat Specimens. Three sets of specimens (“CDG-AE-CP-FDG-...”, “CS-AE-CL-FDG-...”, “CS-AE-CP-FVLG-...”) were finished before the concrete had properly set, resulting in a finished surface that is inconsistent, so additional specimens were fabricated. The second set of specimens from “CS-AE-CP-FVLG-...” was also finished too soon, so a third set was made. The solar reflectance is reported for all specimens made; however, the prematurely finished specimens are not included in the analysis.

Table 3. Fresh Concrete Properties

Mix abbreviated name	Properties of fresh concrete		
	Unit weight, lb/cu yd	Air content, %	Slump, in.
CDG-AE-CP-...-...	145	6%	3.50
CDG-AE-CP-...-SD	147	5%	1.50
CDG-AE-CP-...-SL	145	6%	3.00
CDG-AE-CP-FDG-…	149	2%	2.75
CDG-AM-CP-FDG-...	150	2%	2.50
CR-AB-CP-...-...	146	4%	0.75
CR-AE-CP-...-...	145	6%	2.75
CR-AE-CP-FDG-...	149	2%	3.25
CR-AM-CL-FDG-...	150	2%	1.75
CR-AM-CP-FDG-...	150	1%	6.50
CS-AB-CP-...-...	145	5%	3.25
CS-AB-CP-...-SD	145	5%	2.75
CS-AB-CP-...-SL	141	7%	3.75
CS-AB-CP-FDG-...	148	1%	7.75
CS-AB-CP-FPB-...	148	2%	6.75
CS-AE-CL-...-...	148	4%	1.25
CS-AE-CL-...-SD	147	3%	2.75
CS-AE-CL-FDG-...	151	1%	3.75
CS-AE-CP-...-...	148	4%	0.50
CS-AE-CP-...-SD	142	7%	7.25
CS-AE-CP-...-SL	143	7%	6.50
CS-AE-CP-...-SM	144	no data	7.00
CS-AE-CP-FDG-...	148	2%	7.50
CS-AE-CP-FLG-...	148	4%	7.25
CS-AE-CP-FMG-...	148	2%	8.25
CS-AE-CP-FPB-...	148	4%	7.50
CS-AE-CP-FVLG-...	146	5%	7.50
CS-AE-CP-FYB-...	145	5%	10.50
CS-AL-CP-...-...	144	6%	2.75
CS-AL-CP-...-SD	140	7%	3.50
CS-AL-CP-...-SL	142	7%	3.50
CS-AL-CP-FDG-...	150	2%	1.00
CS-AL-CP-FPB-...-	150	2%	1.25
CS-AM-CL-...-...	146	5%	5.75
CS-AM-CP-...-...	147	6%	1.40
CS-AM-CP-FDG-...	150	2%	3.25
CW-AB-CP-...-...	146	4%	4.00
CW-AE-CP-...-...	148	3%	3.25
CW-AL-CL-FDG-...	150	1%	4.25
CW-AL-CP-...-...	148	3%	2.00
CW-AL-CP-...-SL	145	4%	1.75
CXB-AE-CP-...-...	148	5%	1.75
CXB-AE-CP-FDG-...	149	2%	2.75
CXR-AE-CP...-...	146	5%	4.00
CXR-AE-CP-FDG-...	149	2%	4.00

RESULTS

The solar reflectance of the surface of each specimen was measured in three arbitrarily chosen locations. For each location, the average of five readings was recoded as one measurement.

Therefore, each mix is represented by nine observations of solar reflectance. The solar reflectance measurements are shown in Figure 9, arranged alphabetically, and in Figure 10, by increasing average solar reflectance. The complete results are shown in Table 4.

Observations

The solar reflectance of all concretes tested is greater than 0.3. This corresponds to a calculated solar reflectance *index* (SRI) of 30 to 34 assuming an emittance of 0.85 to 0.95. Therefore; all the concretes in this report, regardless of constituents, would qualify for LEED-NC SS Credit 7.1 Heat Island Effect: Non-Roof and LEED-NC SS Credit 7.2 Heat Island Effect: Roof for steep sloped roofs. The overall average solar reflectance of all mixes is 0.47.

The lowest average solar reflectance is 0.33 from mix “CDG-AE-CP-FDG-... 1”, though as explained earlier, specimens from this mix were improperly finished resulting in a very non-uniform surface. Eliminating these specimens from the sample, the next lowest average solar reflectance is 0.34 from mix “CS-AE-CP-FDG-...”. Both of these mixes contain dark gray fly ash.

Two of the concretes have average solar reflectances of at least 0.64 (corresponding to an SRI of at least 78 using an emittance of 0.90), which meets the requirements for low-sloped roofs in LEED-NC SS 7.2. The first is mix “CS-AL-CP-…-SL”, composed of ordinary portland cement, fine aggregate from crushed limestone, Eau Claire coarse aggregate, and light colored slag cement. The second is “CW-AL-CP-…-…”, composed of white cement, fine aggregate from crushed limestone, and Eau Claire coarse aggregate.

Generally, the higher the solar reflectance of the cementitious material, the higher the solar reflectance of the concrete. The solar reflectances of the ordinary cements (other than the white cement) range from 0.36 to 0.47. The solar reflectances of the fly ashes range above and below that of the cements, from 0.28 to 0.55. The solar reflectances of the slag cements range from 0.71 to 0.75, exceeding that of the ordinary cements and fly ashes. Accordingly, the slag cement concretes generally have the highest solar reflectances. The white cement has the highest solar reflectance, 0.87.

The average effect of replacing 45% of the cement in a mix with slag cement is to increase (lighten) the solar reflectance of the concrete by 0.07. The average effect of replacing 25% of the cement in a mix with dark gray fly ash is to decrease (darken) the solar reflectance by 0.02. The average effect of replacing 25% of the cement in a mix with the other fly ashes is to increase (lighten) the solar reflectance by 0.03.

Analysis of Variance

An analysis of the results was undertaken using analysis of variance (ANOVA) to determine which concrete constituents affect whether or not a concrete passes or fails under the LEED SS Credit 7 criteria. The complete analysis is presented in Appendix C. The analysis is based on nine observations of solar reflectance per mix. Thus, neither the variation of solar reflectance within a particular slab nor the variation of solar reflectance between each group of three slabs per mix is considered. To simplify the calculations, the solar reflectance data were scaled up by a factor of 1000. Further, since the solar spectrum reflectometer measures solar reflectance to three places after the decimal, three digits are used in the analysis. A summary of the findings is presented here.

Analysis of variance is a procedure to determine which variables in an experiment have an effect on the results and which are due to random effects. It uses statistical models to partition the observed variance due to different explanatory variables into its components and to test whether an explanatory variable can account for more of the variation than what is likely to arise from chance. For significant explanatory variables, ANOVA is also used to conduct regression analysis to quantify how much of the observed variation is due to an explanatory variable.

The first result is that the reflectances of the specimens within a particular mix are not different; that is, the differences in solar reflectance *within* a particular mix are not significant, but the differences in solar reflectance *between* mixes are significant.

The second result is that the reflectance of portland cement has a significant effect on slab reflectance. That is, the higher the cement reflectance, the higher the slab reflectance. About 80% of the variability in slab reflectance is explained by variations in cement reflectance when no SCM is present. Further, slab reflectance increases with increasing reflectance of SCM. Supplementary cementitious materials, when used, explains about 75% of the variation in slab reflectance when the cement reflectance is constant.

The next result is that fine aggregate has a significant effect on slab reflectance; however, this effect is very small. Coarse aggregate has no significant effect on slab reflectance. The reflectance of fine aggregate explains less than 5% of the variation in slab reflectance. There is no meaningful interaction between cement and fine aggregate reflectance on slab reflectance because the effect of increasing fine aggregate reflectance does not have a linear effect on slab reflectance. In other words, using a higher solar reflectance cement in a concrete mix increases the solar reflectance of the concrete by the same amount as using a lower solar reflectance cement regardless of the solar reflectance of the fine aggregate.

Slabs with a smoother finish (as observed visually) have higher reflectance than those with a rougher finish. The solar reflectance is approximately 0.07 higher for slabs with a smoother finish. Slab reflectance is lower for uniformly colored slabs (as observed visually). The solar reflectance is approximately 0.06 lower for slabs with a uniform color. Slab reflectance generally increases with increasing reflectance of SCM regardless of whether the slab is smooth or rough or uniform or non-uniform in color. Slabs with a smooth finish tend to have higher reflectances with increasing SCM reflectance compared to slabs with rougher finish.

CONCLUSIONS

The following conclusions are based on the solar reflectance measurements on 135 concrete specimens from 45 concrete mixes representing exterior concrete flat-work:

1. All concretes in this study have average solar reflectances of at least 0.30 (an SRI of at least 29), and therefore meet the requirements of LEED-NC SS 7.1. These concretes also meet the requirements for steep-sloped roofs in LEED-NC SS 7.2. The lowest solar reflectances are from concretes composed of dark gray fly ash.
2. Two of the concretes have average solar reflectances of at least 0.64 (an SRI of at least 78), meeting the requirements of low-sloped roofs in LEED-NC SS 7.2: Heat Island Effect: Roof. The first is composed of ordinary portland cement, fine aggregate from crushed limestone, and light-colored slag cement. The second is composed of white cement and fine aggregate from crushed limestone.
3. The solar reflectance of the cement has more effect on the solar reflectance of the concrete than any other constituent material. The solar reflectance of the supplementary cementitious material (in this study, fly ash or slag cement) has the second greatest effect.

4. The solar reflectance of the fine aggregate has a small effect on the solar reflectance of the concrete. The solar reflectance of the coarse aggregate does not have a significant effect on the solar reflectance of the concrete.
5. All specimens have a light broom finish, but due to the constituent materials, some specimens have a smoother surface than others. Those with a smoother surface have a higher solar reflectance than those with a rougher finish.
6. The solar reflectance of fly ash can be greater than or less than that of ordinary cement. The solar reflectance of slag cement is greater than that of ordinary portland cement or fly ash. The solar reflectance of the white cement in this study is greater than that of the slag cements.

Table 4. Solar Reflectance of Specimens

Mix abbreviated name	Specimen 1			Specimen 2			Specimen 3			Average
	Location			Location			Location			
	1	2	3	1	2	3	1	2	3	
CDG-AE-CP-...-...	0.41	0.41	0.43	0.46	0.44	0.45	0.45	0.44	0.41	0.43
CDG-AE-CP-...-SD	0.52	0.52	0.53	0.50	0.50	0.51	0.48	0.47	0.53	0.51
CDG-AE-CP-...-SL	0.48	0.46	0.49	0.47	0.48	0.46	0.48	0.46	0.48	0.47
CDG-AE-CP-FDG-... 1	0.37	0.37	0.34	0.34	0.31	0.33	0.26	0.33	0.31	0.33
CDG-AE-CP-FDG-... 2	0.39	0.40	0.38	0.37	0.39	0.36	0.42	0.41	0.42	0.39
CDG-AM-CP-FDG-...	0.39	0.39	0.40	0.40	0.39	0.41	0.40	0.41	0.39	0.40
CR-AB-CP-...-...	0.36	0.35	0.35	0.35	0.35	0.38	0.37	0.37	0.38	0.36
CR-AE-CP-...-...	0.37	0.33	0.33	0.35	0.36	0.36	0.38	0.39	0.36	0.36
CR-AE-CP-FDG-...	0.39	0.43	0.40	0.41	0.43	0.41	0.39	0.42	0.42	0.41
CR-AM-CL-FDG-...	0.43	0.42	0.41	0.42	0.45	0.46	0.44	0.43	0.45	0.43
CR-AM-CP-FDG-...	0.37	0.40	0.45	0.39	0.41	0.39	0.39	0.38	0.41	0.40
CS-AB-CP-...-...	0.50	0.50	0.51	0.53	0.51	0.51	0.49	0.49	0.52	0.51
CS-AB-CP-...-SD	0.53	0.52	0.54	0.56	0.55	0.54	0.53	0.55	0.53	0.54
CS-AB-CP-...-SL	0.57	0.58	0.58	0.57	0.54	0.56	0.58	0.57	0.55	0.57
CS-AB-CP-FDG-...	0.46	0.45	0.50	0.51	0.53	0.52	0.43	0.50	0.43	0.48
CS-AB-CP-FPB-...	0.57	0.57	0.54	0.55	0.59	0.56	0.56	0.58	0.59	0.57
CS-AE-CL-...-...	0.53	0.52	0.48	0.43	0.43	0.44	0.42	0.43	0.47	0.46
CS-AE-CL-...-SD	0.59	0.57	0.58	0.58	0.56	0.57	0.58	0.57	0.57	0.57
CS-AE-CL-FDG-... 1	0.38	0.37	0.33	0.39	0.38	0.37	0.45	0.40	0.42	0.39
CS-AE-CL-FDG-... 2	0.43	0.41	0.43	0.42	0.39	0.41	0.41	0.41	0.40	0.41
CS-AE-CP-...-...	0.38	0.39	0.41	0.43	0.41	0.42	0.47	0.44	0.44	0.42
CS-AE-CP-...-SD	0.52	0.51	0.52	0.54	0.54	0.54	0.52	0.51	0.52	0.52
CS-AE-CP-...-SL	0.58	0.58	0.56	0.55	0.56	0.56	0.58	0.59	0.58	0.57
CS-AE-CP-...-SM	0.56	0.56	0.55	0.52	0.52	0.54	0.54	0.53	0.53	0.54
CS-AE-CP-FDG-...	0.33	0.35	0.35	0.33	0.35	0.33	0.33	0.34	0.35	0.34
CS-AE-CP-FLG-...	0.41	0.41	0.42	0.43	0.40	0.42	0.43	0.46	0.44	0.42
CS-AE-CP-FMG-...	0.39	0.40	0.42	0.45	0.44	0.49	0.47	0.46	0.47	0.44
CS-AE-CP-FPB-...	0.47	0.45	0.46	0.48	0.48	0.46	0.48	0.51	0.48	0.47
CS-AE-CP-FVLG-... 1	0.48	0.49	0.48	0.41	0.42	0.41	*	*	*	0.45
CS-AE-CP-FVLG-... 2	0.46	0.49	0.51	0.47	0.43	0.47	0.46	0.42	0.47	0.46
CS-AE-CP-FVLG-... 3	0.49	0.47	0.49	0.49	0.48	0.50	0.50	0.48	0.47	0.48
CS-AE-CP-FYB-...	0.44	0.44	0.44	0.45	0.47	0.46	0.47	0.49	0.48	0.46
CS-AL-CP-...-...	0.53	0.53	0.52	0.55	0.52	0.55	0.52	0.53	0.51	0.53
CS-AL-CP-...-SD	0.61	0.61	0.60	0.61	0.62	0.60	0.60	0.60	0.58	0.60
CS-AL-CP-...-SL	0.64	0.65	0.65	0.64	0.63	0.65	0.62	0.64	0.63	0.64
CS-AL-CP-FDG-...	0.46	0.47	0.45	0.43	0.44	0.41	0.52	0.51	0.49	0.46
CS-AL-CP-FPB-...	0.54	0.53	0.52	0.53	0.54	0.53	0.54	0.55	0.55	0.54
CS-AM-CL-...-...	0.44	0.44	0.43	0.45	0.44	0.44	0.43	0.44	0.43	0.44
CS-AM-CP-...-...	0.55	0.52	0.54	0.54	0.51	0.51	0.52	0.51	0.52	0.52
CS-AM-CP-FDG-...	0.45	0.45	0.44	0.42	0.41	0.42	0.44	0.44	0.43	0.43
CW-AB-CP-...-...	0.61	0.61	0.61	0.56	0.57	0.59	0.61	0.59	0.59	0.59
CW-AE-CP-...-...	0.60	0.59	0.60	0.60	0.60	0.60	0.59	0.58	0.59	0.59
CW-AL-CL-FDG-...	0.43	0.43	0.42	0.45	0.44	0.44	0.45	0.45	0.45	0.44
CW-AL-CP-...-...	0.69	0.68	0.70	0.69	0.70	0.69	0.69	0.70	0.69	0.69
CW-AL-CP-...-SL	0.62	0.62	0.62	0.63	0.64	0.63	0.62	0.62	0.63	0.63
CXB-AE-CP-...-...	0.34	0.35	0.31	0.34	0.39	0.34	0.33	0.36	0.34	0.34
CXB-AE-CP-FDG-...	0.42	0.38	0.40	0.44	0.41	0.46	0.44	0.44	0.47	0.43
CXR-AE-CP-...-...	0.35	0.39	0.38	0.36	0.38	0.35	0.36	0.39	0.37	0.37
CXR-AE-CP-FDG-...	0.41	0.43	0.42	0.40	0.39	0.42	0.41	0.38	0.43	0.41

*no data because specimen accidentally destroyed.

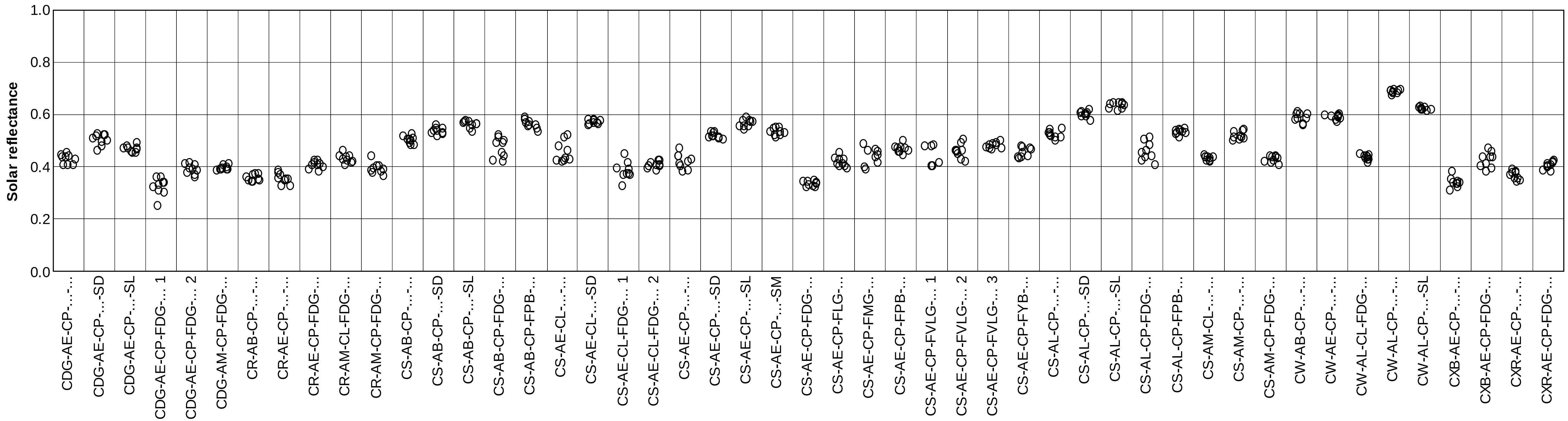


Figure 9. Results arranged alphabetically by concrete abbreviated name.

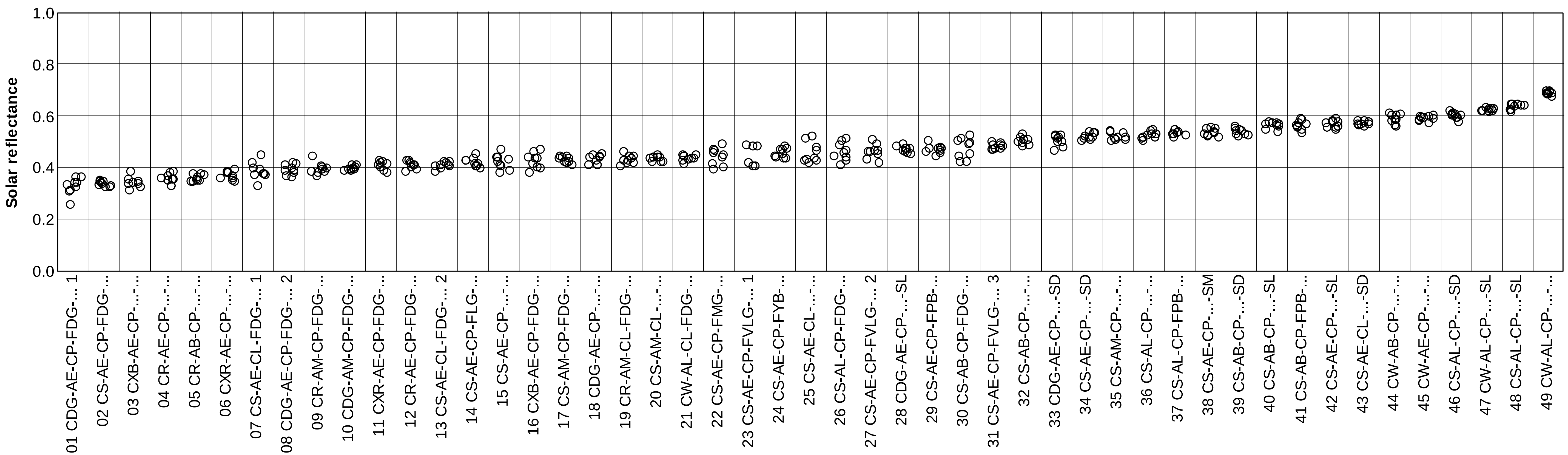


Figure 10. Results arranged by increasing average concrete solar reflectance.

