Evaluation of Retro-Reflective Beads to Increase Airport Surface Marking Conspicuity

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16. Abstract
Manufacturers have postulated that retro-reflective beads that have a higher index of refraction increase the conspicuity of paint markings and, thus, would aid in the prevention of runway incursions. The purpose of this project was to determine the adequacy of various types of retro-reflective beads that are used to increase the conspicuity of painted markings when applied to airport surface markings. The increased conspicuity could assist in the prevention of runway incursions.

Five types of retro-reflective beads were evaluated: three are currently approved by the Federal Aviation Administration (FAA) for use on airfield markings, as indicated in FAA Advisory Circular 150/5370-10D and two are the newly proposed retro-reflective beads. The beads were applied to standard paint on three types of airport pavement surfaces: hot-mix asphalt (HMA), Portland cement concrete (PCC), and aged HMA. Three test sites were chosen. Test Site One was located inside the FAA William J. Hughes Technical Center National Airport Pavement Test Facility on new HMA. Test Site Two was located at the FAA William J. Hughes Technical Center Aircraft Parking Apron on aged PCC surface. Test Site Three was on Taxiway Bravo at the Atlantic City International Airport, which is comprised of aged HMA. This evaluation covered a 1-year period starting in August 2008.

This research validates previous research performed on Type I, Type III, and Type IV retro-reflective beads. No previous research was performed on the two newly proposed retro-reflective beads.

The initial application tests concerning coverage, water, and pull-off strength were deemed successful.

On new HMA, the test marking with Type IV retro-reflective beads remained conspicuous for the longest period of time. Type I, Type III, and Manufacturer B retro-reflective beads remained conspicuous for approximately half that time, and Manufacturer A for approximately one-quarter of the time.

All the approved retro-reflective beads proved suitable for use on aged HMA and aged PCC over a 1-year period. The proposed retro-reflective beads from Manufacturer A and Manufacturer B also proved suitable for use on aged HMA and aged PCC.

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LIST OF ACRONYMS

AC	Advisory Circular
ACY	Atlantic City International Airport
CIE	Commission on Illumination
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
HMA	Hot-mix asphalt
ICAO	International Civil Aviation Organization
IOR	Index of refraction
mil	Millimeter
NAPTF	National Airport Pavement Test Facility
NAPTV	National Airport Pavement Test Vehicle
PCC	Portland cement concrete
psi	Pounds per square inch

EXECUTIVE SUMMARY

Manufacturers have postulated that retro-reflective beads that have a higher index of refraction will increase the conspicuity of paint markings and, thus, would aid in the prevention of runway incursions. The purpose of this project was to determine the adequacy of various types of retro-reflective beads that are used to increase the conspicuity of painted markings when applied to airport surface markings. The increased conspicuity could help prevent runway incursions.

Five types of retro-reflective beads were evaluated. Three of which are currently approved by the Federal Aviation Administration (FAA) for use on airfield markings, as indicated in FAA Advisory Circular 150/5370-10D, and two newly proposed retro-reflective beads. The beads were applied to standard paint on three types of airport pavement surfaces: hot-mix asphalt (HMA), Portland cement concrete (PCC), and aged HMA. Three test sites were chosen. Test Site One was located inside the FAA William J. Hughes Technical Center National Airport Pavement Test Facility on new HMA. Test Site Two was located at the FAA William J. Hughes Technical Center Aircraft Parking Apron on aged PCC surface. Test Site Three was on Taxiway Bravo of the Atlantic City International Airport, which is comprised of aged HMA. The marking material was placed in July 2008, and the evaluation covered a 1-year period starting in August 2008.

Chromaticity, retro-reflectivity, adherence strength, and friction characteristics were measured. Most measurements were taken on a monthly basis.

This research validates previous research performed on Type I, Type III, and Type IV retro-reflective beads. No previous research was performed on the two newly proposed retro-reflective beads.

The initial application tests concerning coverage, water, and pull-off strength were deemed successful.

On new HMA, the test marking with Type IV retro-reflective beads remained conspicuous for the longest period of time. Type I, Type III, and Manufacturer B retro-reflective beads remained conspicuous for approximately half that time, and Manufacturer A remained conspicuous for approximately one-quarter of the time.

All the approved retro-reflective beads proved suitable for use on aged HMA and aged PCC over a 1-year period. The proposed retro-reflective beads from Manufacturer A and Manufacturer B also proved suitable for use on aged HMA and aged PCC.

INTRODUCTION

PURPOSE.

The purpose of this project was to evaluate currently available retro-reflective beads as an aid to increase the conspicuity of painted airport surface markings. This increased conspicuity helps prevent runway incursions. To determine this, a variety of tests were performed on retro-reflective beads to determine their properties of chromaticity, retro-reflectivity, friction characteristics, and adherence to the airport surface.

BACKGROUND.

Manufacturers have postulated that retro-reflective beads that have a higher index of refraction (IOR) will increase the conspicuity of paint markings and, thus, aid in the prevention of runway incursions. Past research has shown that to be true after initial application; however, the retro-reflectivity of markings with higher IOR beads decreases quickly when compared to markings with lower IOR beads during the useful life of the marking. Manufacturers of the higher IOR beads recently indicated that improvements have been made concerning the beads' ability to maintain their retro-reflectivity over time.

Retro-reflective beads provide an effective means to highlight airfield pavement markings for operators (aircraft and ground vehicles) when maneuvering on an airport surface. This can be especially useful at night, during low-visibility conditions, or during weather conditions that leave the surface wet. The Federal Aviation Administration (FAA) requires retro-reflective beads to be used in airfield pavement markings on runway holding positions, threshold bar, threshold lines, designation numbers, centerlines, touchdown zone, and aiming point markings. Retro-reflective beads are also required on taxiway centerlines, movement, and nonmovement boundary lines, and surface position markings.

Five types of retro-reflective beads were evaluated. There are three types of retro-reflective beads currently approved by the FAA for use on airfield markings, as indicated in FAA Advisory Circular (AC) 150/5370-10D [1]. These retro-reflective beads are further detailed in Federal Specification TT-B-1325D as Type I (1.5 IOR) low-index, recycled retro-reflective bead, Type III (1.9 IOR) high-index virgin glass bead, and Type IV (1.5 IOR) low-index, direct-melt glass. Type I beads have less density, roughly 1570 grams per liter, and are commonly referred to as highway beads, while Type III (referred to as airport beads) and Type IV beads have a larger density, roughly 2670 grams per liter. Two newly proposed retro-reflective beads were also evaluated for their effectiveness in increasing the conspicuity of markings.

SCOPE.

The marking material was placed in July 2008 and the evaluation period for this project was 1 year, starting in August 2008. For this evaluation, Type I, Type III, Type IV, and two newly proposed retro-reflective beads were tested. Two manufacturers, hereafter referred to as Manufacturer "A" and Manufacturer "B," provided the newly proposed retro-reflective beads for evaluation.

OBJECTIVE.

The objective of this project was to determine the adequacy of five types of retro-reflective beads currently available to increase the conspicuity of painted airport surface markings over their useful life.

RELATED DOCUMENTATION.

- ASTM D 2177-01, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers."
- DOT/FAA/AR-TN96/74, "Follow-On Friction Testing of Retro-Reflective Glass Beads," July 1996.
- DOT/FAA/CT-94/119, "Evaluation of Alternative Pavement Marking Materials," January 1995.
- DOT/FAA/CT-94/120, "Evaluation of Retro-Reflective Beads in Airport Pavement Markings," December 1994.
- AC 150/5320-12C Change 8, "Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces," February 2007.
- AC 150/5340-1J Change 2, "Standards for Airport Markings," June 2008.
- ICAO Annex 14, Volume I, "Aerodrome Design and Operation," 4th edition, July 2004.
- Specification TT-B-1325D, "Beads (Glass Spheres) Retro-Reflective," August 2007.
- Specification TT-P-1952E, "Paint, Traffic and Airfield Marking, Waterborne," August 2007.

EVALUATION APPROACH

Five different types of retro-reflective beads were installed on three different airport pavement surfaces. Markings were also installed without retro-reflective beads to serve as a baseline.

The five types of retro-reflective beads tested during this project were:

- Type I (1.5 IOR) low-index, recycled glass bead (fire-polished process).
- Type III (1.9 IOR) high-index virgin glass bead.
- Type IV (1.5 IOR) low-index, direct-melt glass.

- Manufacturer A—Bead with dry-performing (1.7 IOR) and wet-performing (2.3 IOR) microcrystalline ceramic beads embedded on a center core.

- Manufacturer B—Bead with premium (1.9 IOR) glass beads and a solid glass bead core.

The specific questions to be answered to meet the objective of this project were:

1. Does the chromaticity of each bead type remain in the acceptable range for the duration of the test per DOT/FAA/AR-TN03/22, "Development of Methods for Determining Airport Pavement Marking Effectiveness" [2]?

2. Does the retro-reflectivity of each bead type remain in the acceptable range for the duration of the test, per DOT/FAA/AR-TN03/22, "Development of Methods for Determining Airport Pavement Marking Effectiveness" [2]?

3. Does the tensile strength of the bond between the paint and surfaces tested remain in accordance with ASTM D 4541-02, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers" [3]?

4. Are the friction readings equal to standard waterborne paint with beads used in DOT/FAA/AR-02/128, "Paint and Bead Durability Study" [4]?

Three surface types were chosen for this evaluation: new hot-mix asphalt (HMA), aged Portland cement concrete (PCC), and aged HMA. These airport pavement surfaces were located at three test sites. The first test site was located inside the FAA William J. Hughes Technical Center National Airport Pavement Test Facility (NAPTF). This site allowed for testing to be done on new HMA. This added the benefit of providing wear data from aircraft operations. The second test site was located at the FAA William J. Hughes Technical Center Aircraft Parking Apron on aged PCC. The third test site was on Taxiway Bravo of the Atlantic City International Airport (ACY), which is comprised of aged HMA.

The retro-reflective beads were applied to the same Type III, specification TT-P-1952E, HD-21A high-build resin waterborne yellow paint material at an application depth of 14-mil wet film thickness (rate of 115 ft^2/gal). For Type I and III, 18-mil wet film thickness (rate of 90 ft^2/gal.) for Type IV per reference 1 and a 25-mil wet film thickness (rate of 65 ft^2/gal), per manufacturers A and B recommendations.

The color yellow was selected for this evaluation since yellow is the color used for airport taxiway systems, such as holding position markings, which are important in preventing runway incursions. The marking material was placed in July 2008, and the evaluation covered a 1-year period starting in August 2008. In July 2008, the FAA Airport Safety Technology R&D Sub-Team monitored the installation of the retro-reflective beads and waterborne paint material to verify that the installation by an airport surface marking paint contractor was a "typical" beaded paint marking installation.

TEST SITE ONE.

Test Site One was located inside the FAA William J. Hughes Technical Center NAPTF. This fully enclosed instrumented test track is 900′ long by 60′ wide and is designed to accelerate the wear on runway materials from aircraft operations to determine useful life of various materials. During this retro-reflective bead project, the National Airport Pavement Test Vehicle (NAPTV), as shown in figure 1, was configured to simulate the taxi loading of a Boeing 747 and 777 aircraft. Using this site added the benefit of providing accelerated operations and provided wear data from two different aircraft.

Figure 1. National Airport Pavement Test Vehicle

Six yellow test edge line markings were applied on new HMA. Each edge line was 12″ wide x 6′ long. Table 1 shows test marking number, type of bead (if any), type of marking, and paint thickness. Figure 2 shows a representation of Test Site One, while figure 3 shows the application of the test markings at Test Site One on new HMA.

Table 1. Test Site One on New HMA

Marking Number	Type of Bead	Type of Marking	Paint Thickness (mil)
1	No bead	12″ x 6′ edge line	14
2	Type I	12″ x 6′ edge line	14
3	Type III	12″ x 6′ edge line	14
4	Type IV	12″ x 6′ edge line	18
5	Manufacturer A	12″ x 6′ edge line	25*
6	Manufacturer B	12″ x 6′ edge line	25*

*Manufacturer’s recommendation

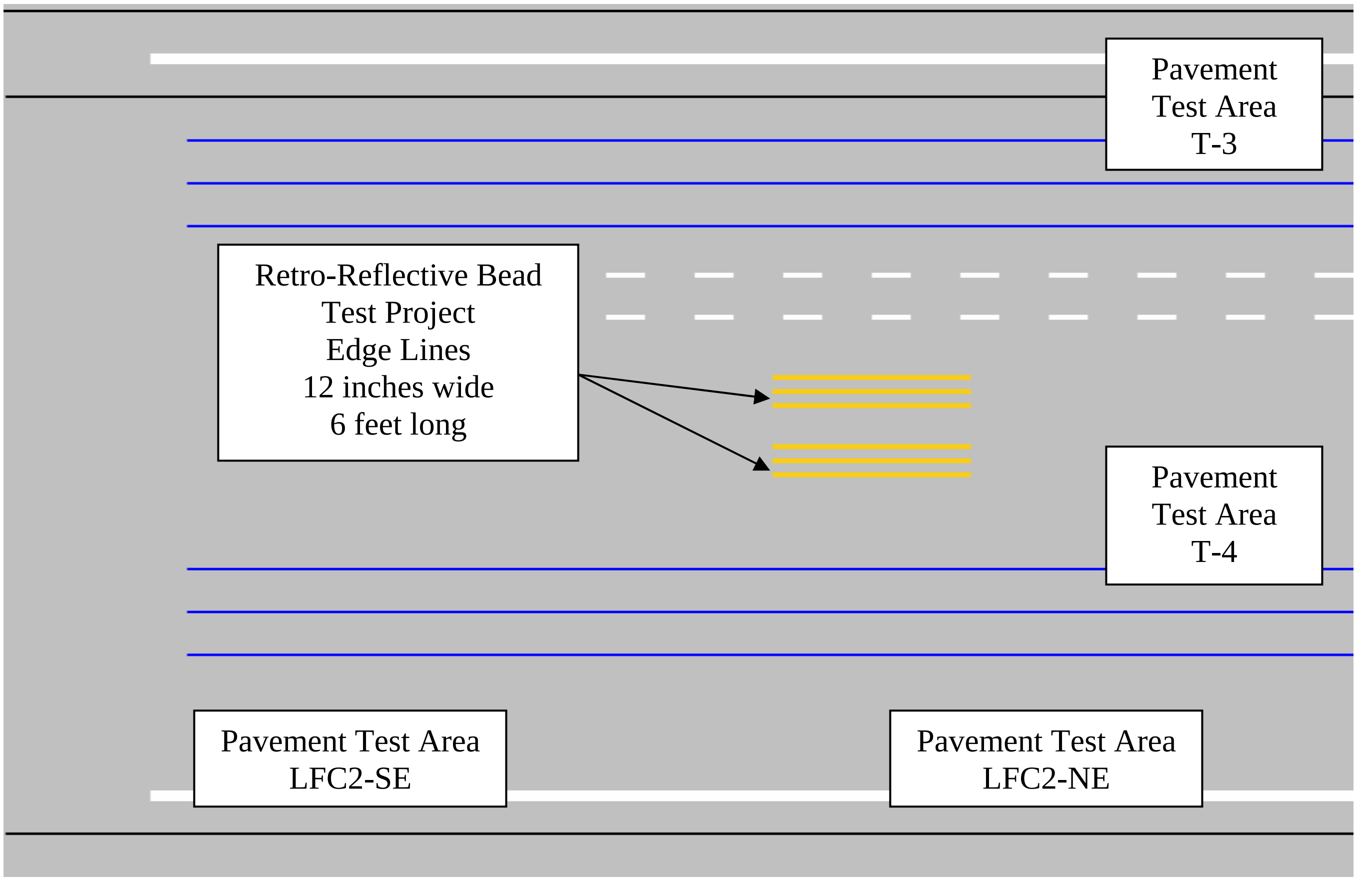

Figure 2. Test Site One Inside the FAA William J. Hughes Technical Center NAPTF

Figure 3. Application of Edge Lines on new HMA at Test Site One
Inside the FAA William J. Hughes Technical Center NAPTF

Figure 4 shows an airport diagram indicating the locations of Test Site Two and Test Site Three.

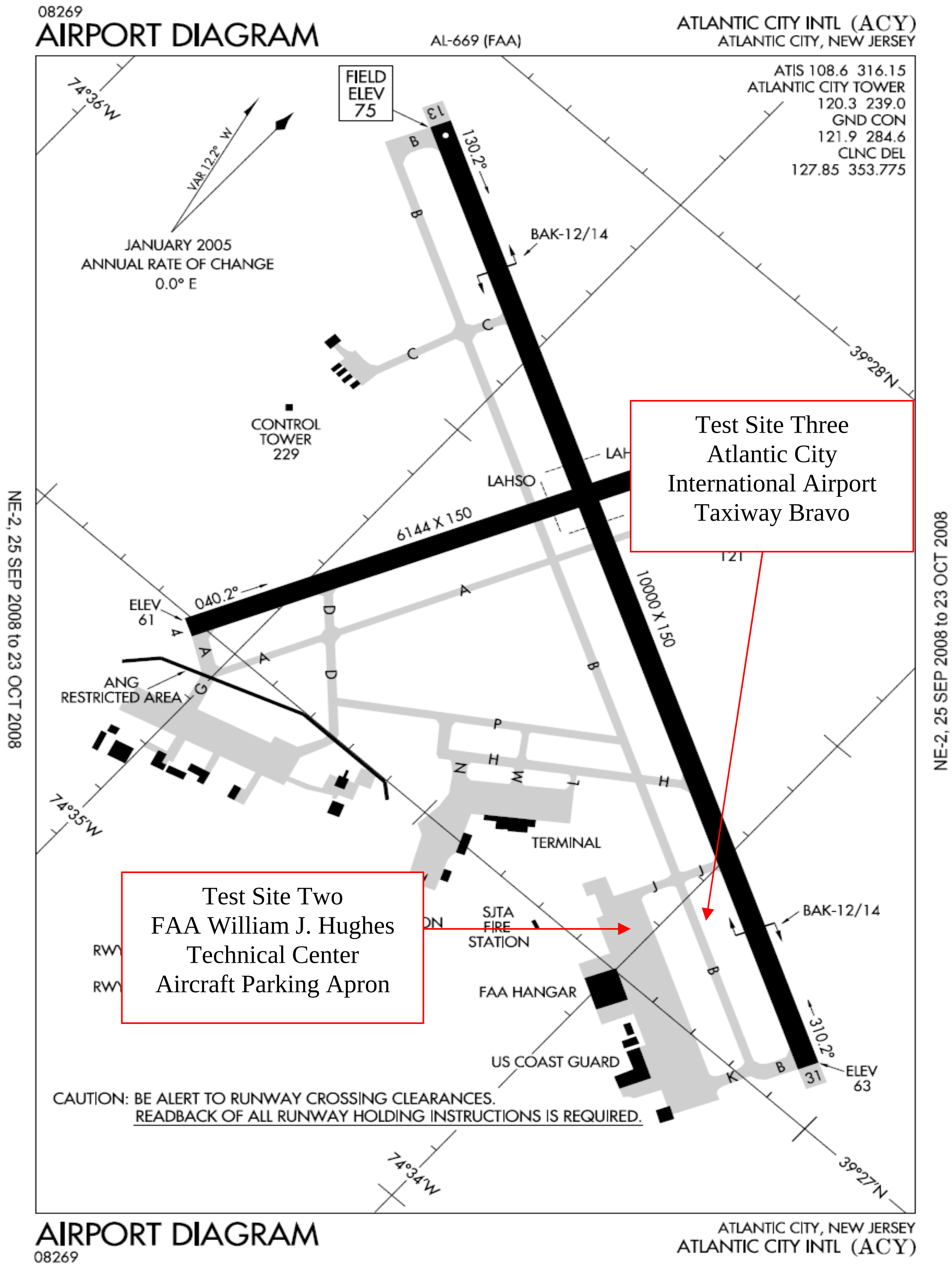

Figure 4. Airport Diagram of ACY Airport Showing Test Sites Two and Three

TEST SITE TWO.

Test Site Two was located on the FAA William J. Hughes Technical Center Aircraft Parking Apron. Six yellow edge lines, each 12″ wide x 6′ long, and six yellow test markings, 18″ wide x 150′ long, were applied on aged PCC. The 18″ wide x 150′ long test markings will be referred to from here on as friction lines. Table 2 shows the test marking number, type of bead (if any), type of marking, and paint thickness.