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APPENDIX A – PHOTOGRAPHS OF SPECIMENS AFTER TESTING

Photographs of the specimens after testing are shown in this appendix. The photographs are arranged alphabetically by mix abbreviated name. Each row of photographs shows the three specimens cast from one mix. The abbreviated names are explained in the text.

CDG-AE-CP-…-… 01

CDG-AE-CP-…-… 02

CDG-AE-CP-…-… 03

CDG-AE-CP-…-SD 01

CDG-AE-CP-…-SD 02

CDG-AE-CP-…-SD 03

CDG-AE-CP-…-SL 01

CDG-AE-CP-…-SL 02

CDG-AE-CP-…-SL 03


CDG-AE-CP-FDG-… 1 01


CDG-AE-CP-FDG-… 1 02


CDG-AE-CP-FDG-… 1 03


CDG-AE-CP-FDG-… 2 01


CDG-AE-CP-FDG-… 2 02


CDG-AE-CP-FDG-… 2 03


CDG-AM-CP-FDG-… 01


CDG-AM-CP-FDG-… 02


CDG-AM-CP-FDG-… 03


CR-AB-CP-…-… 01


CR-AB-CP-…-… 02


CR-AB-CP-…-… 03

CR-AE-CP-…-… 01

CR-AE-CP-…-… 02

CR-AE-CP-…-… 03

CR-AE-CP-FDG-… 01

CR-AE-CP-FDG-… 02

CR-AE-CP-FDG-… 03

CR-AM-CL-FDG-… 01

CR-AM-CL-FDG-… 02

CR-AM-CL-FDG-… 03

CR-AM-CP-FDG-… 01

CR-AM-CP-FDG-… 02

CR-AM-CP-FDG-… 03


CS-AB-CP-…-… 01


CS-AB-CP-…-… 02

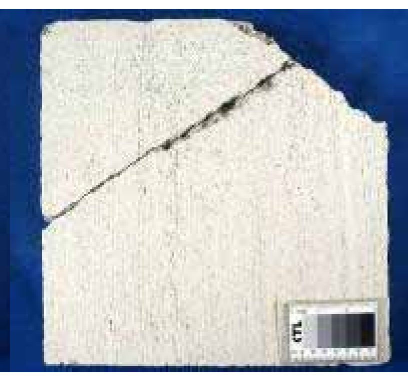

CS-AB-CP-…-… 03


CS-AB-CP-…-SD 01


CS-AB-CP-…-SD 02


CS-AB-CP-…-SD 03


CS-AB-CP-…-SL 01


CS-AB-CP-…-SL 02


CS-AB-CP-…-SL 03


CS-AB-CP-FDG-… 01


CS-AB-CP-FDG-… 02


CS-AB-CP-FDG-… 03

CS-AB-CP-FPB-… 01

CS-AB-CP-FPB-… 02

CS-AB-CP-FPB-… 03

CS-AE-CL-…-… 01

CS-AE-CL-…-… 02

CS-AE-CL-…-… 03

CS-AE-CL-…-SD 01

CS-AE-CL-…-SD 02

CS-AE-CL-…-SD 03

CS-AE-CL-FDG-… 1 01

CS-AE-CL-FDG-… 1 02

CS-AE-CL-FDG-… 1 03


CS-AE-CL-FDG-… 2 01


CS-AE-CL-FDG-… 2 02


CS-AE-CL-FDG-… 2 03


CS-AE-CP-…-… 01


CS-AE-CP-…-… 02


CS-AE-CP-…-… 03


CS-AE-CP-…-SD 01


CS-AE-CP-…-SD 02


CS-AE-CP-…-SD 03


CS-AE-CP-…-SL 01

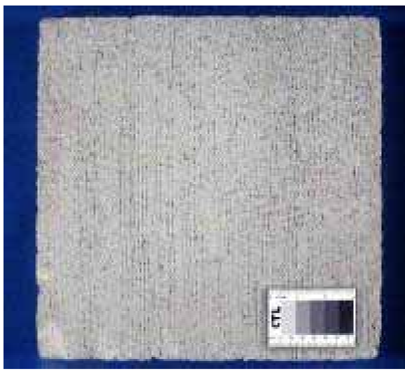

CS-AE-CP-…-SL 02


CS-AE-CP-…-SL 03


CS-AE-CP-…-SM 01


CS-AE-CP-…-SM 02


CS-AE-CP-…-SM 03


CS-AE-CP-FDG-… 01


CS-AE-CP-FDG-… 02


CS-AE-CP-FDG-… 03


CS-AE-CP-FLG-… 01


CS-AE-CP-FLG-… 02


CS-AE-CP-FLG-… 03


CS-AE-CP-FMG-… 01


CS-AE-CP-FMG-… 02

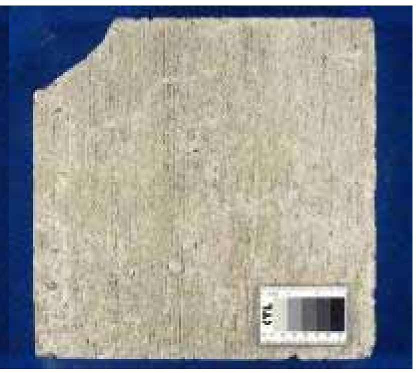

CS-AE-CP-FMG-… 03

CS-AE-CP-FPB-... 01

CS-AE-CP-FPB-... 02

CS-AE-CP-FPB-... 03

CS-AE-CP-FVLG-... 1 01



CS-AE-CP-FVLG-... 1 02

No specimen

CS-AE-CP-FVLG-... 1 03

CS-AE-CP-FVLG-... 2 01

CS-AE-CP-FVLG-... 2 02

CS-AE-CP-FVLG-... 2 03

CS-AE-CP-FVLG-... 3 01

CS-AE-CP-FVLG-... 3 02

CS-AE-CP-FVLG-... 3 03


CS-AE-CP-FYB-… 01


CS-AE-CP-FYB-… 02


CS-AE-CP-FYB-… 03


CS-AL-CP-…-… 01


CS-AL-CP-…-… 02


CS-AL-CP-…-… 03


CS-AL-CP-…-SD 01


CS-AL-CP-…-SD 02


CS-AL-CP-…-SD 03


CS-AL-CP-…-SL 01


CS-AL-CP-…-SL 02


CS-AL-CP-…-SL 03


CS-AL-CP-FDG-… 01


CS-AL-CP-FDG-… 02


CS-AL-CP-FDG-… 03


CS-AL-CP-FPB-… 01


CS-AL-CP-FPB-… 02


CS-AL-CP-FPB-… 03


CS-AM-CL-…-… 01


CS-AM-CL-…-… 02


CS-AM-CL-…-… 03


CS-AM-CP-…-… 01


CS-AM-CP-…-… 02


CS-AM-CP-…-… 03


CS-AM-CP-FDG-… 01


CS-AM-CP-FDG-… 02


CS-AM-CP-FDG-… 03


CW-AB-CP-…-… 01


CW-AB-CP-…-… 02


CW-AB-CP-…-… 03


CW-AE-CP-…-… 01


CW-AE-CP-…-… 02


CW-AE-CP-…-… 03


CW-AL-CL-FDG-… 01


CW-AL-CL-FDG-… 02


CW-AL-CL-FDG-… 03


CW-AL-CP-…-… 01


CW-AL-CP-…-… 02


CW-AL-CP-…-… 03


CW-AL-CP-…-SL 01


CW-AL-CP-…-SL 02


CW-AL-CP-…-SL 03


CXB-AE-CP-…-… 01


CXB-AE-CP-…-… 02


CXB-AE-CP-…-… 03


CXB-AE-CP-FDG-… 01


CXB-AE-CP-FDG-… 02


CXB-AE-CP-FDG-… 03

CXR-AE-CP-…-… 01

CXR-AE-CP-…-… 02

CXR-AE-CP-…-… 03

CXR-AE-CP-FDG-… 01

CXR-AE-CP-FDG-… 02

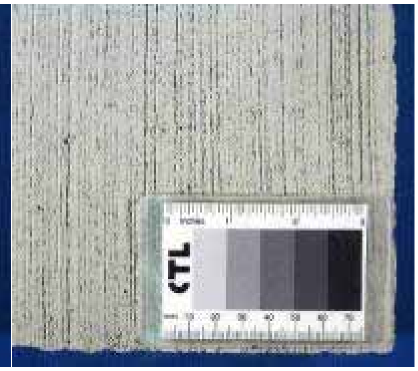
CXR-AE-CP-FDG-… 03

APPENDIX B – CLOSE-UP PHOTOGRAPHS OF SPECIMENS AFTER TESTING

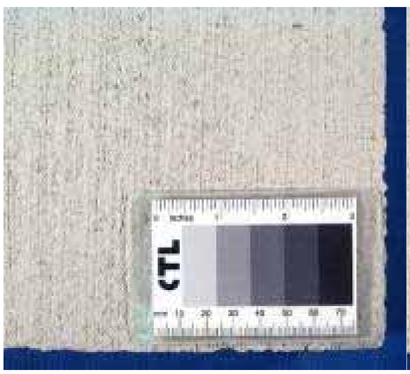
Close-up photographs of the specimens after testing are shown in this appendix. The photographs are arranged alphabetically by mix abbreviated name. Each row of photographs shows the three specimens cast from one mix. The abbreviated names are explained in the text.