Table 2. Test Site Two on Aged PCC

Marking Number	Type of Bead	Type of Marking	Paint Thickness (mil)
7	No bead	12″ x 6′ edge line	14
8	Type I	12″ x 6′ edge line	14
9	Type III	12″ x 6′ edge line	14
10	Type IV	12″ x 6′ edge line	18
11	Manufacturer A	12″ x 6′ edge line	25*
12	Manufacturer B	12″ x 6′ edge line	25*
13	No bead	18″ x 150′ friction line	14
14	Type I	18″ x 150′ friction line	14
15	Type III	18″ x 150′ friction line	14
16	Type IV	18″ x 150′ friction line	18
17	Manufacturer A	18″ x 150′ friction line	25*
18	Manufacturer B	18″ x 150′ friction line	25*

*Manufacturer’s recommendation

Figure 5 shows the edge and friction lines at Test Site Two on the FAA William J. Hughes Technical Center Aircraft Parking Apron. Six 12″ x 6′ edge lines were applied, as shown in figure 6, and six 18″ x 150′ friction lines were applied, as shown in figure 7.

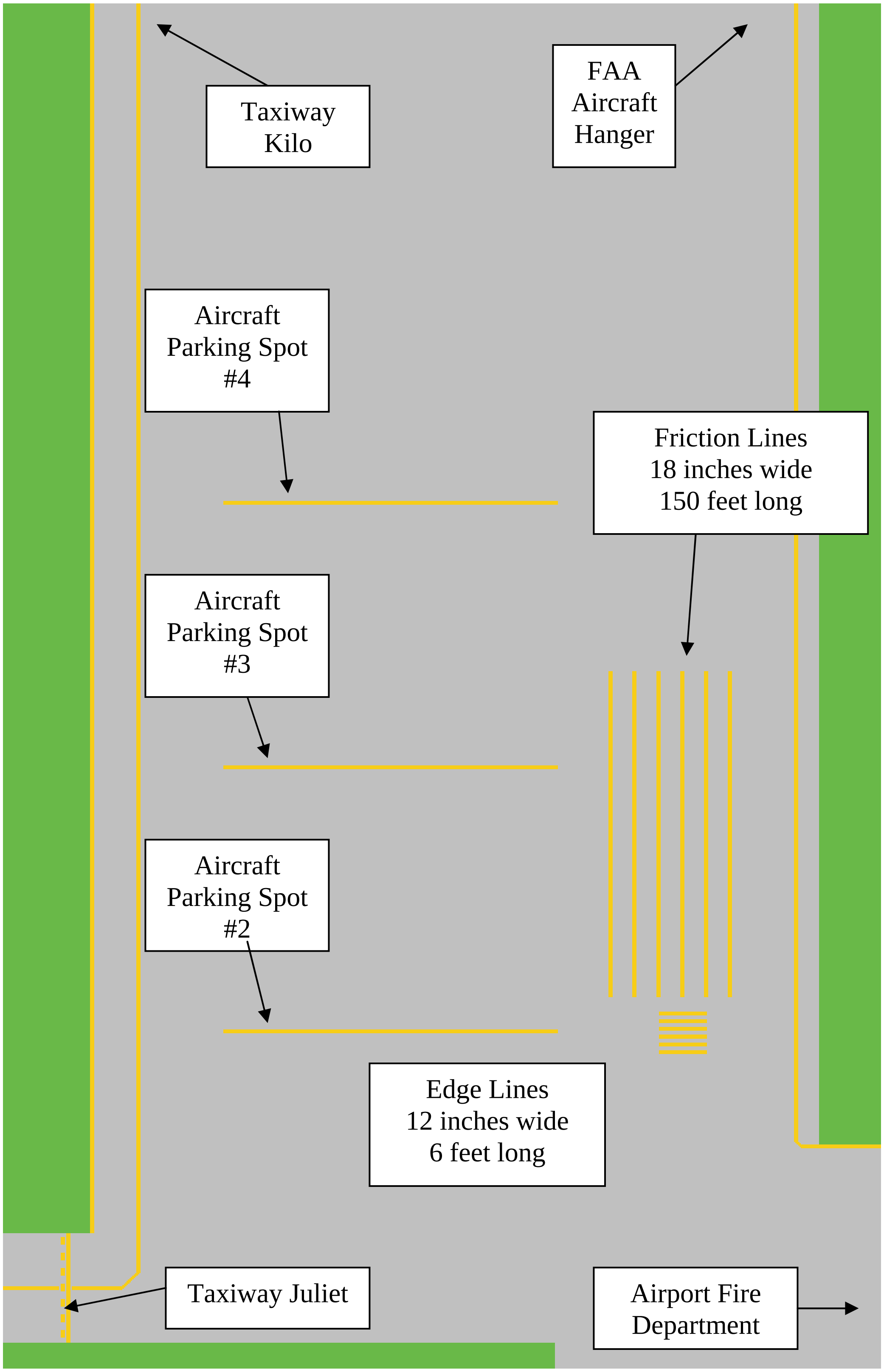

Figure 5. Test Site Two Located on the FAA William J. Hughes Technical Center Aircraft Parking Apron

Figure 6. Applying 12″ x 6′ Edge Lines on Aged PCC at Test Site Two

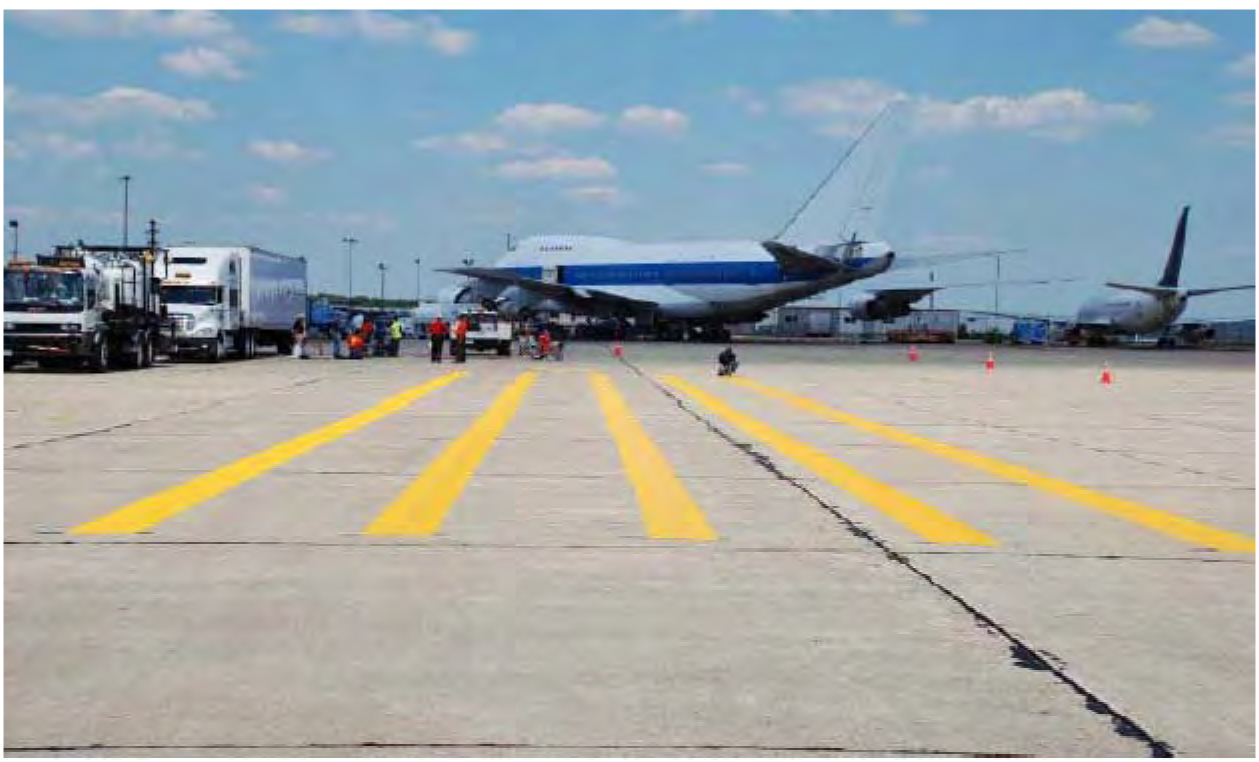

Figure 7. Applying 18″ x 150′ Friction Lines on Aged PCC at Test Site Two

TEST SITE THREE.

Test Site Three was located on Taxiway Bravo of ACY. Twelve yellow test markings, six 12″ wide x 6′ long edge lines and six 18″ wide x 150′ long friction lines, were applied on aged HMA. This site was chosen so each test marking would be subjected to the normal conditions on an airport environment. ACY is used by commercial aircraft (A319, B-717, and B-737), general aviation aircraft, and military F-16 fighter aircraft. Table 3 shows test marking number, type of bead (if any), type of marking, and paint thickness.

Table 3. Test Site Three on Aged HMA

Marking Number	Type of Bead	Type of Marking	Paint Thickness (mil)
19	No bead	12″ x 6′ edge line	14
20	Type I	12″ x 6′ edge line	14
21	Type III	12″ x 6′ edge line	14
22	Type IV	12″ x 6′ edge line	18
23	Manufacturer A	12″ x 6′ edge line	25*
24	Manufacturer B	12″ x 6′ edge line	25*
25	No bead	18″ x 150′ friction line	14
26	Type I	18″ x 150′ friction line	14
27	Type III	18″ x 150′ friction line	14
28	Type IV	18″ x 150′ friction line	18
29	Manufacturer A	18″ x 150′ friction line	25*
30	Manufacturer B	18″ x 150′ friction line	25*

* Manufacturer’s recommendation

Figure 8 shows the edge and friction lines at Test Site Three. Figure 9 shows the 12″ x 6′ edge lines, and the 18″ x 150′ friction lines are shown in figure 10.