CDG-AE-CP-…-… 01

CDG-AE-CP-…-… 02

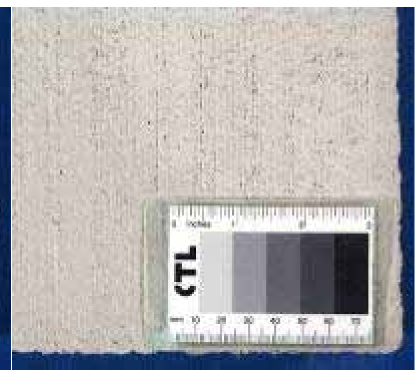


CDG-AE-CP-…-… 03



CDG-AE-CP-…-SD 01

CDG-AE-CP-…-SD 02

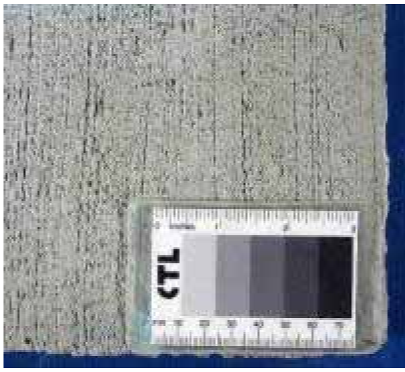


CDG-AE-CP-…-SD 03

CDG-AE-CP-…-SL 01

CDG-AE-CP-…-SL 02

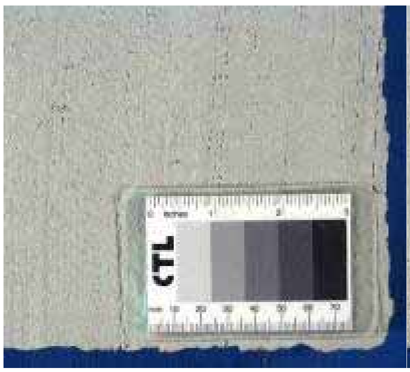
CDG-AE-CP-…-SL 03



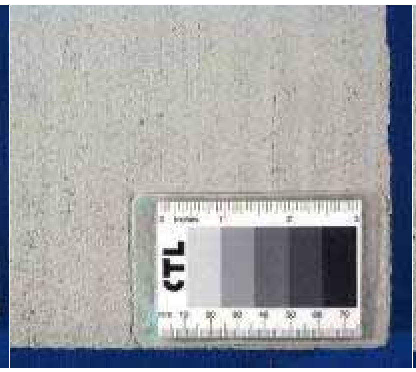
CDG-AE-CP-FDG-… 1 01

CDG-AE-CP-FDG-… 1 02

CDG-AE-CP-FDG-… 1 03

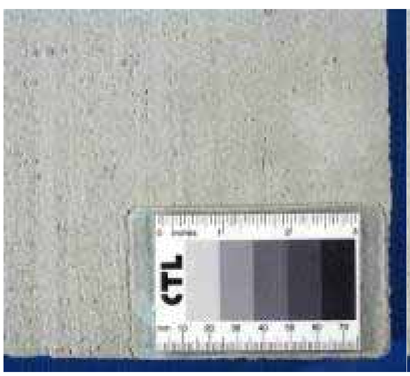


CDG-AE-CP-FDG-… 2 01



CDG-AE-CP-FDG-… 2 02

CDG-AE-CP-FDG-… 2 03



CDG-AM-CP-FDG-… 01

CDG-AM-CP-FDG-… 02

CDG-AM-CP-FDG-… 03

CR-AB-CP-…-… 01

CR-AB-CP-…-… 02

CR-AB-CP-…-… 03

CR-AE-CP-…-… 01

CR-AE-CP-…-… 02

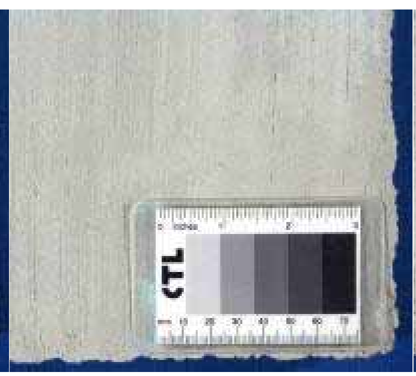
CR-AE-CP-…-… 03

CR-AE-CP-FDG-… 01

CR-AE-CP-FDG-… 02

CR-AE-CP-FDG-… 03

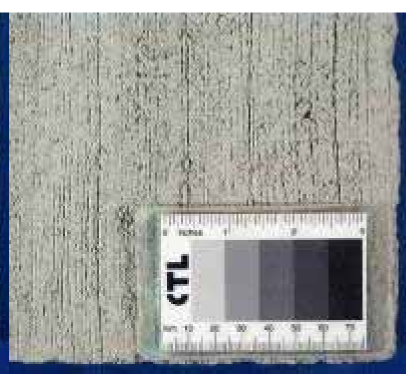
CR-AM-CL-FDG-… 01



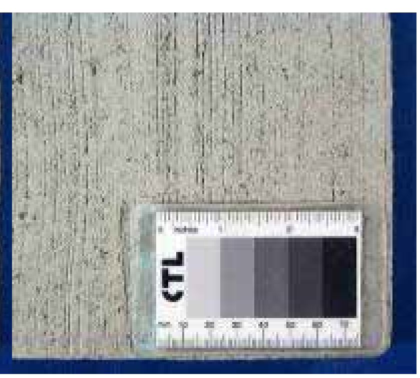
CR-AM-CL-FDG-… 02

CR-AM-CL-FDG-… 03

CR-AM-CP-FDG-… 01

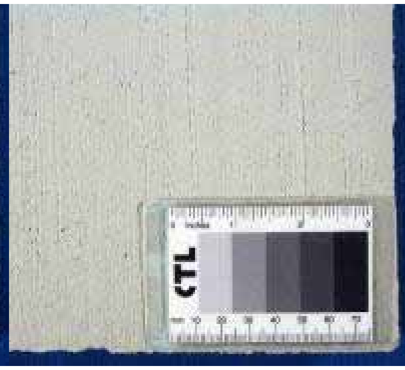


CR-AM-CP-FDG-… 02



CR-AM-CP-FDG-… 03

CS-AB-CP-…-… 01



CS-AB-CP-…-… 02

CS-AB-CP-…-… 03

CS-AB-CP-…-SD 01

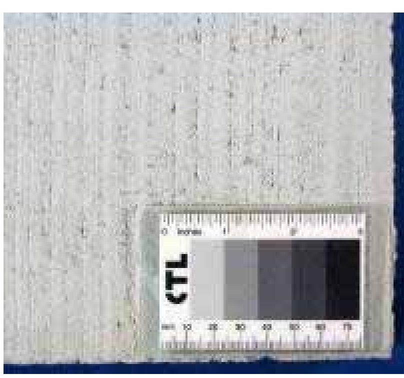
CS-AB-CP-…-SD 02

CS-AB-CP-…-SD 03

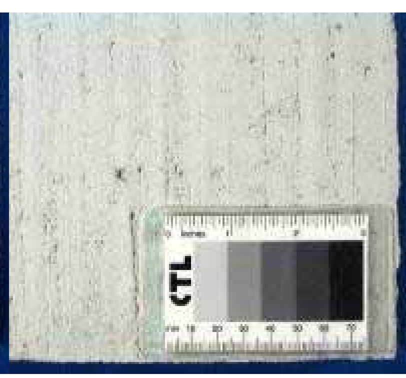
CS-AB-CP-…-SL 01

CS-AB-CP-…-SL 02

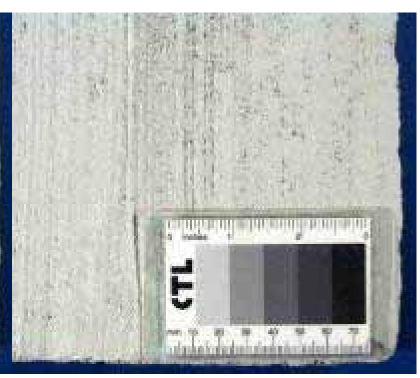
CS-AB-CP-…-SL 03



CS-AB-CP-FDG-… 01



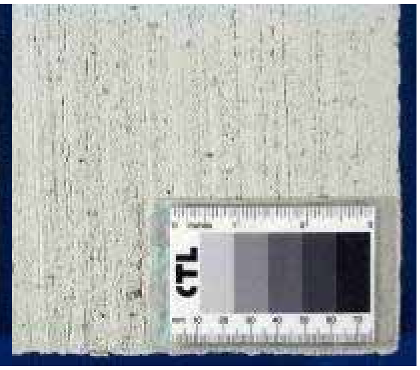
CS-AB-CP-FDG-… 02



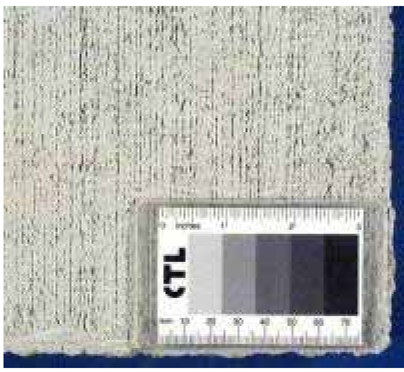
CS-AB-CP-FDG-… 03

CS-AB-CP-FPB-… 01

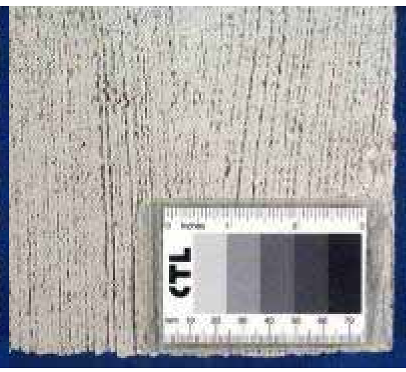
CS-AB-CP-FPB-… 02



CS-AB-CP-FPB-… 03



CS-AE-CL-…-… 01



CS-AE-CL-…-… 02

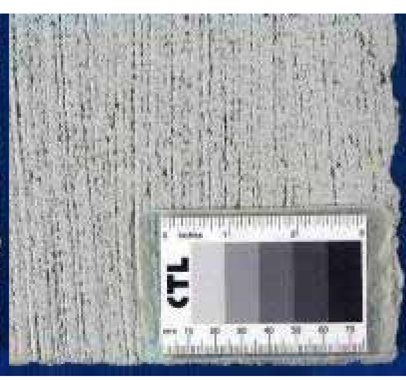
CS-AE-CL-…-… 03

CS-AE-CL-…-SD 01

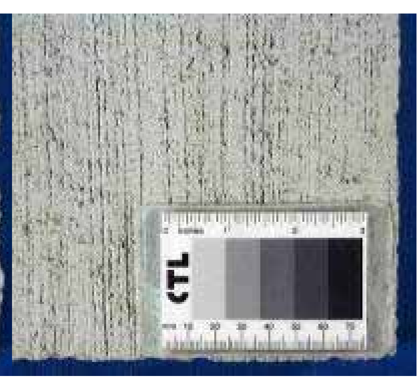
CS-AE-CL-…-SD 02

CS-AE-CL-…-SD 03

CS-AE-CL-FDG-… 1 01



CS-AE-CL-FDG-… 1 02



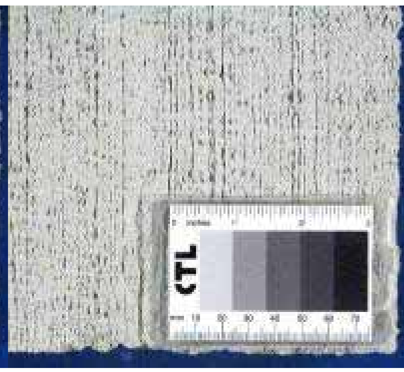
CS-AE-CL-FDG-… 1 03

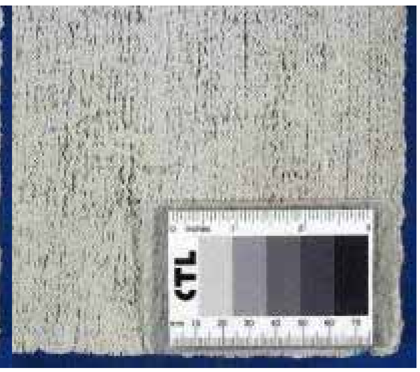

CS-AE-CL-FDG-… 2 01


CS-AE-CL-FDG-… 2 02


CS-AE-CL-FDG-… 2 03

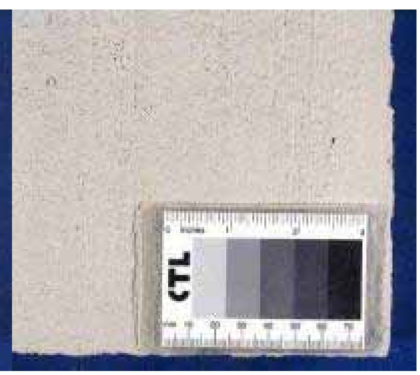

CS-AE-CP-…-… 01

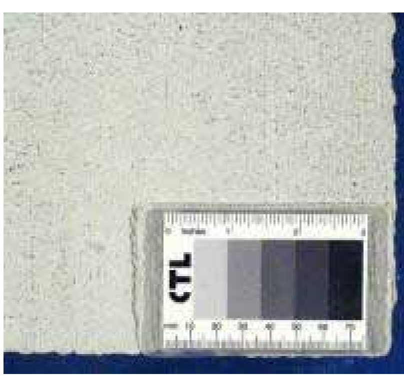

CS-AE-CP-…-… 02

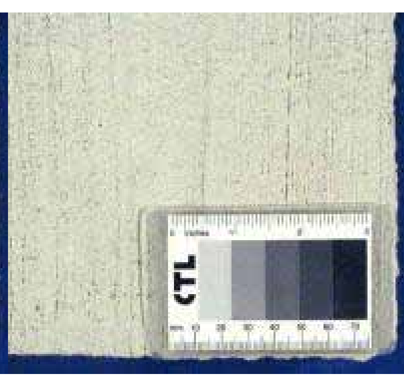

CS-AE-CP-…-… 03

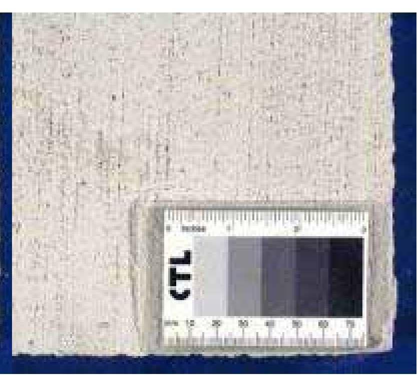

CS-AE-CP-…-SD 01


CS-AE-CP-…-SD 02


CS-AE-CP-…-SD 03

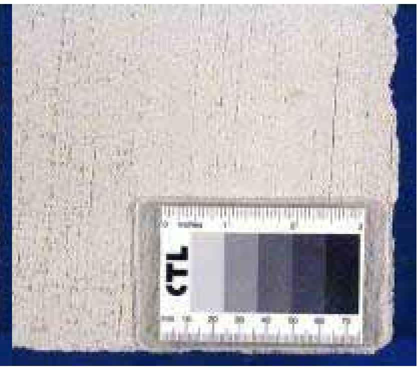

CS-AE-CP-…-SL 01

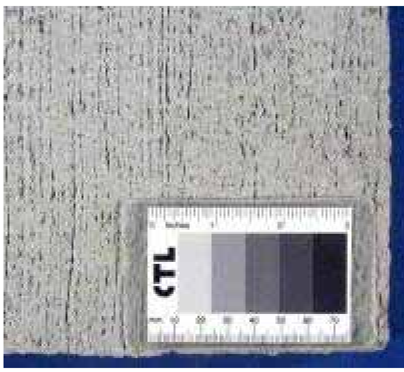

CS-AE-CP-…-SL 02

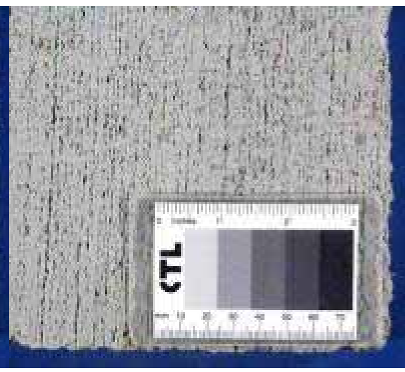

CS-AE-CP-…-SL 03

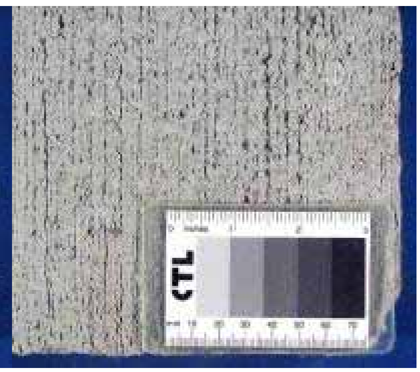

CS-AE-CP-…-SM 01


CS-AE-CP-…-SM 02

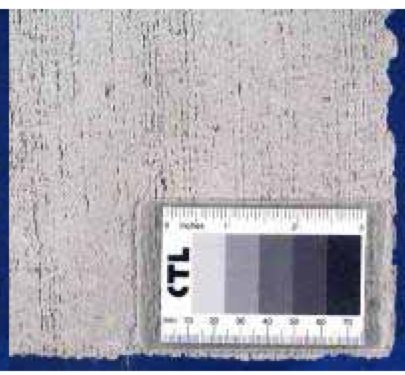

CS-AE-CP-…-SM 03

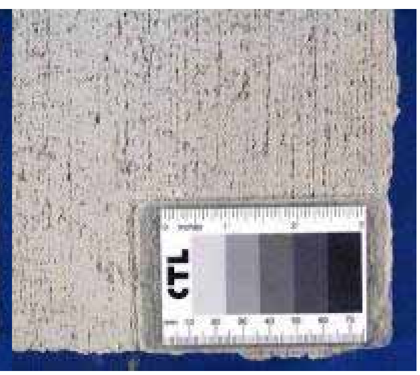

CS-AE-CP-FDG-… 01

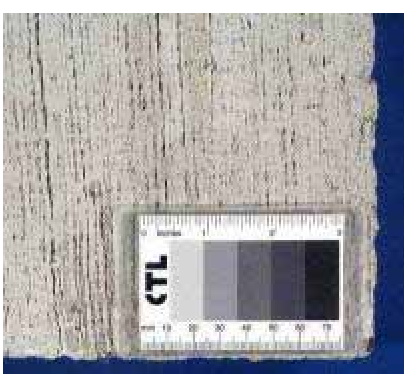

CS-AE-CP-FDG-… 02

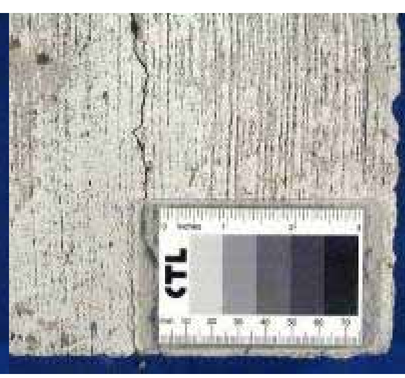

CS-AE-CP-FDG-… 03

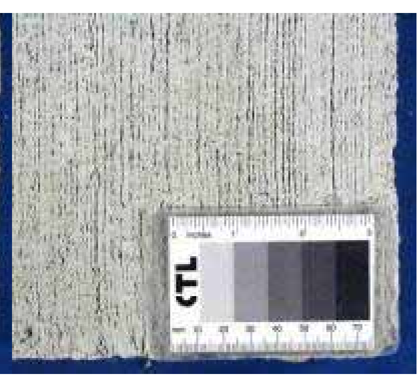

CS-AE-CP-FLG-… 01

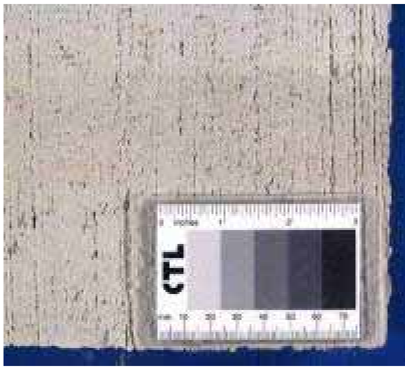

CS-AE-CP-FLG-… 02


CS-AE-CP-FLG-… 03


CS-AE-CP-FMG-… 01

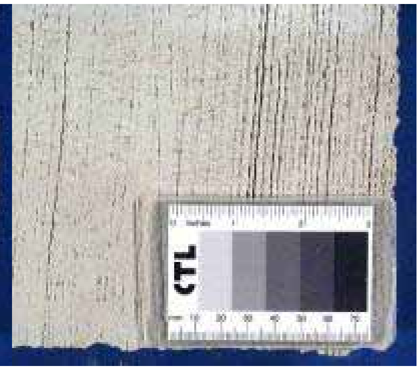

CS-AE-CP-FMG-… 02


CS-AE-CP-FMG-… 03

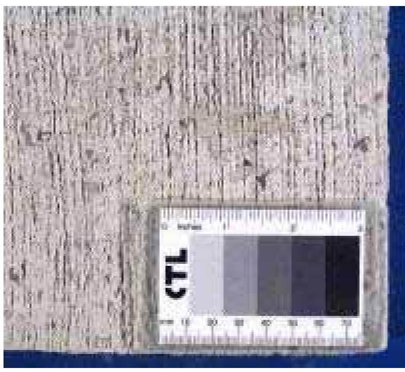


CS-AE-CP-FPB-… 01

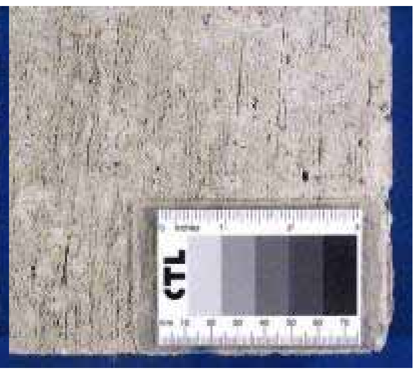
CS-AE-CP-FPB-… 02



CS-AE-CP-FPB-… 03



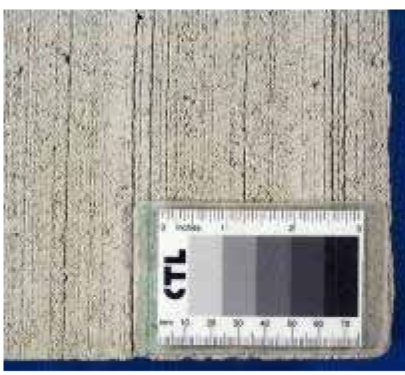
CS-AE-CP-FVLG-… 1 01



CS-AE-CP-FVLG-… 1 02

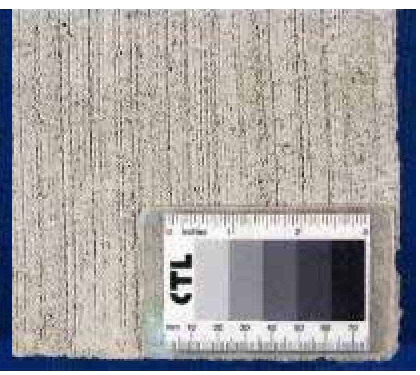
No specimen

CS-AE-CP-FVLG-… 1 03



CS-AE-CP-FVLG-… 2 01

CS-AE-CP-FVLG-… 2 02

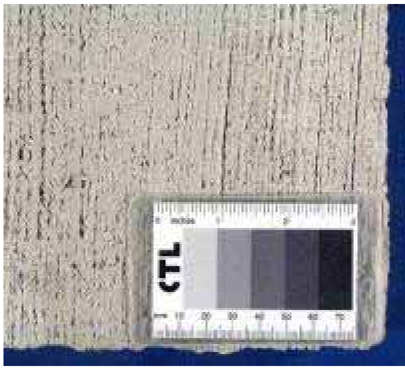


CS-AE-CP-FVLG-… 2 03

CS-AE-CP-FVLG-… 3 01

CS-AE-CP-FVLG-… 3 02

CS-AE-CP-FVLG-… 3 03



CS-AE-CP-FYB-… 01

CS-AE-CP-FYB-… 02

CS-AE-CP-FYB-… 03

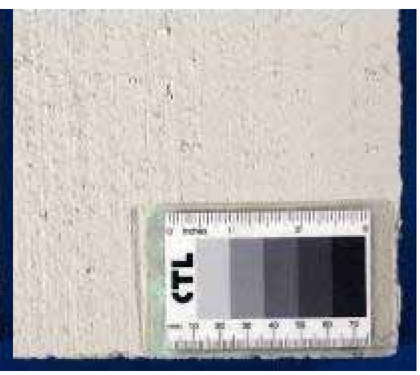
CS-AL-CP-…-… 01

CS-AL-CP-…-… 02

CS-AL-CP-…-… 03

CS-AL-CP-…-SD 01

CS-AL-CP-…-SD 02



CS-AL-CP-…-SD 03

CS-AL-CP-…-SL 01

CS-AL-CP-…-SL 02

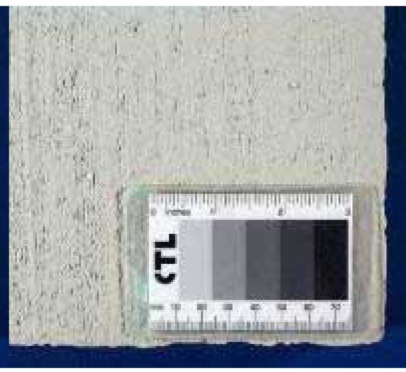
CS-AL-CP-…-SL 03

CS-AL-CP-FDG-… 01

CS-AL-CP-FDG-… 02

CS-AL-CP-FDG-… 03

CS-AL-CP-FPB-… 01



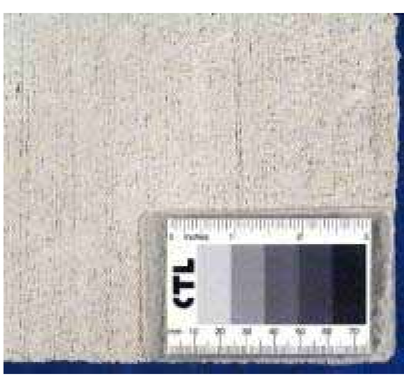
CS-AL-CP-FPB-… 02

CS-AL-CP-FPB-… 03

CS-AM-CL-…-… 01

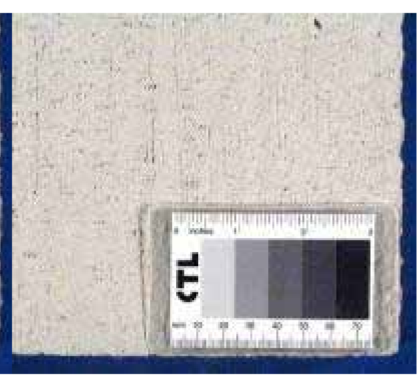
CS-AM-CL-…-… 02

CS-AM-CL-…-… 03

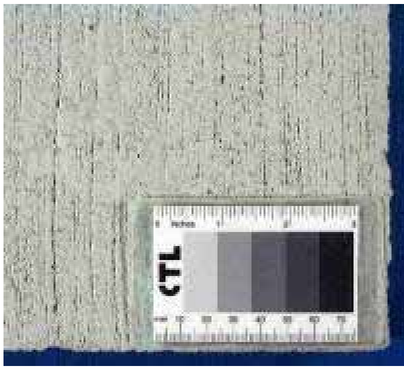


CS-AM-CP-…-… 01

CS-AM-CP-…-… 02



CS-AM-CP-…-… 03



CS-AM-CP-FDG-… 01

CS-AM-CP-FDG-… 02

CS-AM-CP-FDG-… 03

CW-AB-CP-…-… 01

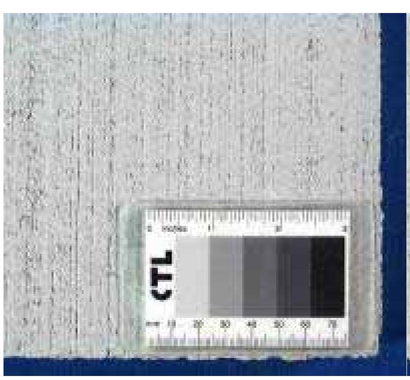
CW-AB-CP-…-… 02

CW-AB-CP-…-… 03

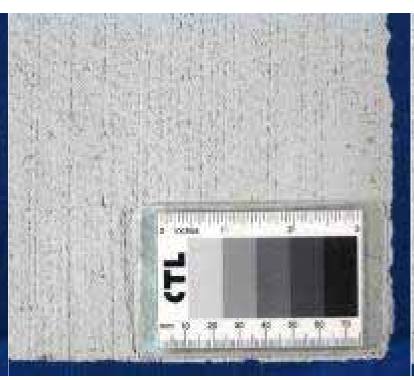
CW-AE-CP-…-… 01

CW-AE-CP-…-… 02

CW-AE-CP-…-… 03



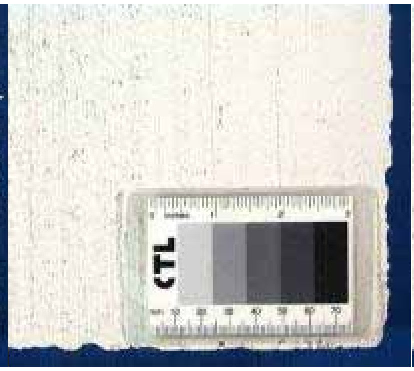
CW-AL-CL-FDG-… 01



CW-AL-CL-FDG-… 02

CW-AL-CL-FDG-… 03


CW-AL-CP-…-… 01


CW-AL-CP-…-… 02

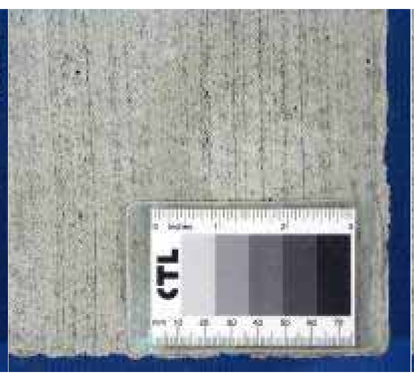

CW-AL-CP-…-… 03


CW-AL-CP-…-SL 01

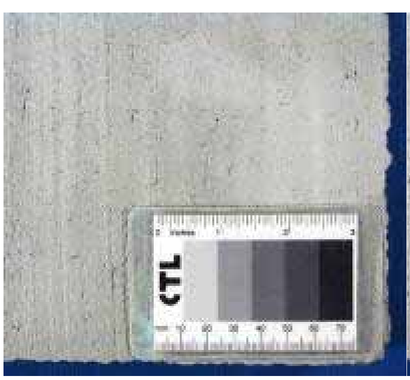

CW-AL-CP-…-SL 02


CW-AL-CP-…-SL 03

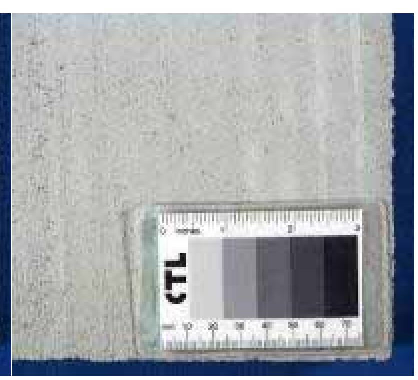

CXB-AE-CP-…-… 01


CXB-AE-CP-…-… 02


CXB-AE-CP-…-… 03


CXB-AE-CP-FDG-… 01

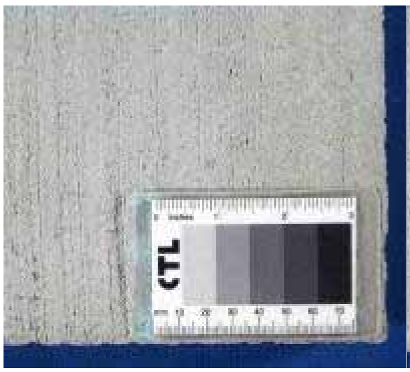

CXB-AE-CP-FDG-… 02


CXB-AE-CP-FDG-… 03

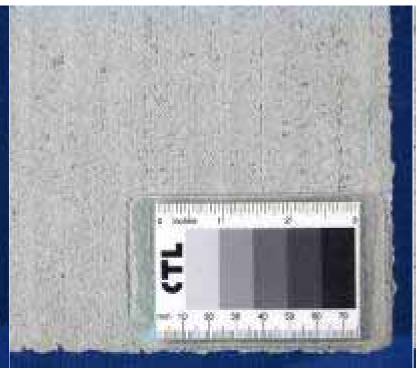
CXR-AE-CP-…-… 01

CXR-AE-CP-…-… 02

CXR-AE-CP-…-… 03



CXR-AE-CP-FDG-… 01



CXR-AE-CP-FDG-… 02

CXR-AE-CP-FDG-… 03

APPENDIX C – ANALYSIS OF VARIANCE

Assumptions

The following assumptions are made in the analysis.

General Linear Model. The analyses of variation (ANOVA) and regression analyses use the General Linear Model (GLM). Tests of significance are based on the restricted form of the model wherever relevant, that is where a test of significance is based on mean-square error of a term in the model rather than the error mean-square.

Factor. A factor is a concrete constituent, such as cement or fly ash.

Random Factor. The levels of each factor are randomly selected from a population, so the factors are considered random. Note that pair-wise comparisons are not possible in MINITAB with random factors.

Least-Squares Regression. Least-squares are based on the nine measurements from each mix: three observations on each of three specimens.

Assumptions for Residuals. The Anderson-Darling test for normality and residual plots are used to test the assumption that residuals are normally distributed (N), independent (I), that is, no apparent pattern in observation order, have a mean of zero (0), and a constant variance (σ^2). The shorthand way to designate that all assumptions are met, is to write that the residuals are NID(0, σ^2).

Level of Significance. The level of significance, alpha or α-level, throughout is 5%. This is the probability of finding a significant association when one really does not exist. Specifically, it is the probability of rejecting the null hypothesis when the null hypothesis is in fact true.

Null Hypothesis, Ho. The null hypothesis is the assumption that a factor being tested is not significant at the predetermined level of significance.

Alternative Hypothesis, Ha. The alternative hypothesis is the assumption that a factor being tested is significant at the predetermined level of significance. One concludes that the alternative hypothesis is true only when the null hypothesis is rejected.

Interaction. Two-way interaction terms are calculated as the square root of the product of two individual terms.

Scale. Solar reflectance is a value between 0 and 1, but throughout this appendix, the reflectance values are scaled up by a factor of 1000, so as to avoid showing the leading zero.

Factor Level. The factor level is the solar reflectance of the concrete constituent. The levels of each factor are shown in Table C-1.

Mix Name. The concretes are referred to as "C…-A…-C…-F…-S…", where the first "C…" is cement, "A…" is fine aggregate, the second "C…" is coarse aggregate, "F…" is fly ash, and "S…" is slag cement. The ellipses above are place-holders for the relative color or source of the constituent. These ellipses are completed in the analysis that follows. If no fly ash or slag cement is used in the mix, the tables and figures show only an ellipsis. For example, "CW-AE-CP-...-SD" is a mix containing white cement, Eau Clair fine aggregate, pea gravel, no fly ash, and dark slag cement.

Analysis Summary

The analysis was performed using the statistical software MINITAB (MINTIAB Release14.20, Minitab Inc., http://www.minitab.com/products/, 2005). Due to the project scope, there were not enough combinations of factors, that is concrete mixes, to do a full factorial analysis. However, groups of mixes were chosen to test specific hypotheses. The tests are described in the following sections.

Table C-1. Measured Levels of Each Factor Scaled up by a Factor of 1000

Material type	Generic description or source*	Abbreviation	Solar reflectance
Cement	Plant XB	CXB	364
	Dark gray	CDG	383
	Plant XR	CXR	399
	Plant R	CR	442
	Plant S	CS	468
	White	CW	866
Fine aggregate	Black	AB	221
	Albuquerque, pink	AA	256
	Eau Claire	AE	271
	McHenry	AM	295
	Limestone, manufactured	AL	423
Coarse aggregate	Pea gravel, Eau Claire	CP	271
	Limestone, crushed	CL	423
Fly ash	Dark gray	FDG	284
	Light gray	FLG	357
	Medium gray	FMG	399
	Pale buff	FPB	441
	Yellow buff	FYB	457
	Very light gray	FVLG	547
Slag cement	Dark	SD	708
	Light	SL	748
	Medium	SM	751

*Color does not necessarily correspond with solar reflectance.

1. Slab Reflectance versus Cement Reflectance

Test: does cement reflectance have an effect on slab reflectance and if so, how much of the variation in slab reflectance is due to cement reflectance? These mixes were used:

- CDG-AE-CP-…-…
- CR-AE-CP-…-…
- CS-AE-CP-…-…
- CW-AE-CP-…-…
- CXB-AE-CP-…-…
- CXR-AE-CP-…-…

ANOVA: Reflectance versus Cement, Specimen

```
Factor            Type    Levels  Values
Cement            random       6  CDG, CR, CS, CW, CXB, CXR
Specimen(Cement)  random       3  1, 2, 3


Analysis of Variance for Reflectance

Source            DF      SS     MS      F      P  Significant at α = 5%
Cement             5  380625  76125  92.97  0.000           yes
Specimen(Cement)  12    9826    819   3.58  0.001           yes
Error             36    8238    229
Total             53  398689


S = 15.1272   R-Sq = 97.93%   R-Sq(adj) = 96.96%


                                      Expected Mean
                                      Square for Each
                        Variance  Error  Term (using
   Source              component   term  restricted model)
1  Cement                 8367.3      2  (3) + 3 (2) + 9 (1)
2  Specimen(Cement)        196.7      3  (3) + 3 (2)
3  Error                   228.8         (3)
```

Figure C-1. ANOVA.

The p-value for the factor *cement* is less than any reasonable choice of alpha (such as 5%, or 0.05); therefore, reject Ho and conclude Ha, that is, cement reflectance has an effect on slab reflectance. The p-value for the factor *specimen nested in cement* is also less than any reasonable choice of alpha (such as 5%, or 0.05); therefore, reject Ho and conclude Ha, that is, specimens from a particular mix have an effect on slab reflectance. However, the effect of *specimen nested in cement* is much smaller than the effect *cement*. In fact, pair-wise comparisons among levels of specimen nested in cement (Tukey Simultaneous Tests using GLM and fixed factors) show that the reflectances of the specimens from a particular mix are not different, except for specimens CS-AE-CP-…-… 01 and CS-AE-CP-…-… 03. These results can be seen in the interaction plot in Figure C-2. The analysis of means (ANOM) plot in Figure C-3 shows similar results.

Figure C-2. An interaction plot shows that the reflectances of most of the specimens from a particular mix are not different.

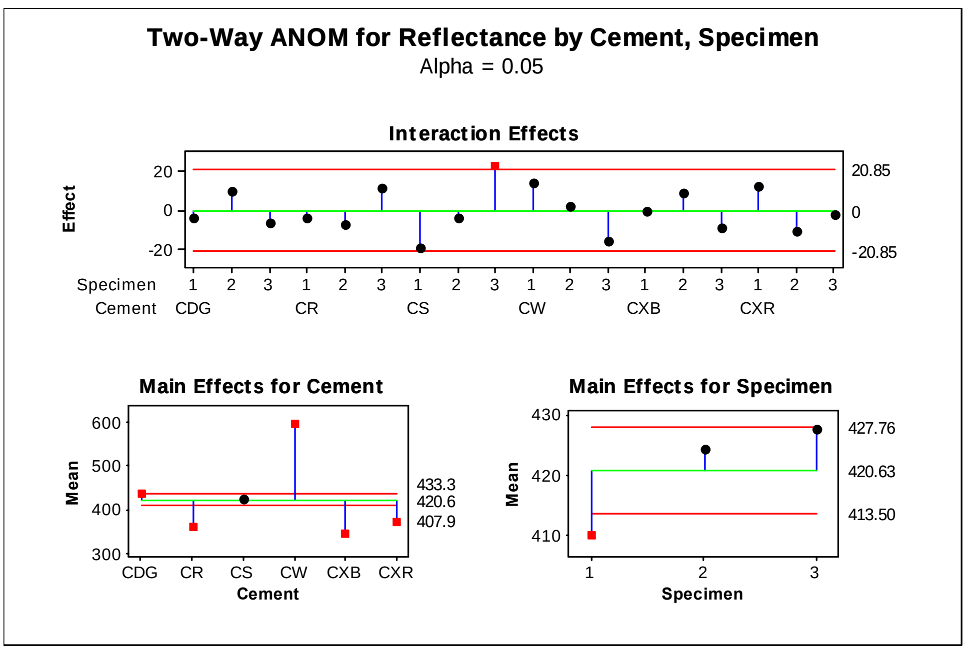


Figure C-3. Pair-wise comparisons among levels of specimen nested in cement shows that reflectances of the specimens from a particular mix are not different, except for specimens CS-AE-CP-…-… 01 and CS-AE-CP-…-… 03.

Check Assumptions. The Anderson-Darling test for normality shows that the residuals are normally distributed because the assumption of normality can not be rejected for any reasonable alpha (p-value = 0.603). Further, the residuals are independent (no apparent pattern in observation order), have a mean of zero and a constant variance.

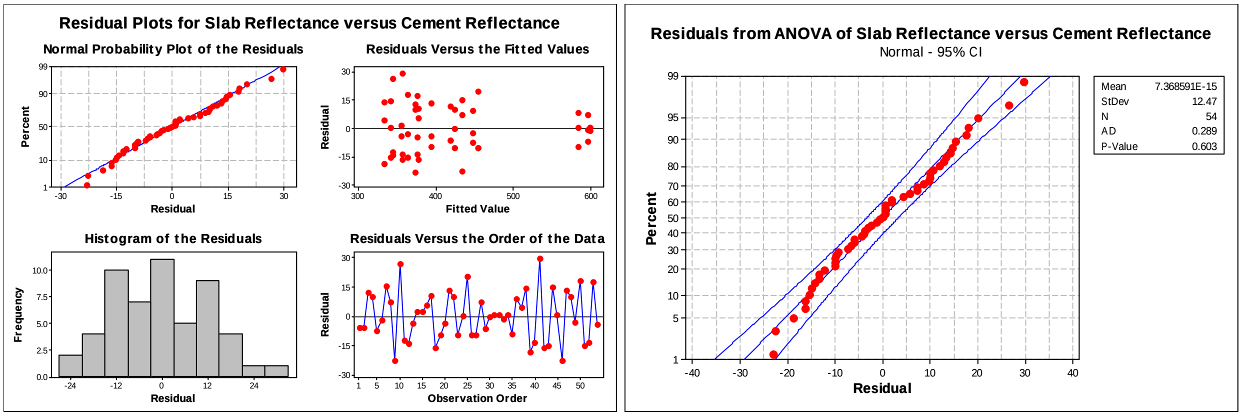


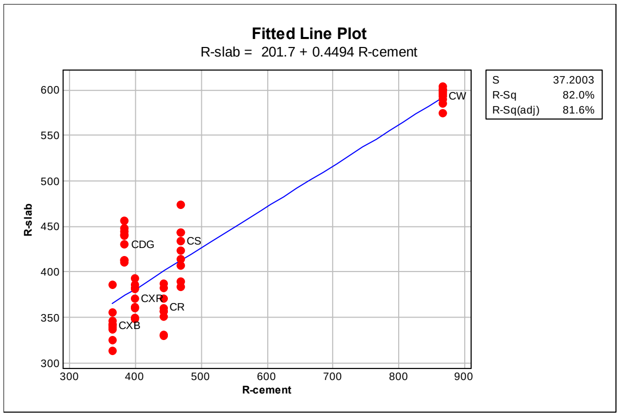
Figure C-4. The residuals plots and the normal probability plot confirms the assumption that residuals are NID(0, σ^2).

Regression Analysis: Reflectance versus R-cement (Reduced Model)

```
The regression equation is
Reflectance = 202 + 0.449 R-cement


Predictor      Coef   SE Coef      T      P  Likely ≠ 0 at α = 5%
Constant     201.75     15.12  13.35  0.000          yes
R-cement    0.44945   0.02925  15.37  0.000          yes


S = 37.2003   R-Sq = 82.0%   R-Sq(adj) = 81.6%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       1  326728  326728  236.10  0.000
Residual Error  52   71961    1384
Total           53  398689
```

Figure C-5. Regression analysis.

Since the effects of specimen nested in cement has a very small effect (from Figure C-1), it is reasonable to exclude it from the regression model (see Figure C-5). The analysis of variance again shows that there is a significant relationship between slab reflectance and cement reflectance (p-value < 0.001). Further, the regression coefficient is non-zero: Ho R-cement = 0 can be rejected for any reasonable value of alpha, so we can conclude Ha, that is, the regression coefficient is non-zero. About 80% of the variability in slab reflectance is explained by variations in cement reflectance.



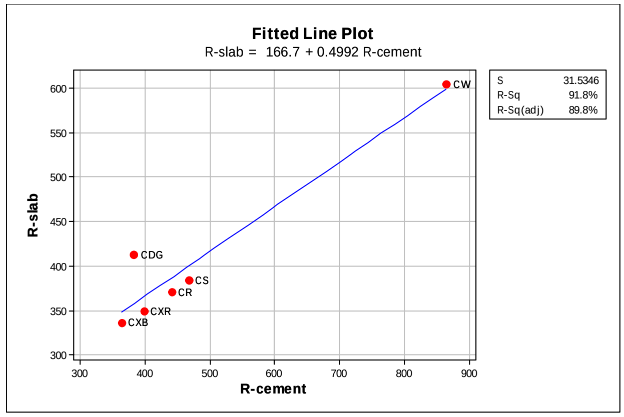


Figure C-6. The least-squares regression plot on the left shows the three reflectance measurements from each specimen (three specimens per mix), the one on the right shows the average reflectances.

Check Assumptions of Reduced Model. The Anderson-Darling test for normality shows that the residuals are normally distributed because the assumption of normality can not be rejected for any reasonable alpha (p-value = 0.097).

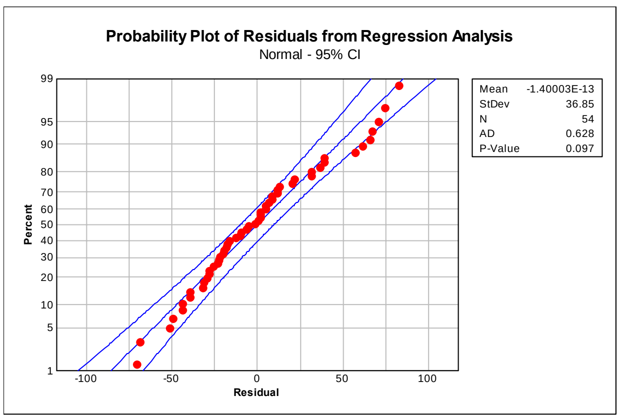


Figure C-7. The residuals plots confirmed the assumption that residuals are NID(0, σ^2).

2. Slab Reflectance versus Cement and Fine Aggregate Reflectance

Test: do cement reflectance, fine aggregate reflectance, or the interaction of the two have an effect on slab reflectance and if so, how much of the variation in slab reflectance is due to cement reflectance, fine aggregate reflectance, and the interaction of cement and fine aggregate reflectance? These mixes were used:

- CR-AB-CP-…
- CR-AE-CP-…
- CS-AB-CP-…
- CS-AE-CP-…
- CW-AB-CP-…
- CW-AE-CP-…

The hypothesis testing (see Figure C-8), at alpha = 5%, shows:

- Cement has an effect (reject Ho because p-value 0.040).
- Fine aggregate has no effect (cannot reject Ho because p-value = 0.427).
- There is a significant interaction between cement and fine aggregate (reject Ho because p-value < 0.001); though the contribution of the interaction to the total reflectance is small.

ANOVA: Reflectance versus Cement, Fine agg

```
Factor    Type    Levels  Values
Cement    random       3  CR, CS, CW
Fine agg  random       2  AB, AE


Analysis of Variance for Reflectance

Source           DF      SS      MS      F      P  Significant at α = 5%
Cement            2  490250  245125  23.79  0.040           yes
Fine agg          1   10086   10086   0.98  0.427            no
Cement*Fine agg   2   20604   10302  30.98  0.000           yes
Error            48   15961     333
Total            53  536901


S = 18.2352   R-Sq = 97.03%   R-Sq(adj) = 96.72%


                                       Expected Mean Square
                     Variance  Error   for Each Term (using
   Source           component   term   restricted model)
1  Cement             13045.7      3   (4) + 9 (3) + 18 (1)
2  Fine agg              -8.0      3   (4) + 9 (3) + 27 (2)
3  Cement*Fine agg     1107.7      4   (4) + 9 (3)
4  Error                332.5          (4)
```

Figure C-8. ANOVA of cement reflectance, fine aggregate reflectance, and their interaction on slab reflectance.

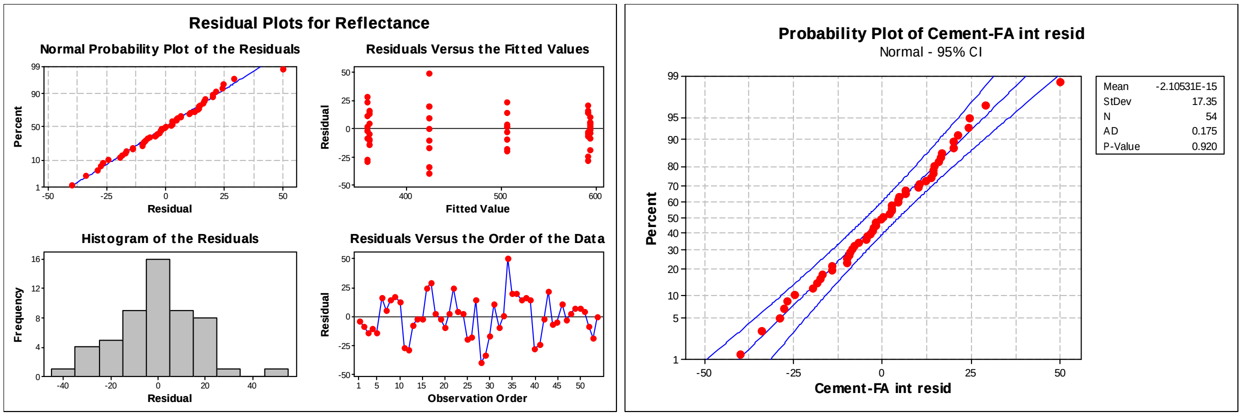


Figure C-9. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

Because the independent terms (cement reflectance and fine aggregate reflectance) are also quantitative, a regression analysis can be used to determine the magnitude of the effect of the factors. Using the full model with the interaction term (see Figure C-10), the sequential sum of squares shows that cement reflectance accounts for most of the variation in slab reflectance (76%). Fine aggregate reflectance and the interaction of cement and fine aggregate reflectance each only account for 2%. The normal probability plot of the residuals shows that they are normally distributed. The plot of residuals versus the fitted values (see Figure C-11) shows that there may be departure from linearity, indicating that a curvilinear model might be more appropriate. However, there are not enough levels of fitted values to be certain. Further, since observation order is not meaningful, we can conclude that the residuals are independent. Therefore, the assumption that the residuals are NID(0, σ^2) is probably met.

Interaction. There interaction plot (see Figure C-13) confirms that there is little interaction between cement and fine aggregate. It also shows that generally smooth slabs and uniformly colored slabs (determined visually) have higher solar reflectance. Note the interaction between surface finish and uniformity of color: uniformly colored slabs have higher solar reflectance than non-uniformly colored slabs, particularly when the surface finish is smooth. These observations confirm our hypothesis that there is no meaningful interaction between cement and fine aggregate reflectance.

Regression Analysis: R-slab versus R-cement, R-fine agg, R-cement fin

The regression equation is
R-slab = 315 - 1.20 R-cement - 4.65 R-fine agg + 5.35 R-cement fine agg

Predictor	Coef	SE Coef	T	P	
Constant	314.90	64.12	4.91	0.000	
R-cement	-1.2019	0.6081	-1.98	0.054	
R-fine agg	-4.647	1.528	-3.04	0.004	
R-cement fine agg	5.346	1.966	2.72	0.009	(this is the interaction term)

S = 45.0150   R-Sq = 81.1%   R-Sq(adj) = 80.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	435583	145194	71.65	0.000
Residual Error	50	101318	2026		
Total	53	536901			

Source	DF	Seq SS	
R-cement	1	410515	76%
R-fine agg	1	10086	2%
R-cement fine agg	1	14983	2%

Figure C-10. Regression analysis of cement reflectance, fine aggregate reflectance, and their interaction on slab reflectance.