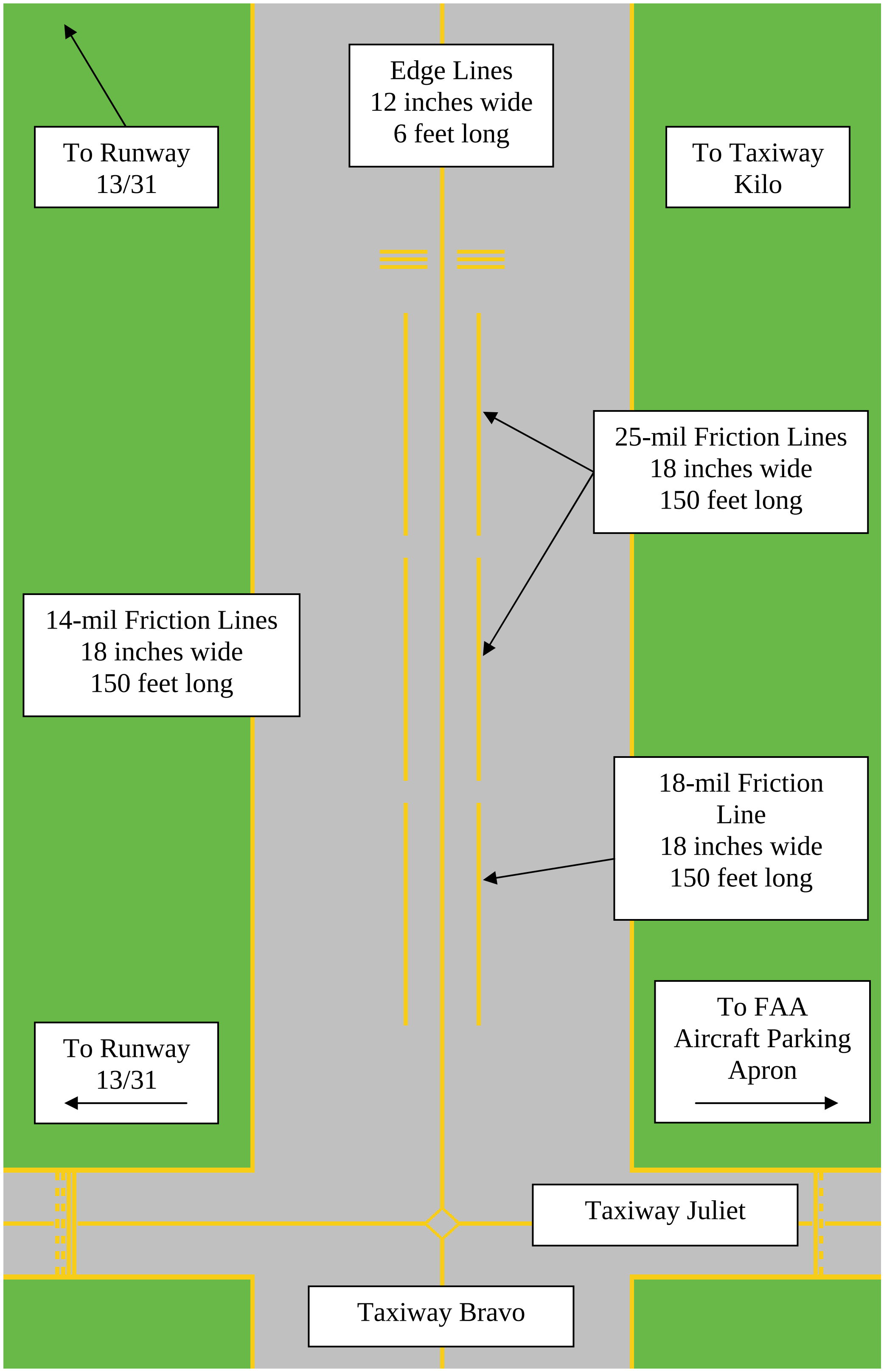

Figure 8. Edge and Friction Lines at Test Site Three

Figure 9. Applying 12″ x 6′ Edge Lines on Aged HMA at Test Site Three
Using a Delta LTL-X Retrometer

Figure 10. Applying 18″ x 150′ Friction Lines on Aged HMA at Test Site Three

APPLICATION TESTS.

After the initial application, the markings were subjected to three tests to ensure they were installed properly. These application tests consisted of coverage tests, water tests, and a pull-off strength test.

These initial application tests were critical. The test would not have continued if any of the application tests failed.

COVERAGE TEST. This test determined whether or not the marking had adequate coverage. Issues such as paint cracking, peeling, and uniformity of coverage of the entire test marking were observed. A grid of one-hundred squares of transparent material, each 1″ by 1″, were used as a tool for a quantitative measure of the specified percentage of coverage. The threshold pass/fail limit for coverage was determined to be 50%, because at less than this percentage, the pavement marking becomes difficult to recognize what the marking represents.

To perform the test, a 10″ x 10″ grid was placed on the test marking to be evaluated. The squares without paint were counted, giving a percentage of coverage. For example, if 3 of the 100 squares on the grid do not have paint, there was 97% coverage. Figure 11 shows the grid used for the coverage test.

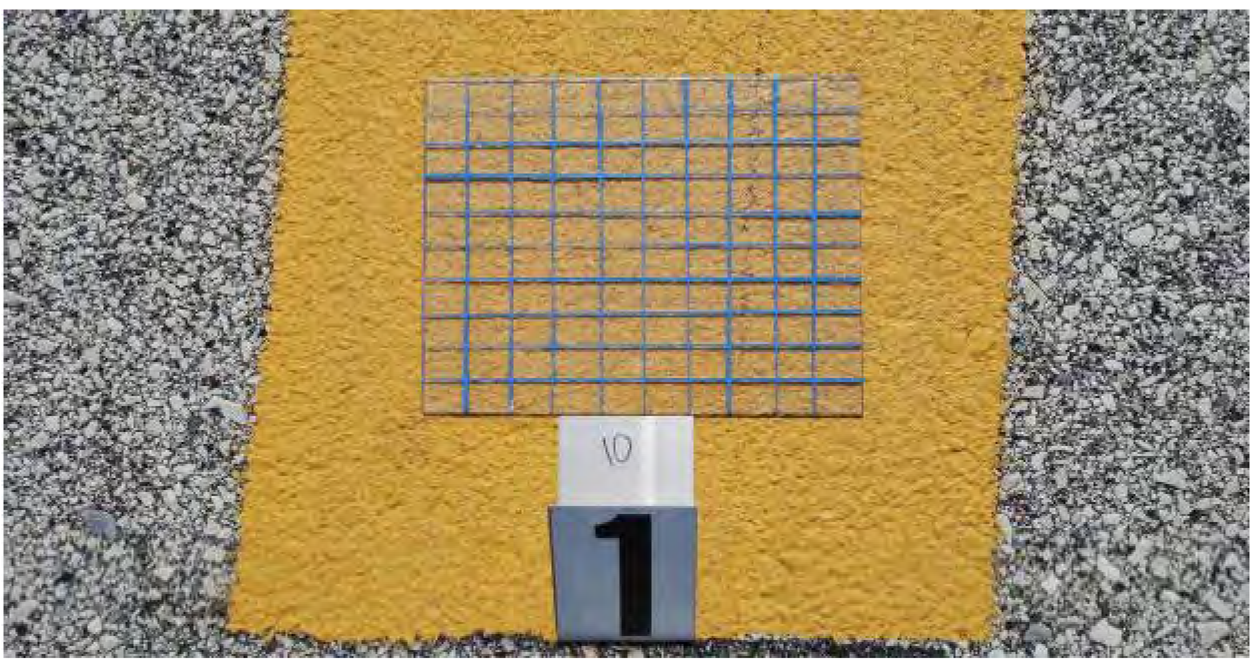

Figure 11. The 10″ x 10″ Coverage Test Grid

WATER TEST. A water test was conducted in compliance with ASTM standards. Using a Skidabrader Out-Flow Meter (figure 12), the dynamic permeability and hydrodynamic drainage characteristics of the surface were measured in accordance with ASTM E 2380-05 [5]. This procedure demonstrated the amount of time it took for a known quantity of water, under gravitational pull, to escape through the voids in the pavement surface. A faster escape time indicated a thinner film of water may have existed between a tire and the pavement surface.

Figure 12. Skidabrader Out-Flow Meter

A Delta LTL-X Retrometer was used (figure 9), in accordance with ASTM E 2176-01 [6], to measure the coefficient of retro-reflected luminance of pavement markings during continuous wetting (simulated rain). This test simulated continuous wetting or rain on pavement markings to observe the retro-reflective readings during a rainfall and to determine if the pavement marking could be seen during a rain event.

The Delta LTL-X Retrometer was also used, in accordance with ASTM E 2177-01 [7], to measure the coefficient of retro-reflected luminance of pavement markings during wetness (after a period of rain). This test simulated a pavement marking after rainfall in which the pavement markings were still wet or were wet from dew or humidity. This test gave the retro-reflective readings after a rain, dew, or humidity event.

<u>PULL-OFF STRENGTH TEST</u>. The pull-off strength test was performed in accordance with ASTM D 4541-02 [3] to determine the tensile strength of the bond between the pavement marking material and the HMA or PCC. Using a Dyna-Meter Z-16 Pull-Off Tester (figure 13), a metal disc was glued to the test marking material and allowed to cure for 24 hours. The Tester was then connected to the disc via a draw bolt and was leveled via adjustable legs. The

instrument was turned on, and the crank was turned, which applied additional pounds per square inch (psi), until the metal disc separated from the pavement.