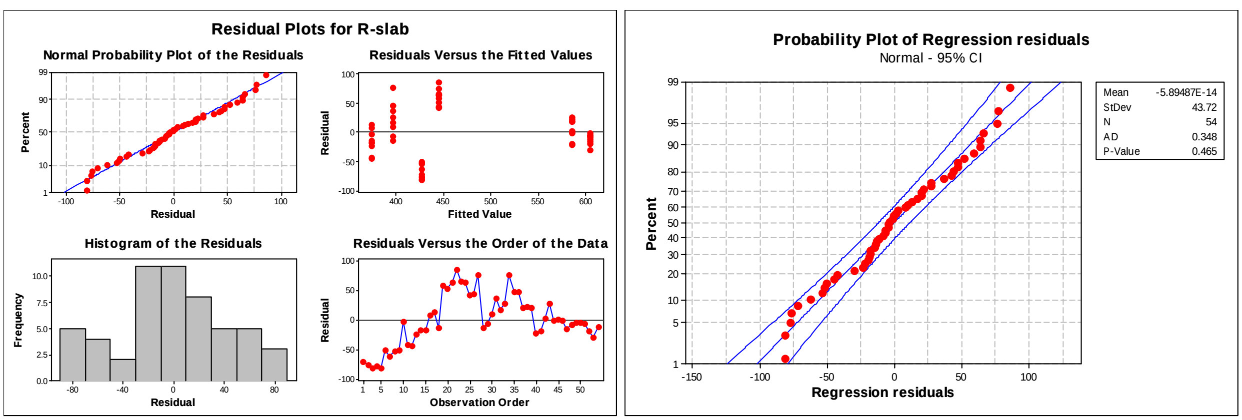


Figure C-11. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

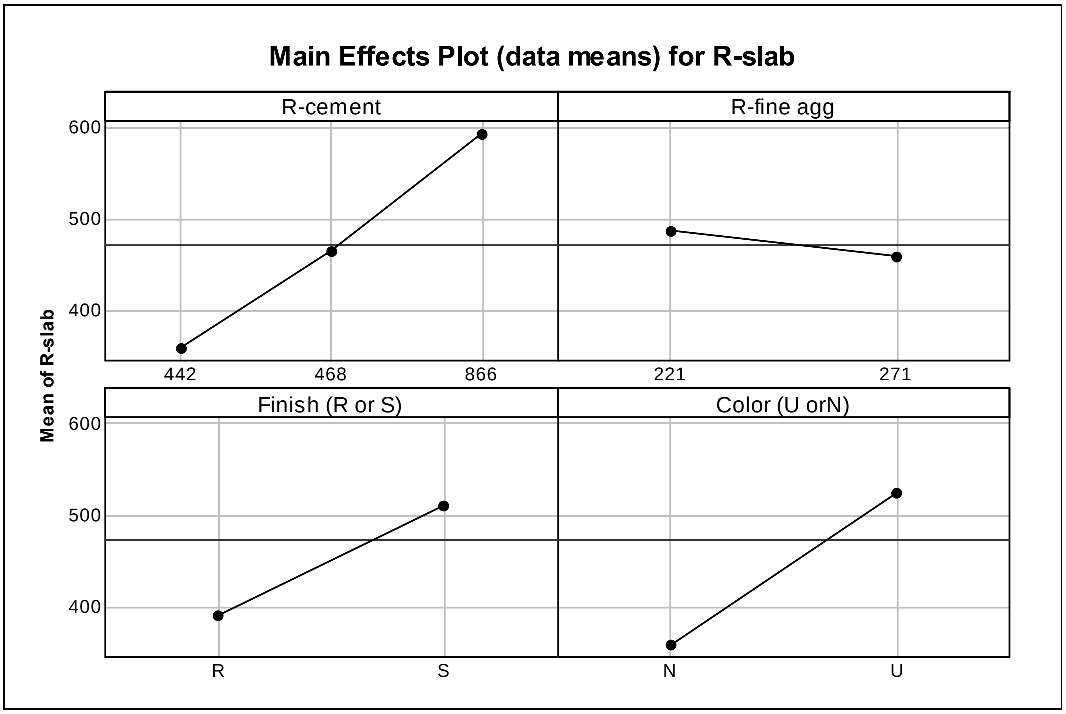


Figure C-12. Main effects plot show the relative magnitude of the factors that affect slab reflectance.

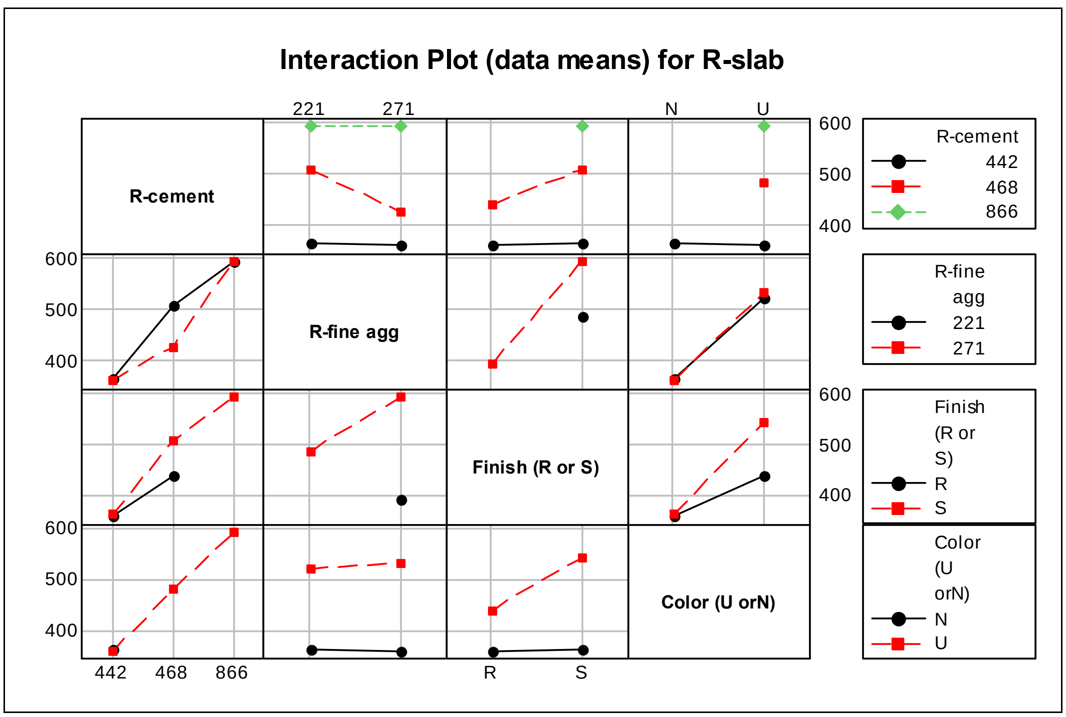


Figure C-13. Interaction plot.

3. Slab Reflectance versus SCM and Fine Aggregate Reflectance

Test: do SCM reflectance, fine aggregate reflectance or the interaction of SCM and fine aggregate reflectance have an effect on slab reflectance; and if so, how much of the variation in slab reflectance is due to SCM reflectance, fine aggregate reflectance, or the interaction of SCM and fine aggregate reflectance? These mixes were used:

- CS-AB-CP-...-...
- CS-AB-CP-...-SD
- CS-AB-CP-...-SL
- CS-AB-CP-FDG-...
- CS-AB-CP-FPB-...
- CS-AE-CP-...-...
- CS-AE-CP-...-SD
- CS-AE-CP-...-SL
- CS-AE-CP-FDG-...
- CS-AE-CP-FPB-...
- CS-AL-CP-...-...
- CS-AL-CP-...-SD
- CS-AL-CP-...-SL
- CS-AL-CP-FDG-...
- CS-AL-CP-FPB-...

The ANOVA results (see Figure C-14) show that fine aggregate has an effect (p-value = 0.006, so we cannot reject null hypothesis of no effect), SCM has an effect (p-value = 0.002, so we cannot reject the null hypothesis of no effect), and the interaction of fine aggregate and SCM has an effect (p-value < 0.001, so we cannot reject the null hypothesis of no effect). However, the assumption of normality of residuals has not been met (Anderson-Darling p-value = 0.035).

Using an expanded model (see Figure C-18) to include surface finish (texture and color consistency, determined visually), we see that all factors are significant at alpha = 5% *and* the assumption of normality of residuals has been met, that is, the residuals are NID(0, σ^2).

The main effects plot shows that slab reflectance increases with increasing reflectance of SCM. It also shows that slabs with a smoother finish have higher reflectance than those with a rougher finish. The effect of increasing fine aggregate reflectance does not have a linear effect on slab reflectance. Slab reflectance is lower for uniformly colored slabs.

The interactions plots show that the slab reflectance generally increases with increasing reflectance of SCM regardless of whether the slab is smooth or rough or uniform or non-uniform in color. Slabs with a smooth finish tend to have higher slab reflectances with increasing SCM reflectance compared to slabs with rougher finish. No other interactions are evident.

ANOVA: R-slab versus Fineagg, SCM

```
Factor    Type    Levels  Values
Fineagg   random       3  AB, AE, AL
SCM       random       5  FDG, FPB, NA, SD, SL  (Note: NA is level with no SCM.)


Analysis of Variance for R-slab

Source        DF      SS      MS      F      P  Significant at α = 5%
Fineagg        2  188702   94351  10.32  0.006           yes
SCM            4  440501  110125  12.04  0.002           yes
Fineagg*SCM    8   73145    9143  24.12  0.000           yes
Error        120   45495     379
Total        134  747843


S = 19.4711   R-Sq = 93.92%   R-Sq(adj) = 93.21%


                                     Expected Mean Square
                  Variance  Error    for Each Term (using
   Source        component  term     restricted model)
1  Fineagg          1893.5     3     (4) + 9 (3) + 45 (1)
2  SCM              3740.1     3     (4) + 9 (3) + 27 (2)
3  Fineagg*SCM       973.8     4     (4) + 9 (3)
4  Error             379.1           (4)
```

Figure C-14. ANOVA of SCM reflectance, fine aggregate reflectance and the interaction of SCM and fine aggregate reflectance on slab reflectance.

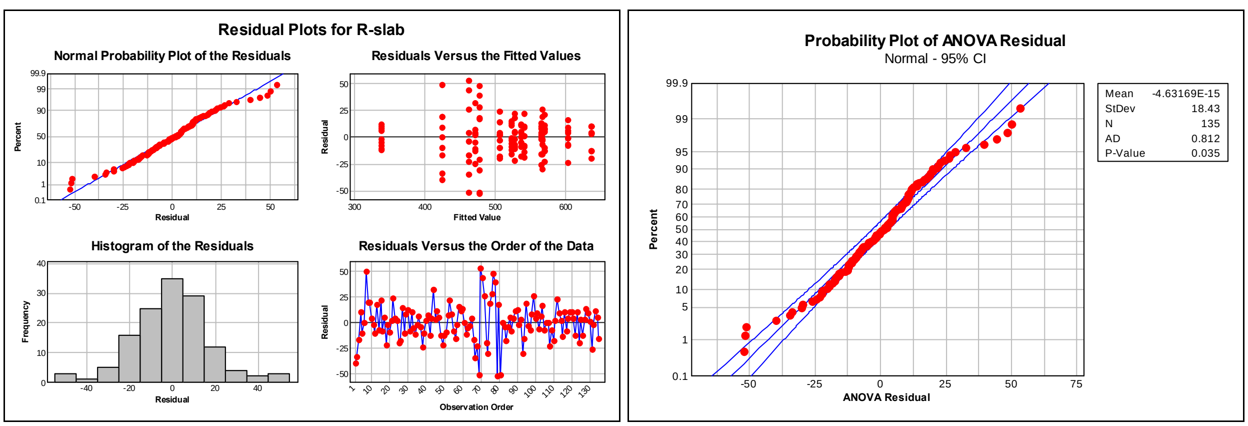


Figure C-15. The ANOVA assumptions are not because the residuals are not normally distributed (shown in the normal probability plot), although they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

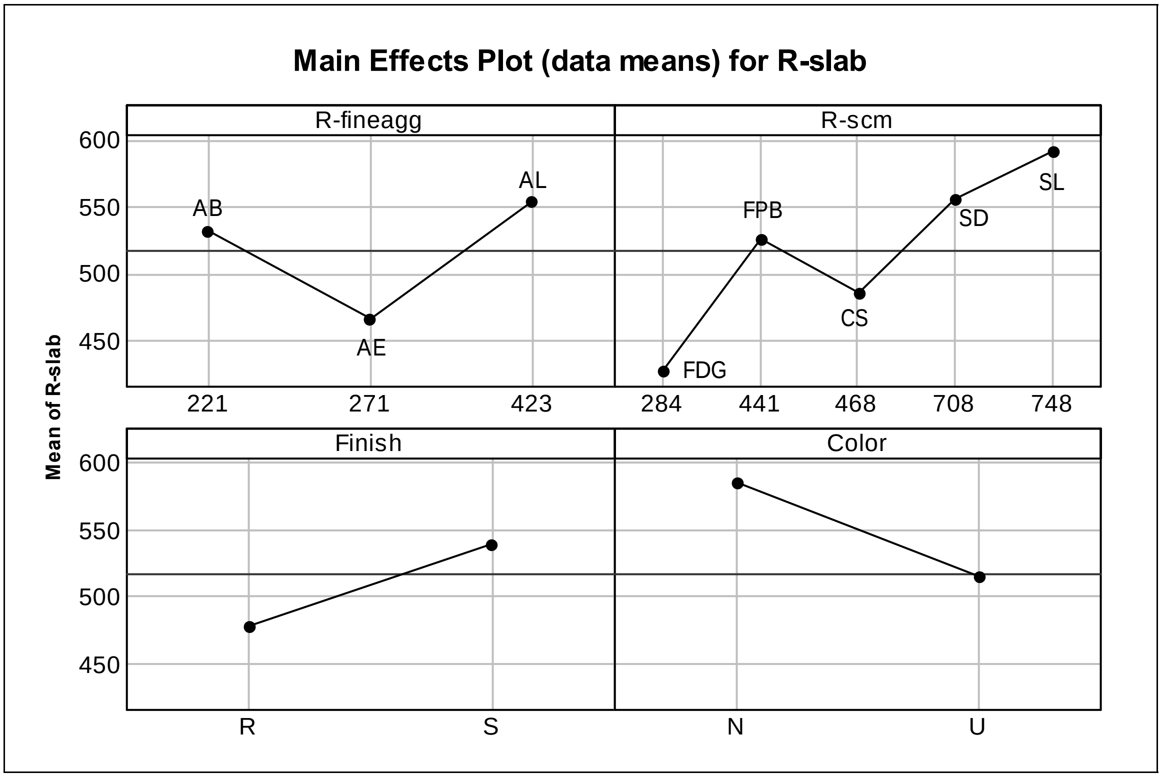


Figure C-16. Main effects plot.

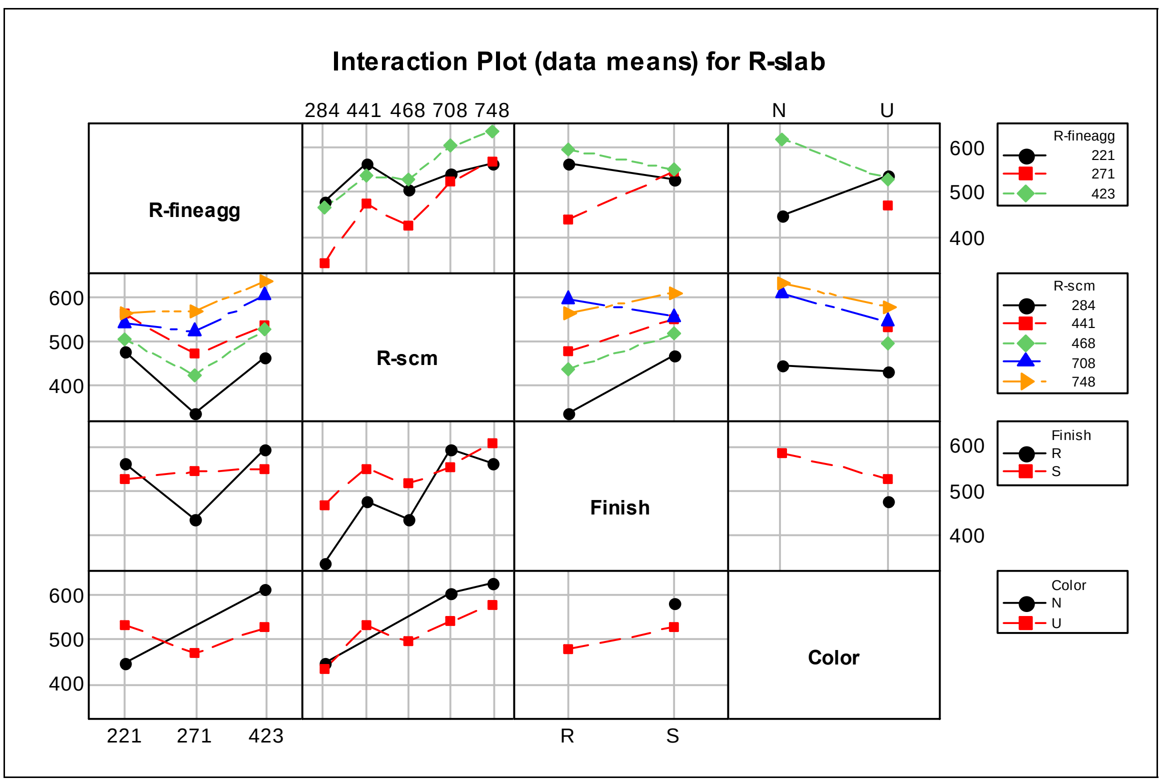


Figure C-17. Interaction plot.

General Linear Model: R-slab versus R-fineagg, R-scm, Finish, Color (Expanded Model)

```
Factor     Type    Levels  Values
R-fineagg  random       3  221, 271, 423
R-scm      random       5  284, 441, 468, 708, 748
Finish     random       2  R, S
Color      random       2  N, U


Analysis of Variance for R-slab, using Adjusted SS for Tests

Source             DF  Seq SS  Adj SS  Adj MS      F      P
R-fineagg           2  128631   46601   23300   4.69  0.044 x
R-scm               4  351521  368628   92157  14.12  0.001 x
R-fineagg*R-scm     8   64047   50604    6326  18.13  0.000
Finish              1     776    1845    1845   5.29  0.023
Color               1    2341    2341    2341   6.71  0.011
Error             103   35932   35932     349
Total             119  583248

x Not an exact F-test.


S = 18.6776   R-Sq = 93.84%   R-Sq(adj) = 92.88%


Expected Mean Squares, using Adjusted SS

   Source           Expected Mean Square for Each Term
1  R-fineagg        (6) + 5.3007 (3) + 26.5035 (1)
2  R-scm            (6) + 7.0955 (3) + 21.2866 (2)
3  R-fineagg*R-scm  (6) + 6.8621 (3)
4  Finish           (6) + 9.6667 (4)
5  Color            (6) + 10.5455 (5)
6  Error            (6)


Error Terms for Tests, using Adjusted SS

   Source           Error DF  Error MS  Synthesis of Error MS
1  R-fineagg            8.26      4966  0.7725 (3) + 0.2275 (6)
2  R-scm                7.97      6529  1.0340 (3) - 0.0340 (6)
3  R-fineagg*R-scm    103.00       349  (6)
4  Finish             103.00       349  (6)
5  Color              103.00       349  (6)


Variance Components, using Adjusted SS

                 Estimated
Source               Value
R-fineagg            691.8
R-scm               4022.6
R-fineagg*R-scm      871.0
Finish               154.8
Color                188.9
Error                348.9
```

Figure C-18. ANOVA expanded model.

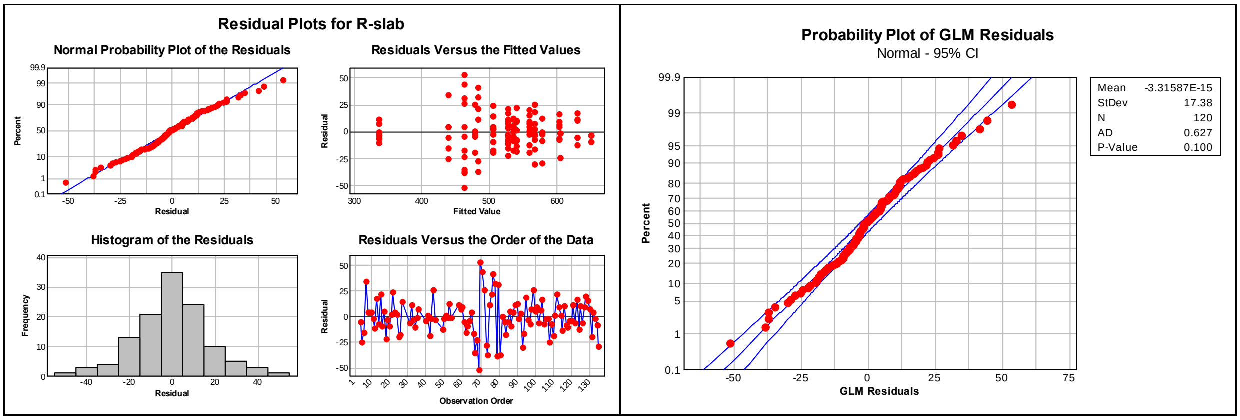


Figure C-19. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

This regression analysis of the quantitative factors in the expanded model (see Figure C-20), shows that none of the regression coefficients (except the constant term) are likely different from zero. However, it does not meet the assumptions of residuals being NID(0, σ^2) (see Figure C-21).

Regression Analysis: R-slab versus R-fineagg, R-scm, R-fineagg x R-scm

```
The regression equation is
R-slab = 290 - 0.196 R-fineagg + 0.056 R-scm + 0.656 R-fineagg x R-scm


Predictor               Coef   SE Coef      T      P  Significant at α = 5%
Constant              289.67     19.93  14.53  0.000             yes
R-fineagg            -0.1964    0.2537  -0.77  0.440              no
R-scm                 0.0560    0.1528   0.37  0.714              no
R-fineagg x R-scm     0.6561    0.3928   1.67  0.097              no


S = 48.2444   R-Sq = 59.2%   R-Sq(adj) = 58.3%


Analysis of Variance

Source           DF      SS      MS      F      P
Regression        3  442938  147646  63.43  0.000
Residual Error  131  304905    2328
Total           134  747843


Source             DF  Seq SS
R-fineagg           1   47983
R-scm               1  388462
R-fineagg x R-scm   1    6493
```

Figure C-20. Regression analysis of the quantitative factors in the expanded model.