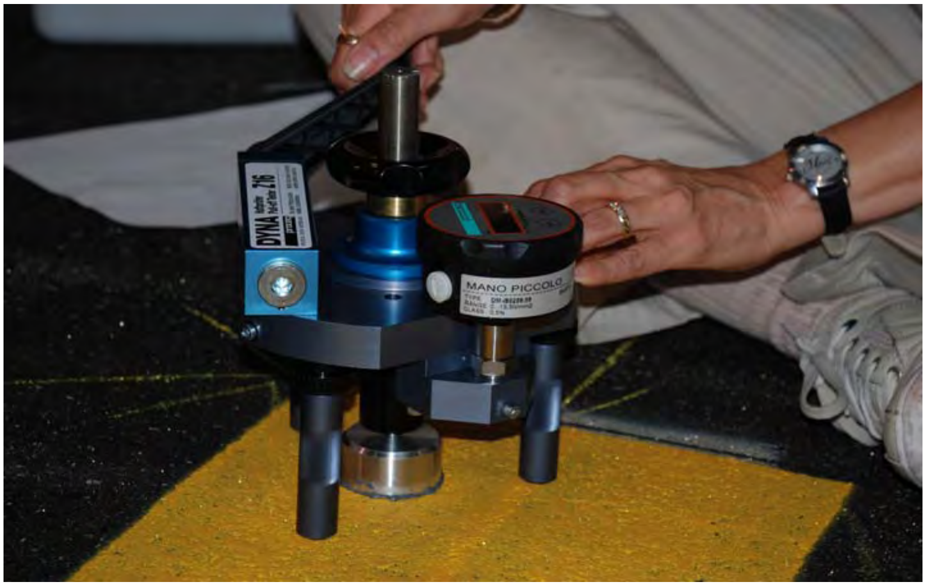

Figure 13. Dyna-Meter Z-16 Pull-Off Tester

If the test marking material separated from the pavement material, a cohesive failure occurred. If the pavement material separated with the marking material, an adhesive failure occurred. The tensile strength readings were measured in psi. The desired result is a pavement failure (adhesive) rather than a material marking failure (cohesive).

TESTS

After application at each test site, the test markings were subjected to chromaticity and retro-reflectivity tests to determine the baseline retro-reflectivity, friction test measurements to determine friction characteristics, and tests to determine conspicuity.

CHROMATICITY TEST.

Chromaticity tests were conducted using a Color-Guide 45/0 Spectro Guide. The readings were taken by placing the instrument on the pavement marking and activating the device. Two readings per marking were taken.

RETRO-REFLECTIVITY TEST.

Retro-reflectivity was measured with a Delta LTL-X Retrometer. The readings were taken by placing the instrument on the pavement marking and activating the device. Six readings per marking were obtained. Prior to each use, the instrument was calibrated and had an accuracy of ±5%.

FRICTION TEST.

Friction tests were conducted using a Saab Sarsys Friction Tester. Multiple friction test runs were conducted in September 2008 and then again in June 2009. The friction test runs were conducted at a speed of approximately 40 miles per hour. The friction test runs were at 30 psi on the ASTM E 1551-93a [8] smooth surface test tire with the self-watering system on, with 1 millimeter of water applied to the test tire during each run. Thirty-six friction test runs were conducted; three per marking. In addition, three baseline friction test runs were conducted on the bare pavement next to the markings at the beginning and end of each test.

SUBJECTIVE TEST.

Human subjects were used to determine if a marking was conspicuous. An evaluation questionnaire was administered that provided subjective data on the conspicuity of the test markings on aged PCC at Test Site Two.

DATA COLLECTION

The useful life of a test marking is complete when the test marking is no longer conspicuous, does not have retro-reflectivity, or is no longer the intended color. A previous paint marking study [1] conducted by the FAA Airport Safety Technology R&D Sub-Team determined that the recommended minimum retro-reflectivity for the color yellow was 70 $mcd/m^2/lx$. Reference 2 elaborates on this. Conformity to the standards set for chromaticity, retro-reflectivity, adhesion, and friction were major factors in arriving at this determination. Additional tests were conducted to ensure the retro-reflective beads were properly applied to the test markings. Data was collected for the duration of the tests.

CHROMATICITY TEST.

Color readings were taken with a Spectro Guide, which produces three coordinates (Y = depth, x = width, and y = height) for its readouts. The standard coordinate system CIE 1931 XYZ color space, created by the International Commission on Illumination (CIE), was used. The readings obtained were compared to the color coordinate boundaries for FAA in-service yellow. The boundaries of FAA in-service yellow are not the same as aviation yellow. The region for FAA in-service yellow is documented in appendix A of reference 2, “Development of Methods for Determining Airport Pavement Marking Effectiveness.” The readings were also charted on the CIE standard illuminant D_{65} chromaticity chart, as shown in figure 14. This chart has been modified to address the FAA in-service yellow used on airports. Color readings were collected after the initial application of the paint marking material and continued monthly thereafter for 1 year. Figure 15 shows chromaticity readings being taken.

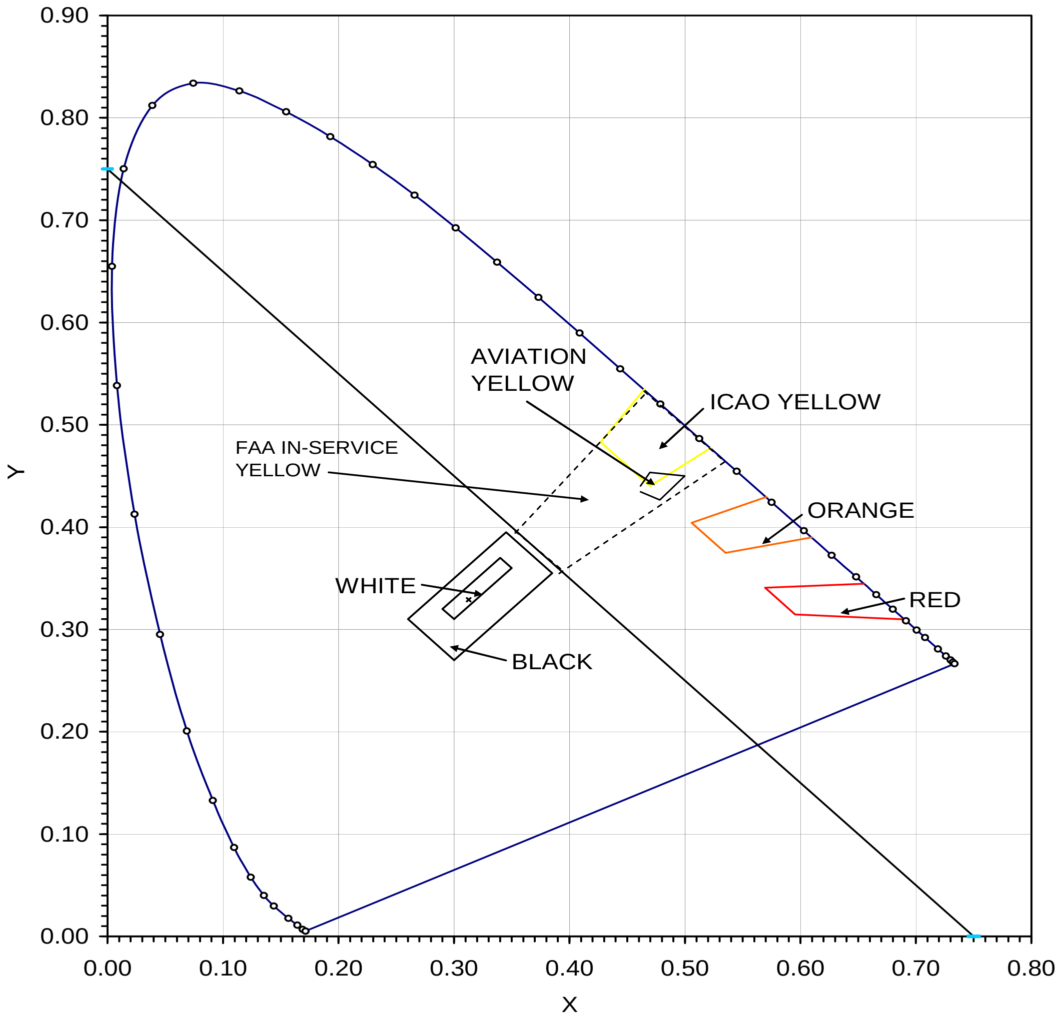

Figure 14. Sample CIE Standard Illuminant D_{65} Color Chart

Figure 15. An FAA Airport Safety Technology R&D Sub-Team Member Taking Chromaticity Readings

RETRO-REFLECTIVITY TEST.

The retrometer used in this evaluation produced millicandela per meter squared per lux readings. Currently, the FAA has no standard for retro-reflectivity limits. In a previous paint marking study [2] conducted by the FAA Airport Safety Technology R&D Sub-Team, it was determined that the recommended minimum retro-reflectivity for the color yellow was 70mcd/m^2/lx. The National Institute of Standards and Technology does not have a reference standard for retro-reflectometers. The 30-meter geometry for retro-reflectivity, which is the distance from the headlights to the pavement markings, is the standard used by the highway departments, as shown in figure 16. No standard has been developed for aircraft due to the variability of cockpit heights. Therefore, the highway department geometry was used.

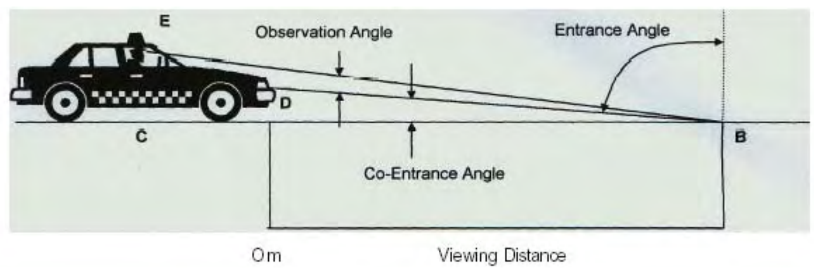

Figure 16. Thirty-Meter Geometry Measurement for Retro-Reflectivity

Using the retrometer, six readings per marking were taken by placing the instrument on the pavement marking and activating the device. Prior to each use, the instrument was calibrated. Readings were taken after the initial application of the paint marking, and then monthly thereafter for 1 year. Figure 17 shows retro-reflective readings being taken. (See appendix C for the readings.)

Figure 17. The FAA Airport Safety Technology R&D Sub-Team Members
Taking Retro-Reflectivity Readings

FRICTION TEST.

Using a Saab Sarsys Friction Tester, multiple friction test runs were conducted, as shown in figure 18. Tests were conducted at Test Site Two on aged PCC and at Test Site Three on aged HMA, where friction lines, 150′ long, were located. The friction test runs were conducted with a self-watering system on at a speed of approximately 40 miles per hour.

Figure 18. Saab Sarsys Friction Tester in Action

SUBJECTIVE TEST.

The FAA Airport Safety Technology R&D Sub-Team collected subjective data at night on the conspicuity of six test markings on aged PCC at Test Site Two. An evaluation questionnaire was filled out by each test subject after viewing each individual marking. Each test subject started from the same distance away from each test marking and moved toward each individual test marking until the test subject stated that it was visible and then continued until a point of conspicuity was achieved.

RESULTS

The evaluation of retro-reflective beads was conducted on three different airport pavement surfaces at separate sites at the FAA William J. Hughes Technical Center and Atlantic City International Airport. At the first site, the test markings were not subjected to weather conditions, but the test markings were installed on new HMA and were subjected to the NAPTV operations, which included collecting contaminates, such as rubber deposits. At the second and third sites, the test markings were subjected to various weather conditions on aged PCC and HMA, as well as actual aircraft operations, although not as many as in the NAPTF. The evaluation period for this project was 1 year, with monthly data collection commencing in August 2008 and ending in June 2009.

The ACY Air Traffic Control Tower recorded 89,435 aircraft operations between August 2008 and June 2009. A portion of these operations were on Test Site Three.

The NAPTV recorded 12,540 complete passes during the evaluation period or 1,140 operations per month simulating the main gear loading of a B-747 and a B-777. These operations included the area where test markings were installed.

Using the average monthly operations at Newark Liberty International Airport (EWR) of 265 for the B-747 and 755 for the B-777, for a total of 1140 simulated operations in the NAPTF, the equivalent extended data collection months were calculated for the new HMA test markings. Based on these calculations, the 11-month data collection period was equivalent to 24.6 months of actual airport operations.

COVERAGE TEST.

Using a 10″ x 10″ transparent grid, it was determined that all the test markings had 100% coverage. Table 4 shows the coverage test results of all three test sites. (Refer to appendix E for additional data.)

Table 4. Coverage Test Results

Bead Type	Test Site One New HMA (%)	Test Site Two Aged PCC (%)	Test Site Three Aged HMA (%)
No bead	100	100	100
Type I	100	100	100
Type III	100	100	100
Type IV	100	100	100
Manufacturer A	100	100	100
Manufacturer B	100	100	100

WATER TESTS.

DRAINAGE CHARACTERISTICS. In accordance with ASTM E 2380-05, the Skidabrader Out-Flow Meter was used to measure the time for a known quantity of water, under gravitational pull, to escape through the voids in the pavement surface. A faster escape time would indicate better traction between an aircraft tire and the pavement surface.

On new HMA, Manufacturer B beads showed the fastest drainage characteristics, while Type I beads showed the slowest. On aged HMA, Manufacturer B showed the fastest drainage characteristics, followed by Type IV and Manufacturer A. The slowest drainage characteristics were shown to be Type III. On aged PCC, Manufacturer A was shown to have the fastest drainage characteristics while Type I beads showed the slowest.

Table 5 shows a side-by-side comparison of the drainage characteristics at the three test sites. Figures 19, 20, and 21 illustrate the drainage characteristics of the test markings on new HMA, aged HMA, and aged PCC, respectively. (Refer to appendix B for additional data.)

Table 5. Skidabrader Test Results

Drainage Characteristics			
Bead Type	Test Site One New HMA (sec.)	Test Site Two Aged PCC (sec.)	Test Site Three Aged HMA (sec.)
No bead	8	7	7
Type I	13	11	5
Type III	11	7	6
Type IV	10	6	4
Manufacturer A	9	3	4
Manufacturer B	5	5	3

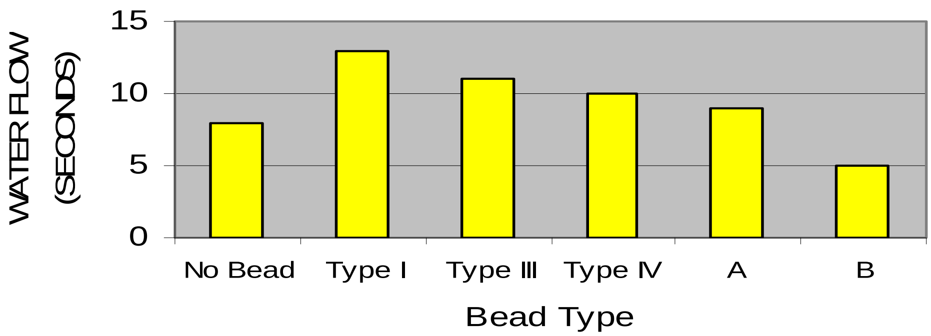

Figure 19. Test Site One Skidabrader Out-Flow Meter Test on New HMA

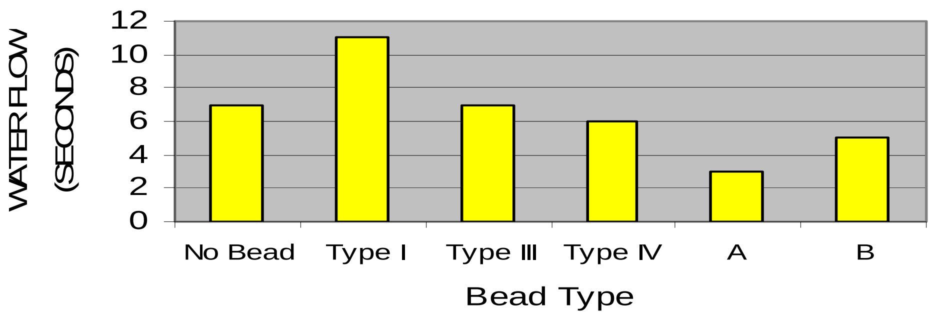

Figure 20. Test Site Two Skidabrader Out-Flow Meter Test on Aged PCC

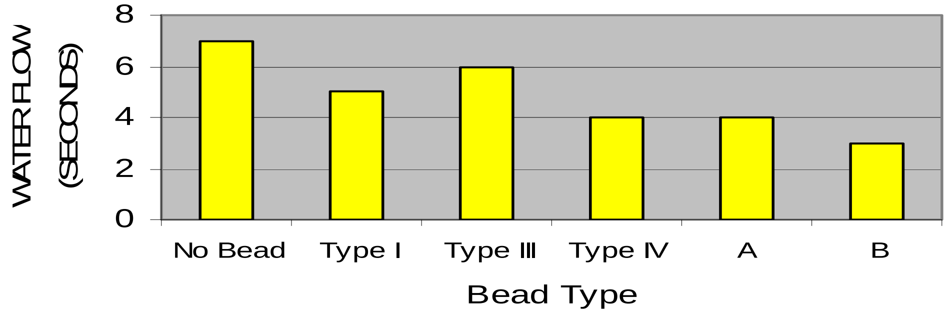

Figure 21. Test Site Three Skidabrader Out-Flow Meter Test on Aged HMA

CONTINUOUS WETTING TEST. Using a Delta LTL-X Retrometer, the retro-reflected luminance of the pavement markings in a continuous wetting condition (rain) was measured in accordance with ASTM E 2176-01 [6] to observe the retro-reflective readings during a rainfall. On new HMA inside the NAPTF, Manufacturer B had the highest retro-reflectivity readings during the test, followed closely by Manufacturer A, Type I, Type III, and Type IV beads. On aged HMA, Manufacturer A had the highest retro-reflectivity readings, and Type I had the lowest retro-reflectivity readings. On aged PCC, Manufacturer B had the highest retro-reflectivity readings, followed by Type III and Manufacturer A, with Type I and Type IV having the lowest retro-reflectivity readings.

Table 6 shows a side-by-side comparison of the retro-reflected luminance of the pavement surfaces at the three test sites. Figures 22, 23, and 24 illustrate the retro-reflected luminance of the test markings on new HMA, aged HMA, and aged PCC, respectively. (Refer to appendix B for additional data.)

Table 6. Continuous Wetting Test Results

Bead Type	Test Site One New HMA ($mcd/m^2/lx$)	Test Site Two Aged PCC ($mcd/m^2/lx$)	Test Site Three Aged HMA ($mcd/m^2/lx$)
No bead	9	11	11
Type I	8	11	12
Type III	8	26	13
Type IV	8	11	15
Manufacturer A	9	26	21
Manufacturer B	10	30	17

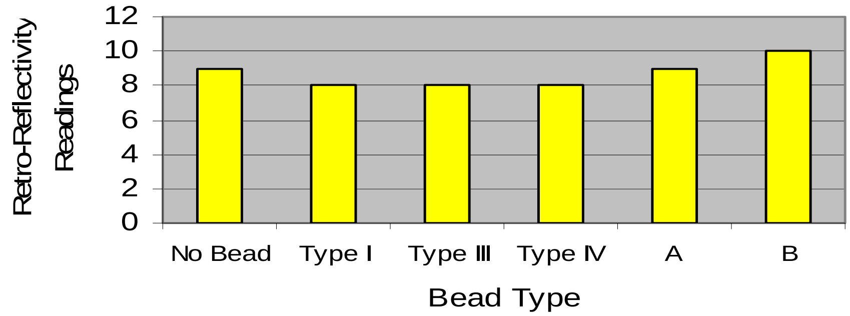

Figure 22. Test Site One Continuous Wetting Test on New HMA

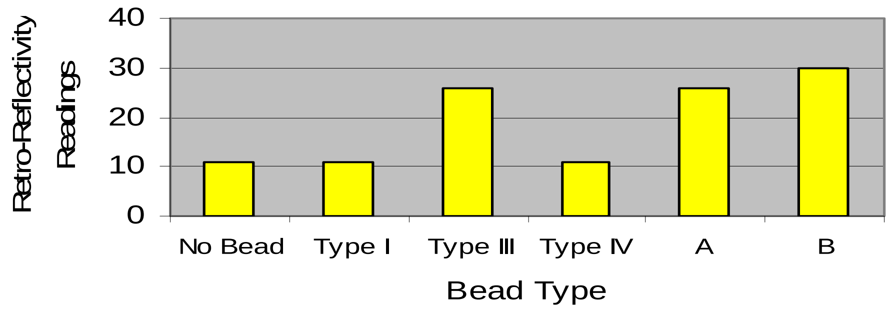

Figure 23. Test Site Two Continuous Wetting Test on Aged PCC

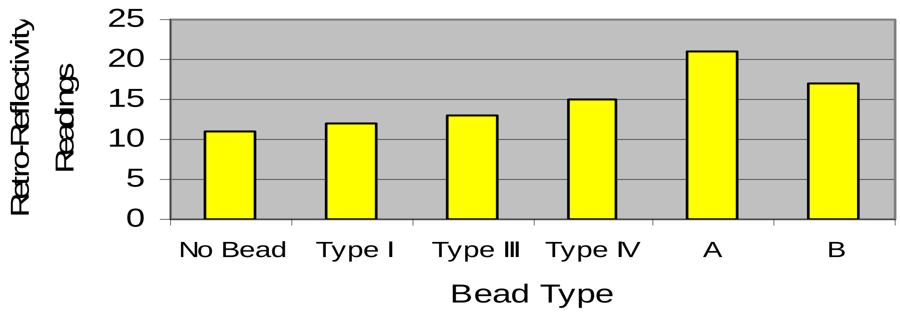

Figure 24. Test Site Three Continuous Wetting Test on Aged HMA

RECOVERY TEST. A Delta LTL-X Retrometer was also used to measure the coefficient of retro-reflected luminance of pavement markings in a standard condition of wetness (after a period of rain) in accordance with ASTM E 2177-01 [7]. This test simulates pavement markings when they are still wet after a rainfall or when they are wet from dew or humidity, looking for a recovery rate back to normal luminance.