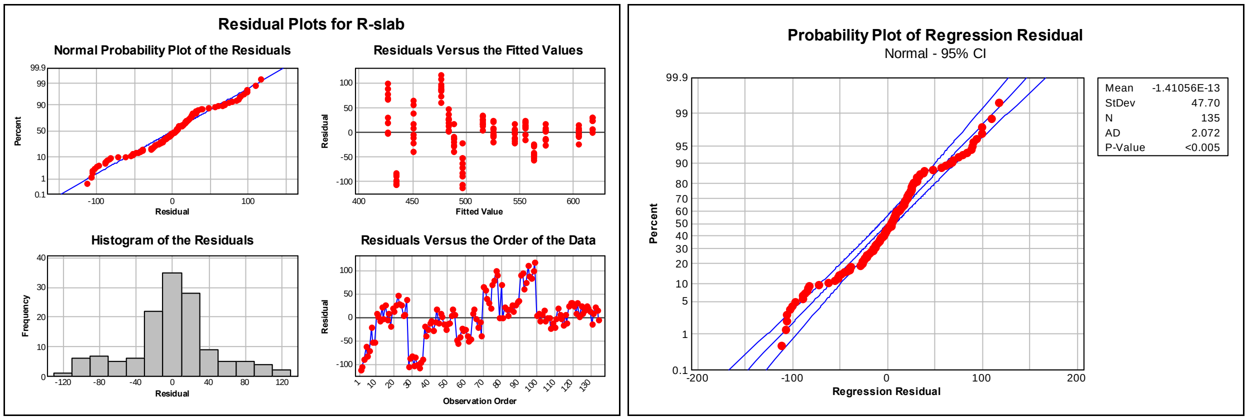


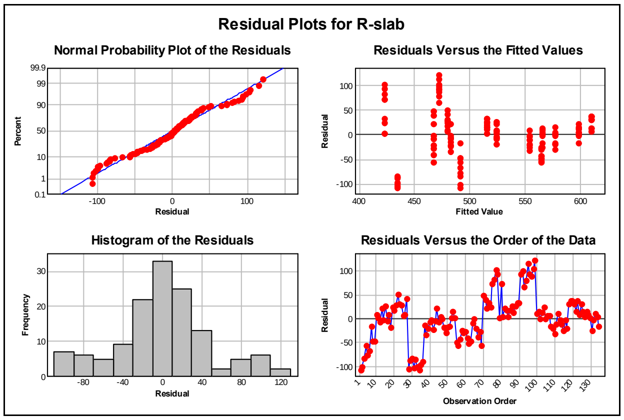
Figure C-21. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

The regression analysis of the reduced model (see Figure C-22) shows that the reflectance of the fine aggregate explains about 6% of the variation in slab reflectance, and the reflectance of SCM explains about 52% of the variation in slab reflectance. However, it also does not meet the assumptions of residuals being NID(0, σ^2) (see Figure C-23).

Regression Analysis: R-slab versus R-fineagg, R-scm (Reduced Regression Model)

```
The regression equation is
R-slab = 287 + 0.219 R-fineagg + 0.308 R-scm


Predictor      Coef  SE Coef      T      P
Constant     286.75    19.99  14.34  0.000
R-fineagg   0.21948  0.04866   4.51  0.000
R-scm       0.30818  0.02402  12.83  0.000


S = 48.5703   R-Sq = 58.4%   R-Sq(adj) = 57.7%


Analysis of Variance

Source           DF      SS      MS      F      P
Regression        2  436444  218222  92.50  0.000
Residual Error  132  311398    2359
Total           134  747843


Source     DF  Seq SS
R-fineagg   1   47983
R-scm       1  388462
```

Figure C-22. Regression analysis of reduced model.



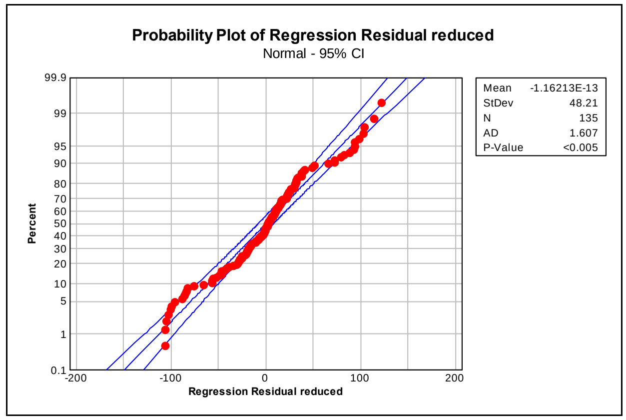


Figure C-23. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

4. Slab Reflectance versus Cement and SCM Reflectance

Test: do cement reflectance and SCM reflectance have an interactive effect on slab reflectance and if so, how much of the variation in slab reflectance is due to cement reflectance, SCM reflectance, and the interaction of cement and SCM reflectance? These mixes were used:

- CDG-AE-CP-...-…
- CDG-AE-CP-...-SD
- CDG-AE-CP-...-SL
- CDG-AE-CP-FDG-…
- CS-AE-CP-...-…
- CS-AE-CP-...-SD
- CS-AE-CP-...-SL
- CS-AE-CP-FDG-…

The ANOVA of the full model (see Figure C-24) shows that only the interaction term (cement and SCM) is significant; however, it only explains 9% of the variation in slab reflectance (see Figure C-28). Therefore it is reasonable to remove the interaction term from the model. The resulting reduced model (see Figure C-30) shows that <u>SCM is significant and explains 76% of the variation in slab reflectance</u>. It should be noted that in this analysis, the solar reflectances of the two cements are relatively much less different then the solar reflectances of the SCMs (see Figure C-26). Therefore, in this case, it is expected that any effect cement reflectance might have on slab reflectance might be dwarfed by SCM reflectance.

General Linear Model: R-slab versus Cement, SCM

Factor	Type	Levels	Values
Cement	random	2	CDG, CS
SCM	random	4	FDG, NA, SD, SL

Analysis of Variance for R-slab, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significant at α = 5%
Cement	1	2640	2640	2640	0.14	0.731	no
SCM	3	297603	297603	99201	5.33	0.101	no
Cement*SCM	3	55788	55788	18596	58.67	0.000	yes
Error	64	20284	20284	317			
Total	71	376316					

S = 17.8029   R-Sq = 94.61%   R-Sq(adj) = 94.02%

Unusual Observations for R-slab

Obs	R-slab	Fit	SE Fit	Residual	St Resid	
17	468.000	507.667	5.934	-39.667	-2.36	R
37	384.000	423.889	5.934	-39.889	-2.38	R
38	390.000	423.889	5.934	-33.889	-2.02	R
43	474.000	423.889	5.934	50.111	2.99	R

R denotes an observation with a large standardized residual.

Expected Mean Squares, using Adjusted SS

	Source	Expected Mean Square for Each Term
1	Cement	(4) + 9.0000 (3) + 36.0000 (1)
2	SCM	(4) + 9.0000 (3) + 18.0000 (2)
3	Cement*SCM	(4) + 9.0000 (3)
4	Error	(4)

Error Terms for Tests, using Adjusted SS

	Source	Error DF	Error MS	Synthesis of Error MS
1	Cement	3.00	18596	(3)
2	SCM	3.00	18596	(3)
3	Cement*SCM	64.00	317	(4)

Variance Components, using Adjusted SS

Source	Estimated Value
Cement	-443.2
SCM	4478.1
Cement*SCM	2031.0
Error	316.9

Figure C-24. ANOVA.

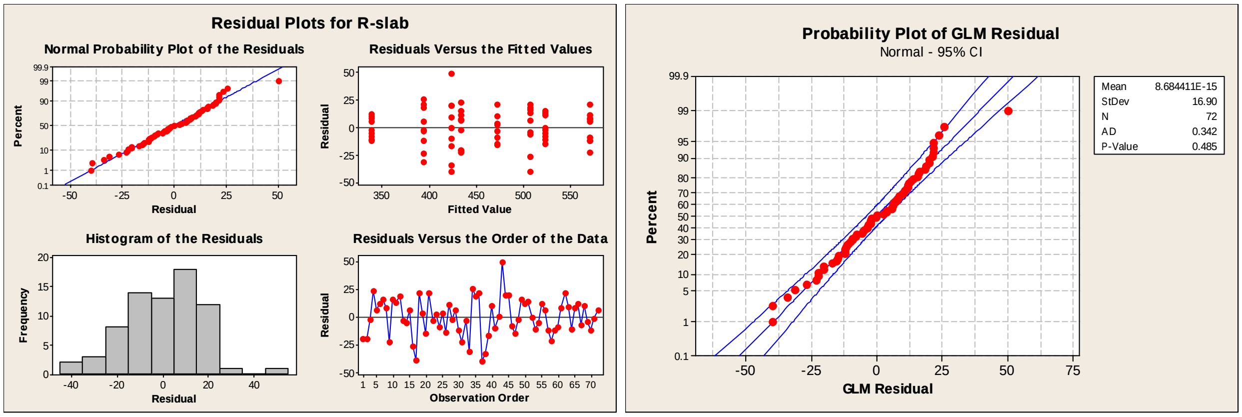


Figure C-25. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

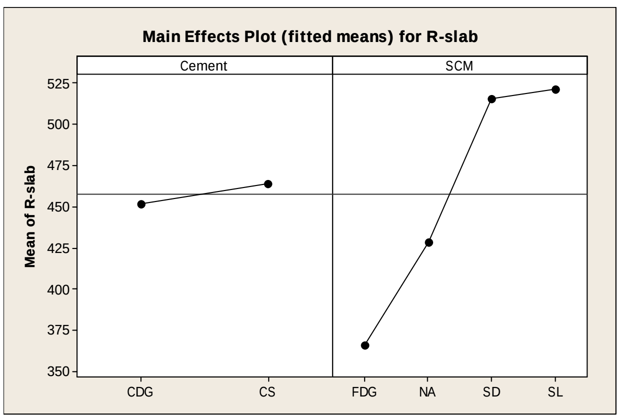


Figure C-26. Main effects plot.

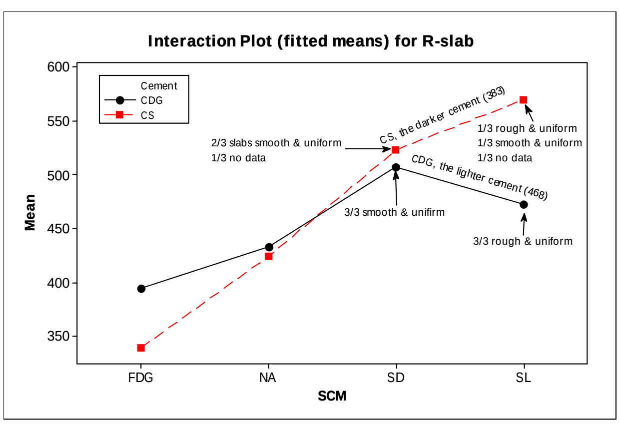


Figure C-27. Interaction plot.

Although the interaction of cement and SCM only explains 9% of the variability in slab reflectance, the interaction plot (see Figure C-27) shows that slabs made with the darker cement (CS, with a solar reflectance of 0.383) become relatively lighter than slabs made with the lighter cement (CDG, with a solar reflectance if 0.468) with increasing slag cement reflectance. Portland cements tend to be darker when they have more calcium aluminoferite (C_4AF). Slag cements are white, but the oxidation of sulfides in slag cement results in a color change from white to cream. The more oxidation of sulfides in slag cement, the darker the color (St John, Donald A., Poole, Alan W., Sims, Ian, *Concrete Petrography: A Handbook of Investigative Techniques*, John Wiley and Sons, Inc., New York, New York, 1986.). Figure C-27 suggests that the presence of increased C_4AF in a cement increases the reflectance (whiteness) of slag cement concrete compared to a cement with a lower C_4AF content by decreasing the amount of oxidation of sulfides in slag cement.

Regression Analysis: R-slab versus R-cement, R-scm, Interaction

```
The regression equation is
R-slab = 315 - 1.76 R-cement - 1.16 R-scm + 3.23 Interaction


Predictor       Coef  SE Coef      T      P
Constant      314.99    35.64   8.84  0.000
R-cement     -1.7618   0.2983  -5.91  0.000
R-scm        -1.1609   0.2350  -4.94  0.000
Interaction   3.2289   0.5096   6.34  0.000


S = 28.3307   R-Sq = 85.5%   R-Sq(adj) = 84.9%


Analysis of Variance

Source          DF      SS      MS       F      P
Regression       3  321737  107246  133.62  0.000
Residual Error  68   54579     803
Total           71  376316


Source       DF  Seq SS
R-cement      1    2640
R-scm         1  286870 ← 76% of variation explained by SCM reflectance
Interaction   1   32227 ←  9% of explained by interaction


Unusual Observations

Obs  R-cement  R-slab     Fit  SE Fit  Residual  St Resid
 37       468  384.00  458.31    6.00    -74.31     -2.68R
 38       468  390.00  458.31    6.00    -68.31     -2.47R
 62       468  592.00  532.55    5.85     59.45      2.14R

R denotes an observation with a large standardized residual.
```

Figure C-28. Regression analysis.

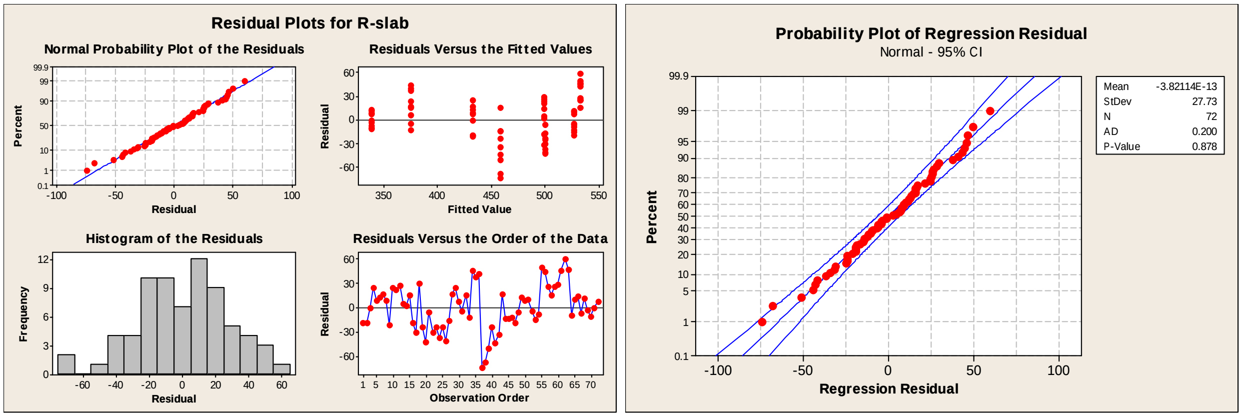


Figure C-29. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

General Linear Model: R-slab versus Cement, SCM (Reduce Model)

```
Factor  Type    Levels  Values
Cement  random       2  CDG, CS
SCM     random       4  FDG, NA, SD, SL


Analysis of Variance for R-slab, using Adjusted SS for Tests

Source  DF  Seq SS  Adj SS  Adj MS      F      P
Cement   1    2640    2640    2640   2.33  0.132
SCM      3  297603  297603   99201  87.37  0.000
Error   67   76072   76072    1135
Total   71  376316


S = 33.6958   R-Sq = 79.78%   R-Sq(adj) = 78.58%


Expected Mean Squares, using Adjusted SS

           Expected Mean
           Square for Each
   Source  Term
1  Cement  (3) + 36.0000 (1)
2  SCM     (3) + 18.0000 (2)
3  Error   (3)


Error Terms for Tests, using Adjusted SS

                               Synthesis
                               of Error
   Source  Error DF  Error MS  MS
1  Cement     67.00      1135  (3)
2  SCM        67.00      1135  (3)


Variance Components, using Adjusted SS

        Estimated
Source      Value
Cement      41.80
SCM       5448.09
Error     1135.41
```

Figure C-30. ANOVA of reduced model.

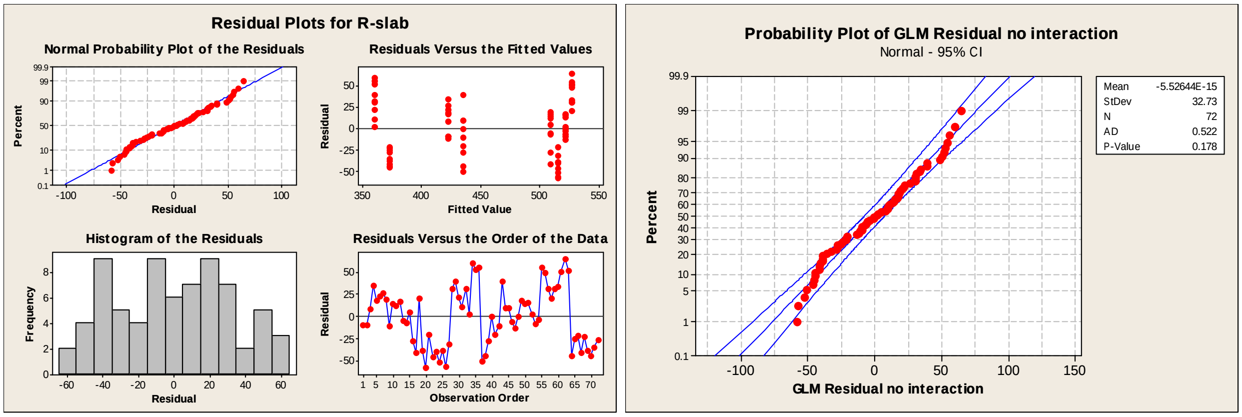


Figure C-31. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

5. Slab Reflectance versus SCM Reflectance

Test: does SCM reflectance have an effect on slab reflectance and if so, how much of the variation in slab reflectance is due to SCM reflectance? These mixes were used:

- CS-AE-CP-...-...
- CS-AE-CP-FDG-...
- CS-AE-CP-FLG-...
- CS-AE-CP-FMG-...
- CS-AE-CP-FVLG-...
- CS-AE-CP-FPB-...
- CS-AE-CP-FYB-...
- CS-AE-CP-...-SD
- CS-AE-CP-...-SL
- CS-AE-CP-...-SM

Note that “no SCM” is a treatment level. Its value is the reflectance of the cement in the mix. It is shown as the factor level “CS” in the analysis below.

The ANOVA (see Figure C-32) shows that SCM has a significant effect on slab reflectance, and the regression analysis (see Figure C-34) shows that 81% of the variation in slab reflectance can be explained by the reflectance of the SCM. Considering only the mixes above with fly ash (see Figure C-38), the reflectance of fly ash can explain 73% of the slab reflectance. Considering only the mixes above with slag cement (see Figure C-41), the reflectance of slag cement can explain 32% of the slab reflectance.

General Linear Model: R-slab versus SCM

```
Factor  Type    Levels  Values
SCM     random      10  CS, FDG, FLG, FMG, FPB, FVLG, FYB, SD, SL, SM


Analysis of Variance for R-slab, using Adjusted SS for Tests

Source  DF  Seq SS  Adj SS  Adj MS       F      P  Significant at α =5%
SCM      9  360531  360531   40059  111.55  0.000           yes
Error   80   28730   28730     359
Total   89  389261


S = 18.9506   R-Sq = 92.62%   R-Sq(adj) = 91.79%


Unusual Observations for R-slab

Obs   R-slab      Fit  SE Fit  Residual  St Resid
 19  394.000  444.111   6.317   -50.111     -2.80 R
 20  402.000  444.111   6.317   -42.111     -2.36 R
 24  493.000  444.111   6.317    48.889      2.74 R
 55  384.000  423.889   6.317   -39.889     -2.23 R
 61  474.000  423.889   6.317    50.111      2.80 R

R denotes an observation with a large standardized residual.


Expected Mean Squares, using Adjusted SS

           Expected Mean
           Square for Each
   Source  Term
1  SCM     (2) + 9.0000 (1)
2  Error   (2)


Error Terms for Tests, using Adjusted SS

                            Synthesis
                     Error  of Error
   Source  Error DF     MS  MS
1  SCM        80.00    359  (2)


Variance Components, using Adjusted SS

        Estimated
Source      Value
SCM        4411.1
Error       359.1
```

Figure C-32. ANOVA.