Inside the NAPTF on new HMA, rubber contamination from the NAPTV lowered the retro-reflectivity readings. No test markings were able to recover to the retro-reflectivity level of a dry state in the allotted time of approximately 30 minutes. On aged HMA, Type III beads recovered the fastest, followed by Type I and Manufacturer B. Type IV and Manufacturer A failed to recover in the time allotted. On aged PCC, Manufacturer A recovered the fastest, followed by Type I, Type III, and Type IV beads, and Manufacturer B failed to recover in the allotted time.

Figures 25, 26, and 27 illustrate the recovery time of retro-reflected luminance of test markings on new HMA, aged HMA and aged PCC, respectively. (Refer to appendix B for additional data.)

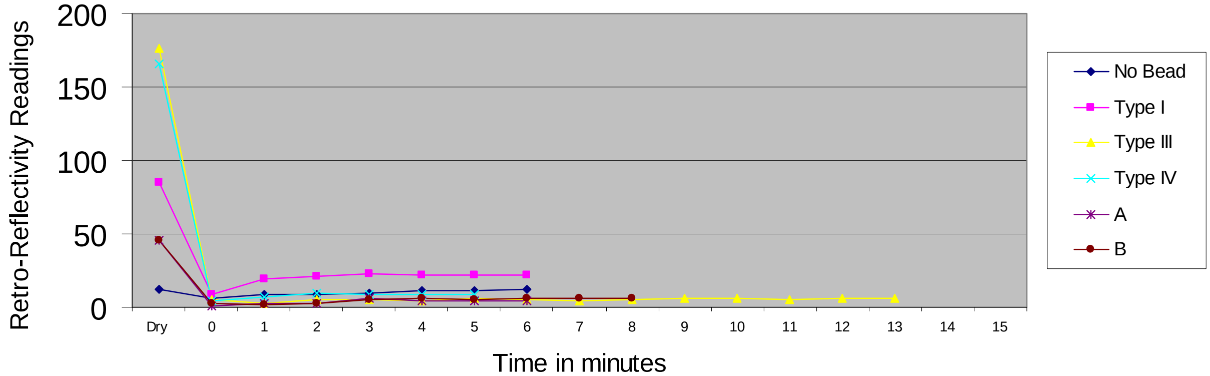

Figure 25. Recovery Test on New HMA

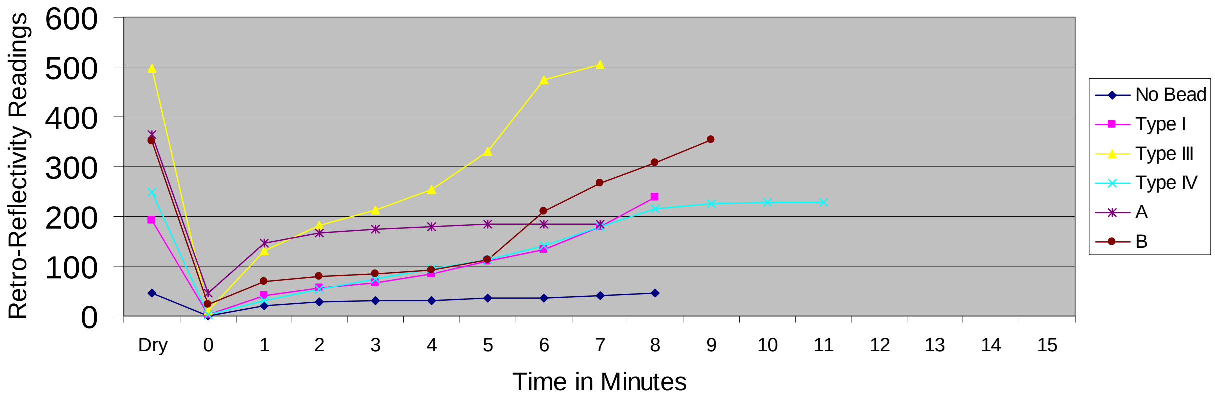

Figure 26. Recovery Test on Aged HMA

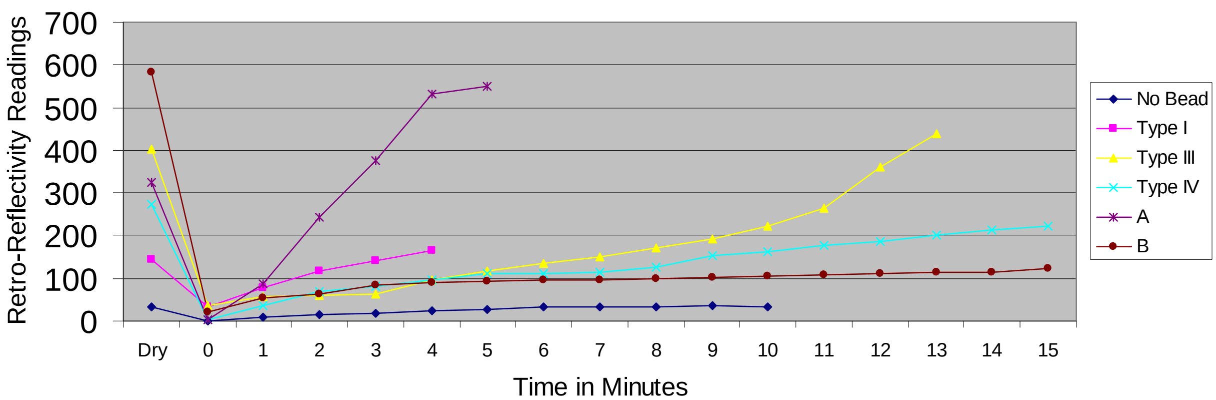

Figure 27. Recovery Test on Aged PCC

PULL-OFF STRENGTH TEST. Based on a previous study of Specification TT-P-1952D waterborne paint [4], yellow waterborne paint had an average tensile strength of 77 psi. All the beaded test markings on new HMA and aged PCC maintained a higher tensile strength than the average strength of 77 psi.

The test determines the greatest perpendicular force (psi) that a surface area can bear before a portion of the surface material is detached. When using this procedure to test paint adhesion, two results are considered: (1) if the paint pulls off the surface material, it is an adhesive failure at that psi and (2) if surface material is detached, the paint has passed at that psi value.

The test markings were tested on new HMA and aged PCC, as shown in table 7.

Table 7. Pull-Off Strength Test Results

Bead Type	Test Site One New HMA		Test Site Two Aged PCC		Test Site Three Aged HMA*	
	psi Rating	Pass or Fail	psi Rating	Pass or Fail	psi Rating	Pass or Fail
No Bead	123.3 psi	Pass	384.4 psi	Pass	---	---
Type I	121.8 psi	Pass	522.1 psi	Pass	---	---
Type III	117.5 psi	Pass	496.0 psi	Pass	---	---
Type IV	123.3 psi	Pass	308.9 psi	Pass	---	---
Manufacturer A	88.5 psi	Pass	272.7 psi	Adhesive failure	---	---
Manufacturer B	117.5 psi	Pass	188.5 psi	Adhesive failure	---	---

*Active airport taxiway; tests were not performed on this surface.

Initial application tests concerning coverage, water, and pull-off strength were acceptable. Therefore, chromaticity and retro-reflectivity tests were continued.

CHROMATICITY TEST.

On new HMA at Test Site One, all the test markings were within the defined FAA in-service aviation yellow region. (See appendix A for additional data.)

On aged PCC at Test Site Two, each bead type had 24 data points with only one data point falling outside the region for Type I, Type III, and Manufacturer B. (See appendix A and figures A-9, A-12, and A-14.) The remaining test markings were within the defined FAA in-service aviation yellow region.

On aged HMA at Test Site Three, all the test markings were within the defined FAA in-service aviation yellow region. (See appendix A for additional data.)

The chromaticity of all the test markings on new HMA, aged HMA, and aged PCC were within the acceptable range for FAA in-service yellow. (The CIE standard illuminant D_{65} chromaticity charts are located in appendix A of this report.) Table 8 provides a side-by-side comparison of the chromaticity readings for the bead types at each test site.

Table 8. Initial Chromaticity Readings July 2008

Bead Type	Test Site One New HMA	Test Site Two Aged PCC	Test Site Three Aged HMA
No bead	Acceptable	Acceptable	Acceptable
Type I	Acceptable	Acceptable	Acceptable
Type III	Acceptable	Acceptable	Acceptable
Type IV	Acceptable	Acceptable	Acceptable
Manufacturer A	Acceptable	Acceptable	Acceptable
Manufacturer B	Acceptable	Acceptable	Acceptable

RETRO-REFLECTIVITY TEST.

The recommended minimum for retro-reflectivity of the color yellow is 70 mcd/m^2/lx. The initial retro-reflectivity readings taken immediately after installation in July 2008 for all test markings containing beads were above the recommended minimum retro-reflectivity. Only the test markings with no beads fell below this number.

Using the average monthly operations at Newark Liberty International Airport (EWR) of 265 for the B-747 and 755 for the B-777, for a total of 1140 simulated operations in the NAPTF, the equivalent extended data collection months were calculated for the new HMA test markings. Based on these calculations, the 11-month data collection period was equivalent to 24.6 months of actual airport operations.

The readings from the first test month (August 2008) indicated that the retro-reflective bead with the highest reading was Type III at 599 mcd/m^2/lx. The Type I bead had the lowest reading at 199 mcd/m^2/lx.