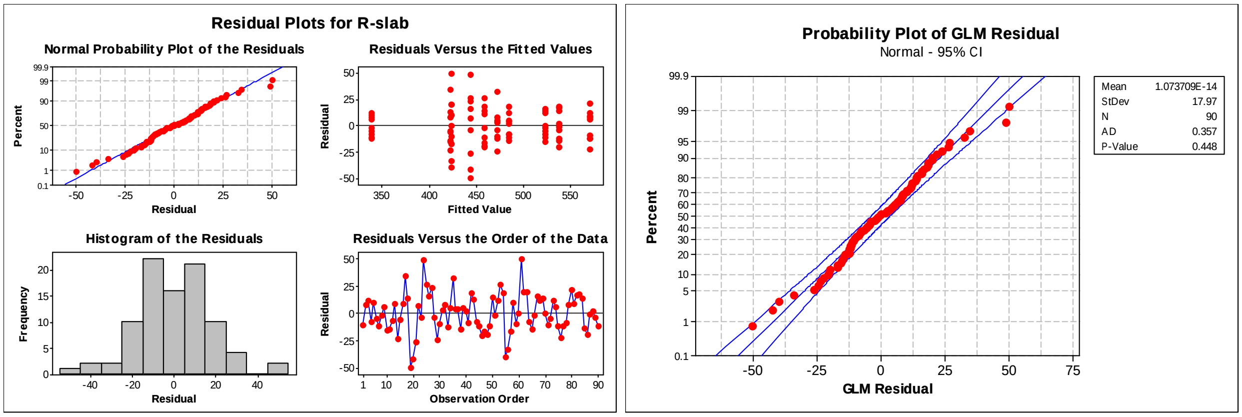


Figure C-33. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

Check Assumptions. The Anderson-Darling test for normality shows that the residuals are normally distributed because the assumption of normality can not be rejected for any reasonable alpha (p-value = 0.448). Further, the residual plots show that the residuals are independent (no apparent pattern in observation order), have a mean of zero and a constant variance. Therefore the residuals are NID(0, σ^2), and the assumptions for using ANOVA and least-squares regression are satisfied.

Regression Analysis: R-slab versus R-scm

```
The regression equation is
R-slab = 275.2 + 0.3729 R-scm


S = 29.2047   R-Sq = 80.7%   R-Sq(adj) = 80.5%


Analysis of Variance

Source      DF      SS      MS       F      P
Regression   1  314204  314204  368.39  0.000
Error       88   75057     853
Total       89  389261
```

Figure C-34. Regression analysis.

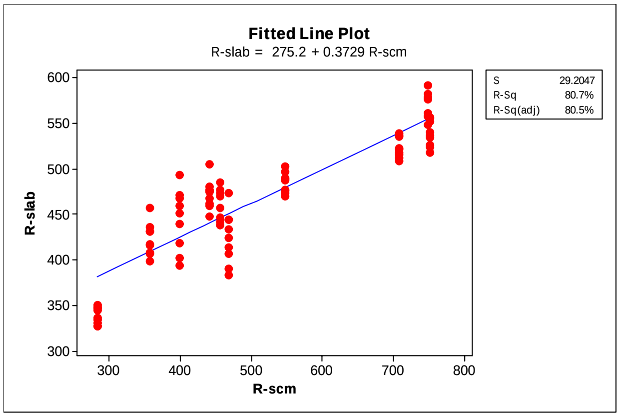


Figure C-35. Fitted line plot.

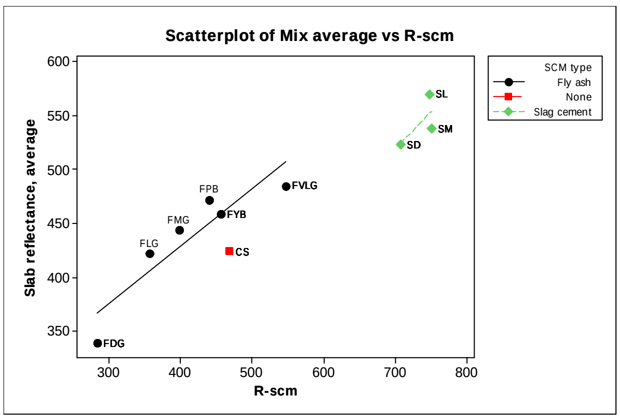


Figure C 36. Fitted line plot showing fly ashes and slag cements separately.

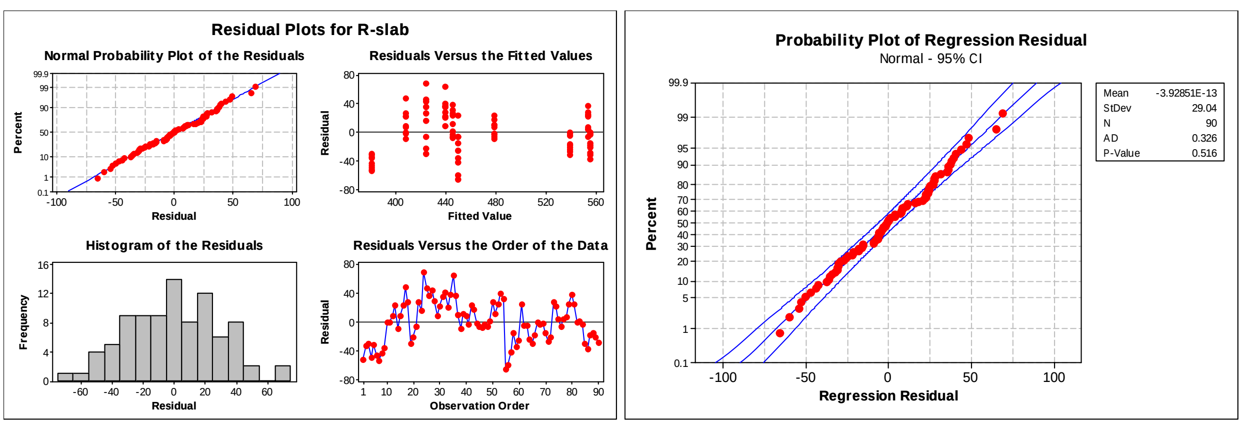


Figure C 37. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

Regression Analysis: R-slab versus R-scm

```
The regression equation is
R-slab = 215.5 + 0.5344 R-scm


S = 27.2350   R-Sq = 73.0%   R-Sq(adj) = 72.5%


Analysis of Variance

Source      DF      SS      MS       F      P
Regression   1  104447  104447  140.81  0.000
Error       52   38571     742
Total       53  143017
```

Figure C-38. Regression analysis fly ashes only.

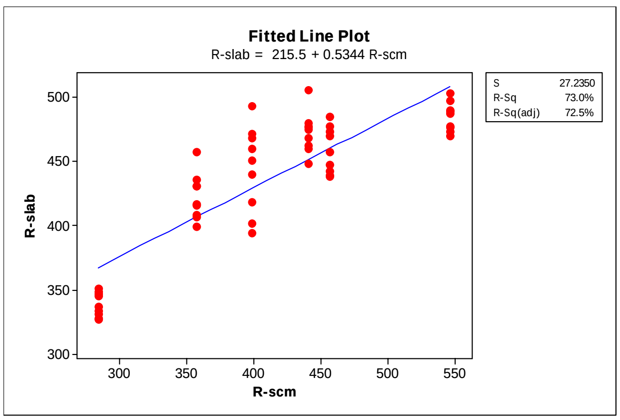


Figure C-39. Fitted line plot.

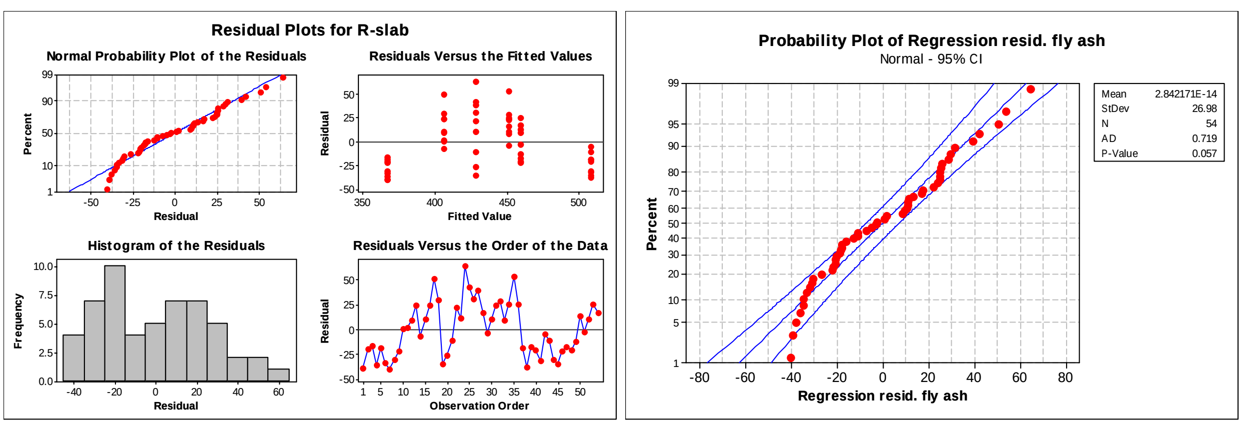


Figure C-40. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

Regression Analysis: R-slab versus R-scm

The regression equation is
R-slab = 27.2 + 0.7021 R-scm

S = 19.5860   R-Sq = 34.8%   R-Sq(adj) = 32.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5114.4	5114.39	13.33	0.001
Error	25	9590.3	383.61		
Total	26	14704.7			

Figure C-41. Regression analysis slag cements only.

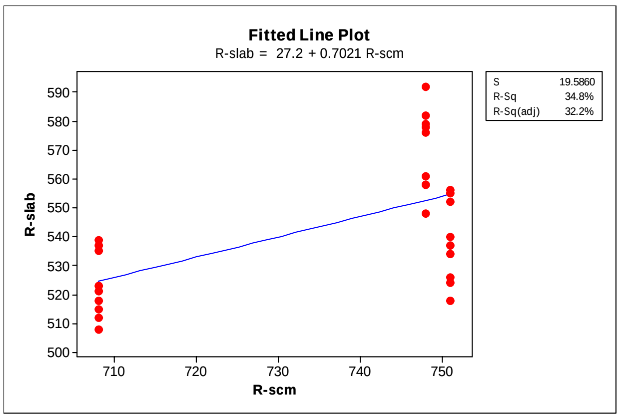


Figure C-42. Fitted line plot.

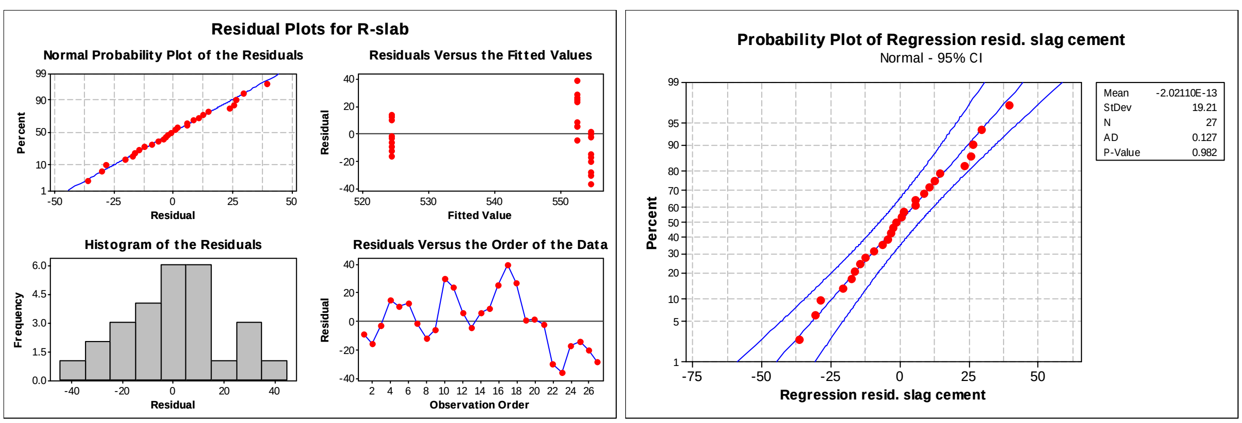


Figure C-43. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

6. Slab Reflectance versus Cement and “FDG” Fly Ash Reflectance

Test: does cement reflectance or FDG have an effect on slab reflectance and if so, how much of the variation in slab reflectance is due to cement reflectance, how much to FDG reflectance, and how much to the interaction of the two factors? These mixes were used:

- CDG-AE-CP-...-...
- CDG-AE-CP-FDG-... [Second set (…-2) used because first set (…-1) poorly made.]
- CR-AE-CP-...-...
- CR-AE-CP-FDG-...
- CS-AE-CP-...-...
- CS-AE-CP-FDG-...
- CXB-AE-CP-...-...
- CXB-AE-CP-FDG-...
- CXR-AE-CP-...-...
- CXR-AE-CP-FDG-...

The ANOVA shows that neither cement not FDG have a significant effect (see Figure C-44). If the model is expanded to include an interaction term, the interaction term is significant (see Figure C-48). However, even in this case the interaction only explains 24% of the variability in slab reflectance. An analysis of the average effect of fly ash (see the “Main Effect for SCM type” in Figure C-47) shows that the slabs made with dark gray fly ash (FDG) have a solar reflectance significantly higher (darker) than the average slabs.

General Linear Model: R-slab versus Cement, Fly ash

Factor	Type	Levels	Values
Cement	random	5	CDG, CR, CS, CXB, CXR
Fly ash	random	2	FDG, None

Analysis of Variance for R-slab, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significant at α = 5%
Cement	4	12102	12102	3025	2.10	0.088	no
Fly ash	1	2423	2423	2423	1.68	0.198	no
Error	84	120810	120810	1438			
Total	89	135335					

S = 37.9239   R-Sq = 10.73%   R-Sq(adj) = 5.42%

Unusual Observations for R-slab

Obs	R-slab	Fit	SE Fit	Residual	St Resid
43	474.000	376.144	9.792	97.856	2.67 R
72	473.000	391.356	9.792	81.644	2.23 R

R denotes an observation with a large standardized residual.

Expected Mean Squares, using Adjusted SS

	Source	Expected Mean Square for Each Term
1	Cement	(3) + 18.0000 (1)
2	Fly ash	(3) + 45.0000 (2)
3	Error	(3)

Error Terms for Tests, using Adjusted SS

	Source	Error DF	Error MS	Synthesis of Error MS
1	Cement	84.00	1438	(3)
2	Fly ash	84.00	1438	(3)

Variance Components, using Adjusted SS

Source	Estimated Value
Cement	88.18
Fly ash	21.89
Error	1438.22

Figure C-44. ANOVA.

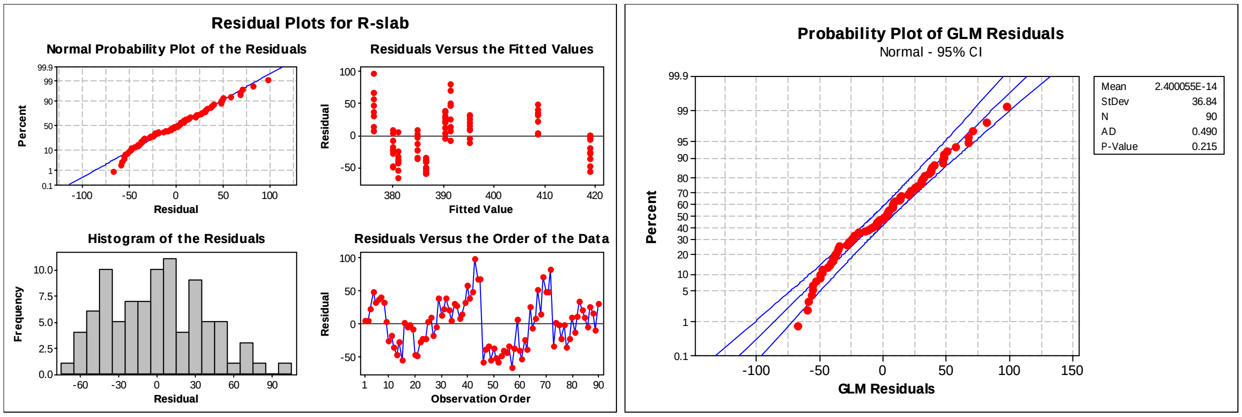


Figure C-45. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

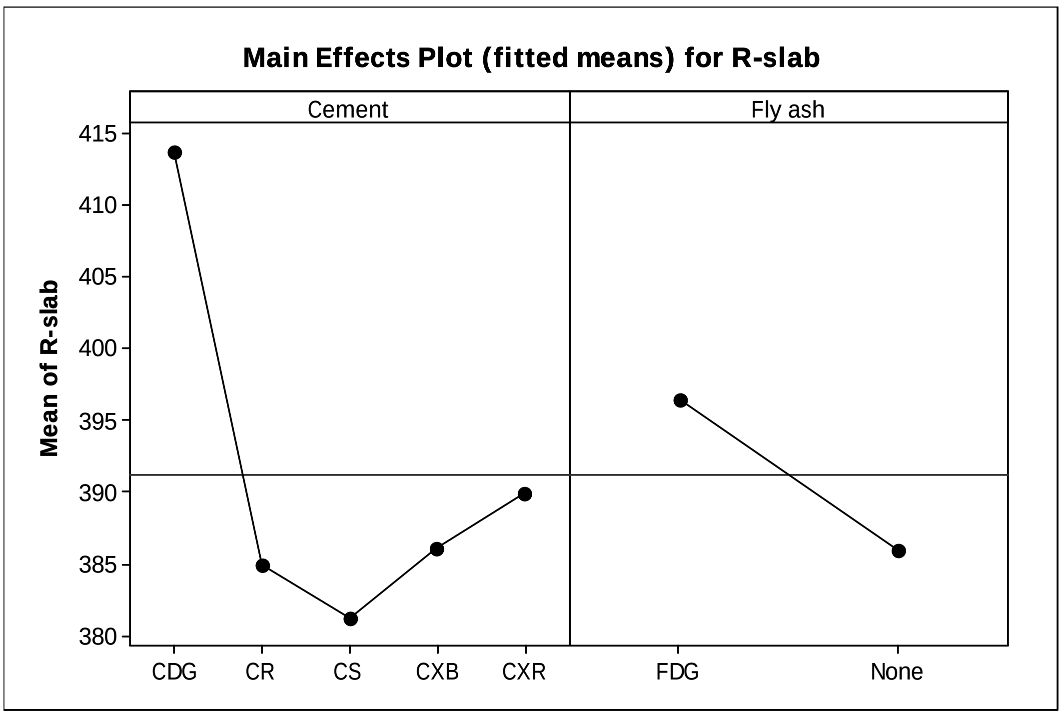


Figure C-46. Main effects plots.

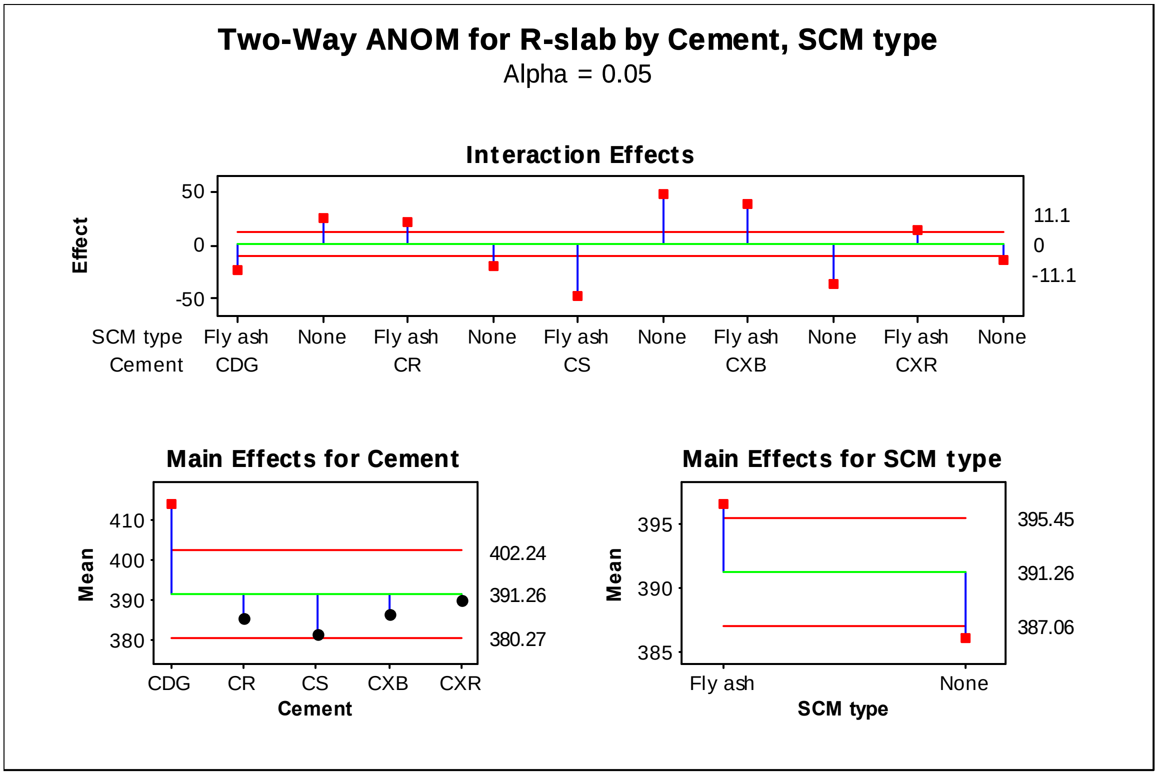


Figure C-47. Analysis of means.

General Linear Model: R-slab versus Cement, Fly ash (Expanded with Interaction Term)

Factor	Type	Levels	Values
Cement	random	5	CDG, CR, CS, CXB, CXR
Fly ash	random	2	FDG, None

Analysis of Variance for R-slab, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significant at α = 5%
Cement	4	12102	12102	3025	0.14	0.960	no
Fly ash	1	2423	2423	2423	0.11	0.758	no
Cement*Fly ash	4	88834	88834	22209	55.56	0.000	yes
Error	80	31976	31976	400			
Total	89	135335					

S = 19.9925   R-Sq = 76.37%   R-Sq(adj) = 73.71%

Unusual Observations for R-slab

Obs	R-slab	Fit	SE Fit	Residual	St Resid	
37	384.000	423.889	6.664	-39.889	-2.12	R
43	474.000	423.889	6.664	50.111	2.66	R
59	386.000	343.444	6.664	42.556	2.26	R
65	384.000	428.889	6.664	-44.889	-2.38	R
72	473.000	428.889	6.664	44.111	2.34	R

R denotes an observation with a large standardized residual.

Expected Mean Squares, using Adjusted SS

	Source	Expected Mean Square for Each Term
1	Cement	(4) + 9.0000 (3) + 18.0000 (1)
2	Fly ash	(4) + 9.0000 (3) + 45.0000 (2)
3	Cement*Fly ash	(4) + 9.0000 (3)
4	Error	(4)

Error Terms for Tests, using Adjusted SS

	Source	Error DF	Error MS	Synthesis of Error MS
1	Cement	4.00	22209	(3)
2	Fly ash	4.00	22209	(3)
3	Cement*Fly ash	80.00	400	(4)

Variance Components, using Adjusted SS

Source	Estimated Value
Cement	-1065.7
Fly ash	-439.7
Cement*Fly ash	2423.2
Error	399.7

Figure C-48. ANOVA expanded with interaction term.

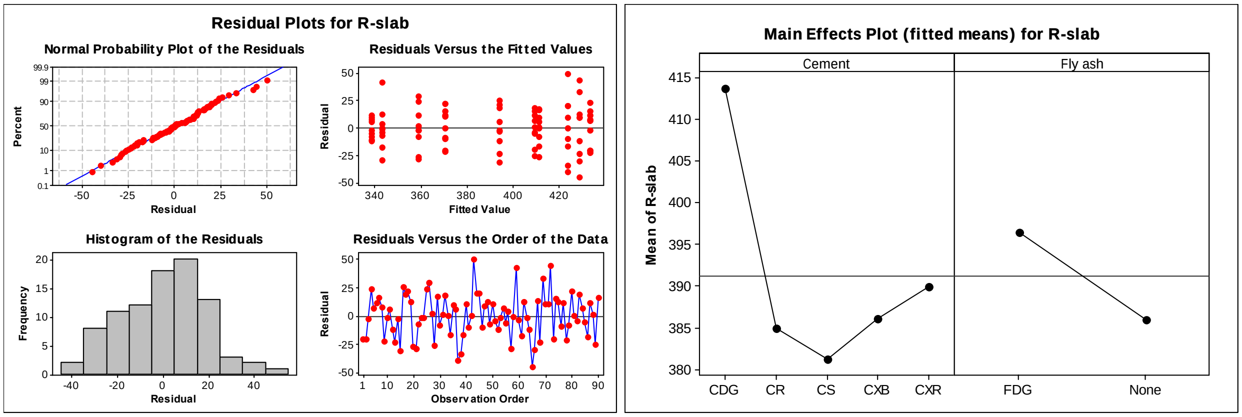


Figure C-49. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

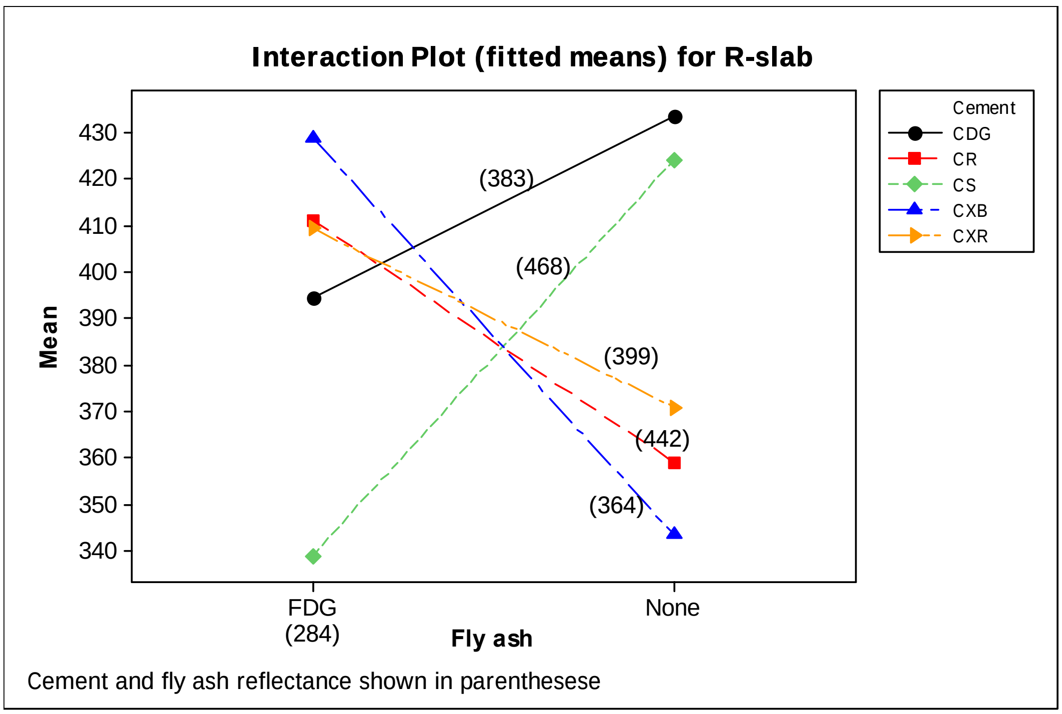


Figure C-50. Interaction plot.

Regression Analysis: R-slab versus R-cement, R-scm

```
The regression equation is
R-slab = 455 - 0.155 R-cement + 0.0003 R-scm


Predictor      Coef  SE Coef      T      P  Likely ≠ 0 at α = 5%
Constant     454.79    45.13  10.08  0.000           yes
R-cement    -0.1547   0.1116  -1.39  0.169            no
R-scm       0.00028  0.06185   0.00  0.996            no


S = 38.9775   R-Sq = 2.3%   R-Sq(adj) = 0.1%


Analysis of Variance

Source          DF      SS    MS     F      P
Regression       2    3161  1581  1.04  0.358  Conclude there is no regression
Residual Error  87  132174  1519               relationship
Total           89  135335


Source    DF  Seq SS
R-cement   1    3161
R-scm      1       0


Unusual Observations

Obs  R-cement  R-slab     Fit  SE Fit  Residual  St Resid
 43       468  474.00  382.50    9.29     91.50     2.42R
 57       364  314.00  398.56    6.97   - 84.56    -2.21R

R denotes an observation with a large standardized residual.
```

Figure C-51. Regression analysis.

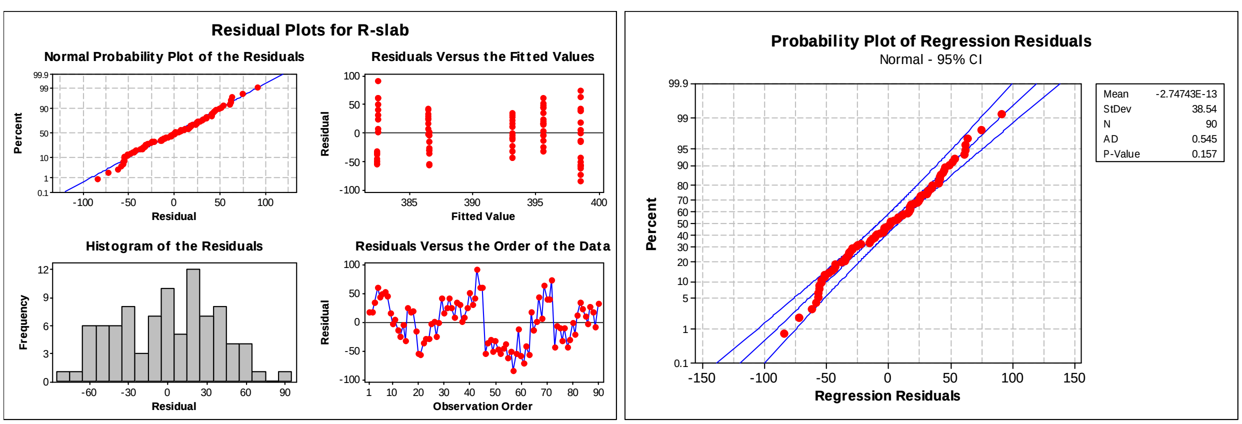


Figure C-52. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

Regression Analysis: R-slab versus R-cement, R-scm, R-cement x R-scm (Expanded Model with Interaction Term)

The regression equation is
R-slab = 260 - 11.7 R-cement - 14.8 R-scm + 26.7 R-cement x R-scm

Predictor	Coef	SE Coef	T	P	Likely ≠ 0 at α = 5%
Constant	259.94	53.76	4.84	0.000	yes
R-cement	-11.665	2.165	-5.39	0.000	yes
R-scm	-14.760	2.774	-5.32	0.000	yes
R-cement x R-scm	26.731	5.022	5.32	0.000	yes

S = 34.0015   R-Sq = 26.5%   R-Sq(adj) = 24.0%

Analysis of Variance

Source	DF	SS	MS	F	P	
Regression	3	35911	11970	10.35	0.000	Conclude there is a regression relationship.
Residual Error	86	99425	1156			
Total	89	135335				

Source	DF	Seq SS	
R-cement	1	3161	
R-scm	1	0	
R-cement x R-scm	1	32750	(explains 24% of the variation in slab reflectance)

Unusual Observations

Obs	R-cement	R-slab	Fit	SE Fit	Residual	St Resid
4	383	457.00	377.31	6.23	79.69	2.38R
6	383	445.00	377.31	6.23	67.69	2.03R
7	383	449.00	377.31	6.23	71.69	2.14R
43	468	474.00	403.35	9.00	70.65	2.15R

R denotes an observation with a large standardized residual.

Figure C-53. Regression analysis of expanded model.

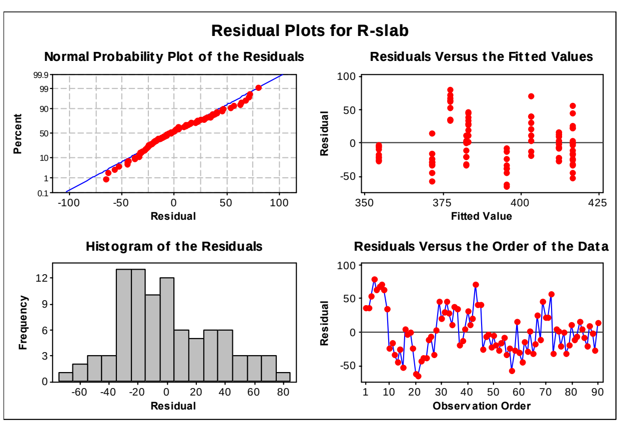


Figure C-54. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

7. Slab Reflectance versus Fine and Coarse Aggregate Reflectance

Test: does fine aggregate reflectance or coarse aggregate have an effect on slab reflectance and if so, how much of the variation in slab reflectance is due to fine aggregate reflectance, how much to coarse aggregate reflectance, and how much to the interaction of the two factors? These mixes were used:

- CS-AE-CL-...-...
- CS-AE-CP-...-...
- CS-AM-CL-...-...
- CS-AM-CP-...-...

The ANOVA shows that neither fine aggregate reflectance nor coarse aggregate has a significant effect on slab reflectance, although the interaction of the two factors does (see Figure C-55). However, only 46% of the variability of slab reflectance is explained by the interaction (see Figure C-59). This is less than the amount that one would expect would be explained by pure chance (50%).

General Linear Model: R-slab versus Fine agg, Coarse agg

```
Factor      Type    Levels  Values
Fine agg    random       2  AE, AM
Coarse agg  random       2  CL, CP


Analysis of Variance for R-slab, using Adjusted SS for Tests

Source               DF  Seq SS  Adj SS  Adj MS      F      P  Significant at α = 5%
Fine agg              1   12996   12996   12996   0.38  0.647             no
Coarse agg            1    5675    5675    5675   0.17  0.753             no
Fine agg*Coarse agg   1   33979   33979   33979  51.01  0.000            yes
Error                32   21316   21316     666
Total                35   73966


S = 25.8094   R-Sq = 71.18%   R-Sq(adj) = 68.48%


Unusual Observations for R-slab

Obs   R-slab      Fit  SE Fit  Residual  St Resid
  7  474.000  423.889   8.603    50.111      2.06 R
 10  525.000  460.222   8.603    64.778      2.66 R
 11  515.000  460.222   8.603    54.778      2.25 R

R denotes an observation with a large standardized residual.


Expected Mean Squares, using Adjusted SS

   Source                Expected Mean Square for Each Term
1  Fine agg              (4) + 9.0000 (3) + 18.0000 (1)
2  Coarse agg            (4) + 9.0000 (3) + 18.0000 (2)
3  Fine agg*Coarse agg   (4) + 9.0000 (3)
4  Error                 (4)


Error Terms for Tests, using Adjusted SS

                                            Synthesis
                                            of Error
   Source                Error DF  Error MS  MS
1  Fine agg                  1.00     33979  (3)
2  Coarse agg                1.00     33979  (3)
3  Fine agg*Coarse agg      32.00       666  (4)


Variance Components, using Adjusted SS

                     Estimated
Source                   Value
Fine agg               -1165.7
Coarse agg             -1572.4
Fine agg*Coarse agg     3701.4
Error                    666.1
```

Figure C-55. ANOVA.

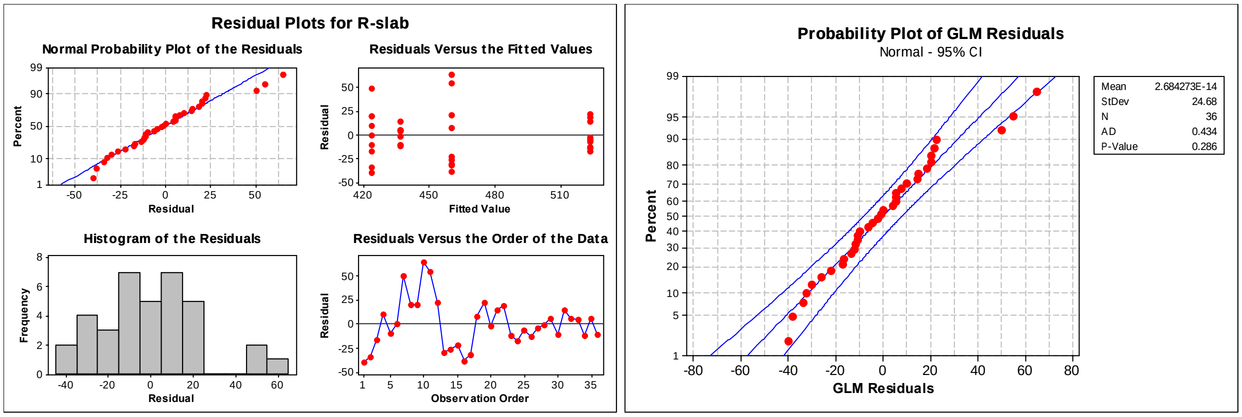


Figure C-56. The ANOVA assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).

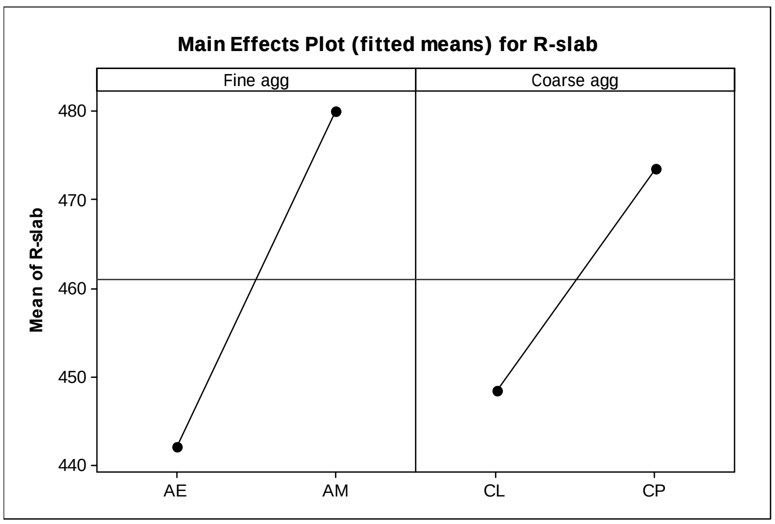


Figure C-57. Main Effects Plot.

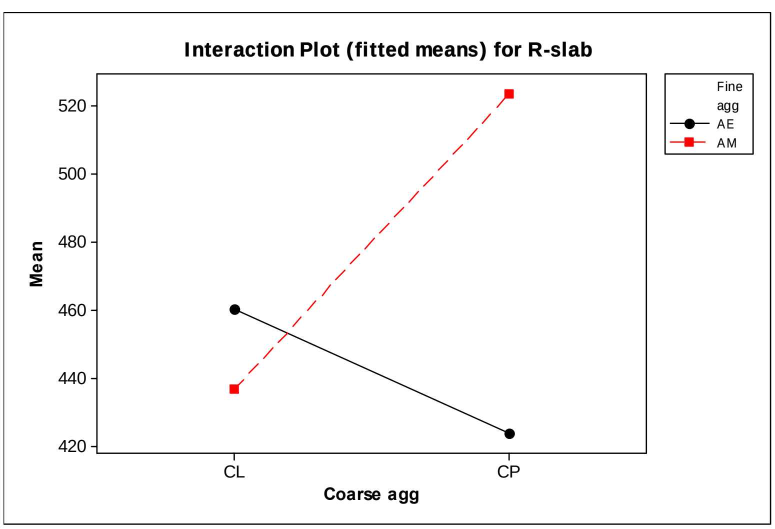


Figure C-58. Interaction plot.

Regression Analysis: R-slab versus R-fine, R-coarse, R-fine x R-coarse

```
The regression equation is
R-slab = - 13 + 24.7 R-fine + 18.9 R-coarse - 42.0 R-fine x R-coarse


Predictor               Coef  SE Coef      T      P  Likely ≠ 0 at α = 5%
Constant               -12.9    104.1  -0.12  0.902             no
R-fine                24.678    3.253   7.59  0.000            yes
R-coarse              18.893    2.669   7.08  0.000            yes
R-fine x R-coarse    -41.959    5.875  -7.14  0.000            yes


S = 25.8094   R-Sq = 71.2%   R-Sq(adj) = 68.5%


Analysis of Variance

Source          DF     SS     MS      F      P
Regression       3  52650  17550  26.35  0.000
Residual Error  32  21316    666
Total           35  73966


Source             DF  Seq SS
R-fine              1   12996  (explains 18% of the variability in slab reflectance)
R-coarse            1    5675  (explains  8% of the variability in slab reflectance)
R-fine x R-coarse   1   33979  (explains 46% of the variability in slab reflectance


Unusual Observations

Obs  R-fine  R-slab     Fit  SE Fit  Residual  St Resid
  7     271  474.00  423.89    8.60     50.11     2.06R
 10     271  525.00  460.22    8.60     64.78     2.66R
 11     271  515.00  460.22    8.60     54.78     2.25R

R denotes an observation with a large standardized residual.
```

Figure C-59. Regression analysis.

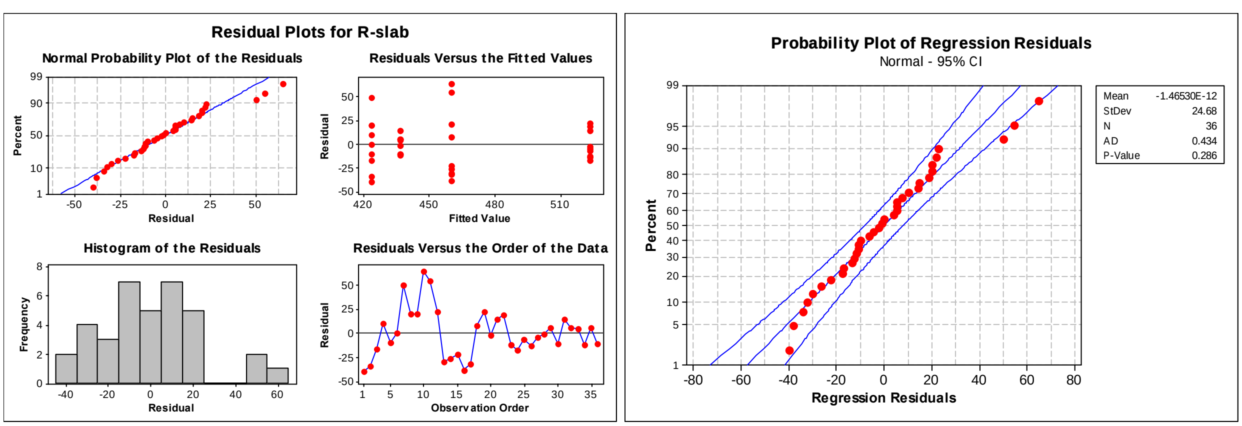


Figure C-60. The regression assumptions are met because the residuals are normally distributed (shown in the normal probability plot), and they are independent, have a mean of zero, and have constant variance (shown in the residual plot).