After the equivalent of 11.2 months (5 months of EWR data) of operations, only Type IV beads were above the 70-mcd/m^2/lx baseline with a reading of 82 mcd/m^2/lx (table C-1). Manufacturer B was equal to the baseline with 70 mcd/m^2/lx and Manufacturer A had the lowest with 41 mcd/m^2/lx. After the equivalent of 15.6 months (7 months of EWR data), only Type IV beads remained above the 70-mcd/m^2/lx baseline with 98 mcd/m^2/lx. After the equivalent of 24.6 months (11 months of EWR data), Type IV beads dropped below the 70-mcd/m^2/lx baseline with a reading of 67 mcd/m^2/lx.

During the test period, the only markings that collected significant contaminants, such as rubber deposits, were the markings in the NAPTF. This explains the lower retro-reflectivity readings compared to the other airport surfaces.

Table 9 provides a side-by-side comparison of the retro-reflectivity readings for the bead types on the pavement surfaces at each test site.

Table 9. Initial Retro-Reflectivity Readings July 2008

Bead Type	Test Site One New HMA	Test Site Two Aged PCC	Test Site Three Aged HMA
No bead	22	48	70
Type I	88	163	122
Type III	364	538	419
Type IV	189	280	179
Manufacturer A	582	412	498
Manufacturer B	513	602	407

*Retro-reflectivity readings in mcd/m^2/lx.

Tables 10, 11, and 12 show the beginning, midpoint, and ending averages of retro-reflective readings for test markings on new HMA at Test Site One, aged PCC at Test Site Two, and aged HMA at Test Site Three, respectively. The percentage change of the retro-reflective readings from the start to the midpoint and from the midpoint to the end are also presented. Figures 28, 29, and 30 show charts of the beginning, midpoint, and ending averages of retro-reflective readings at each test site, respectively.

Table 10. Average Retro-Reflectivity Readings of Test Markings on New HMA

Marking Number	Bead Type	Start (August 2008) (mcd/m^2/lx)	Midpoint (January 2009)* (mcd/m^2/lx)	Percent Change From Start to Midpoint	Finish (June 2009)** (mcd/m^2/lx)	Percent Change From Midpoint to End
1	No bead	30	18	-40	19	+1
2	Type I	199	70	-65	46	-34
3	Type III	599	85	-86	55	-35
4	Type IV	356	119	-67	67	-44
5	Manufacturer A	352	34	-90	27	-21
6	Manufacturer B	367	61	-83	49	-20

*Equivalent to 13.4 months of operations.
**Equivalent to 24.6 months of operations.

Table 11. Average Retro-Reflectivity Readings of Test Markings on Aged HMA

Marking Number	Bead Type	Start (August 2008) (mcd/m²/lx)	Midpoint (January 2009) (mcd/m²/lx)	Percent Change From Start to Midpoint	End (June 2009) (mcd/m²/lx)	Percent Change From Midpoint to End
19	No bead	52	74	+30	31	-58
20	Type I	206	196	-5	144	-27
21	Type III	442	398	-10	145	-64
22	Type IV	211	233	+9	128	-45
23	Manufacturer A	259	257	-1	118	-54
24	Manufacturer B	222	272	-18	167	-39

Table 12. Average Retro-Reflectivity Readings of Test Markings on Aged PCC

Marking Number	Bead Type	Start (August 2008) (mcd/m²/lx)	Midpoint (January 2009) (mcd/m²/lx)	Percent Change From Start to Midpoint	End (June 2009) (mcd/m²/lx)	Percent Change From Midpoint to End
7	No bead	39	39	0	39	0
8	Type I	174	163	-6	170	+4
9	Type III	601	404	-33	347	-14
10	Type IV	363	336	-7	298	-11
11	Manufacturer A	303	334	+9	416	+20
12	Manufacturer B	510	634	+20	535	-16

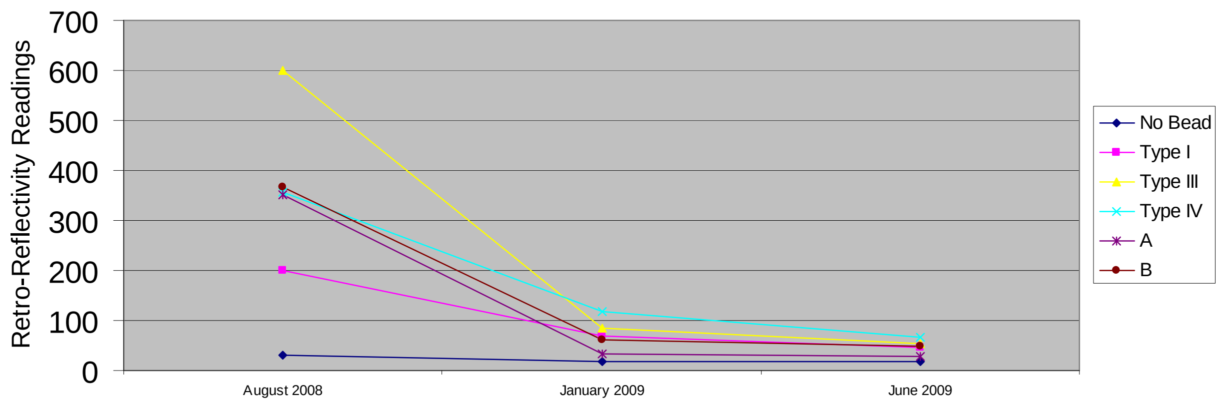

Figure 28. Average Retro-Reflectivity Readings of Test Markings on New HMA

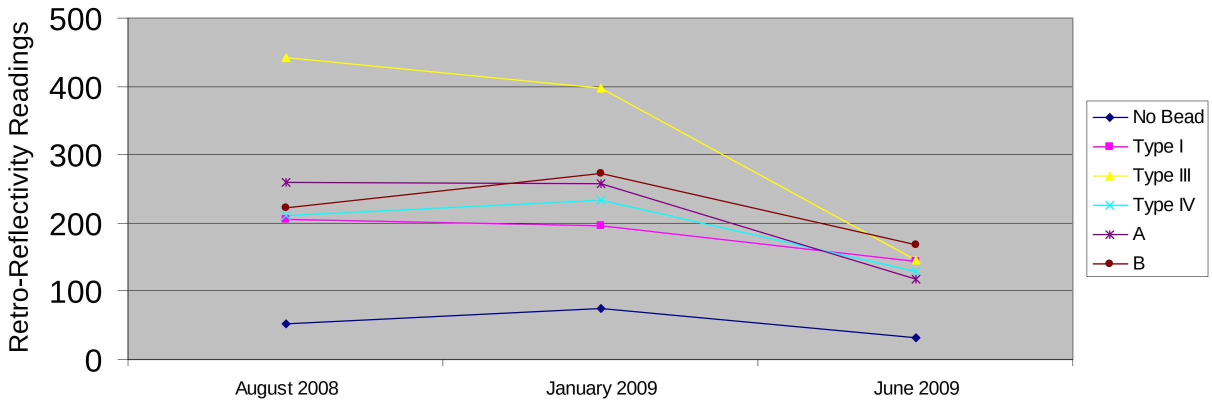

Figure 29. Average Retro-Reflectivity Readings of Test Markings on Aged HMA

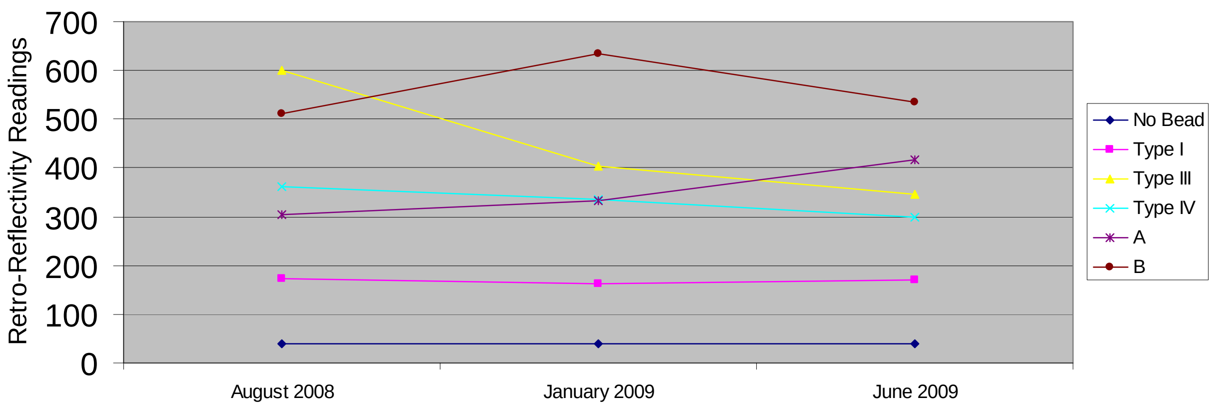

Figure 30. Average Retro-Reflectivity Readings of Test Markings on Aged PCC

On aged HMA, minor fluctuations occurred, but all beaded test markings remained above the 70-mcd/m^2/lx acceptability level for the test period. Fluctuations in the retro-reflectivity of the test markings on aged PCC also occurred and all test markings remained above the 70-mcd/m^2/lx acceptability level for the test period. Table 13 provides a side-by-side comparison of the ending retro-reflectivity readings for the bead types at each test site.

Table 13. Ending Average Retro-Reflectivity Readings of Test Markings

Bead Type	New HMA* (mcd/m^2/lx)	Aged PCC (mcd/m^2/lx)	Aged HMA (mcd/m^2/lx)
Type I	60	170	144
Type III	67	347	145
Type IV	82	298	128
Manufacturer A	41	416	118
Manufacturer B	70	535	167

*Based on the equivalence of 5 months in the NAPTF with accumulating rubber deposits.

FRICTION TEST.

Using a Saab Sarsys Friction Tester, multiple friction test runs were conducted at Test Site Two on aged PCC and Test Site Three on aged HMA. Because the friction lines were only 150 feet long, the vehicle was operated in manual mode. The operator lowered the test wheel prior to the test markings and started the water flow and friction measurements. The test wheel was manually lifted at the end of the pass, which stopped the measurements and turned off the water flow.

To provide a baseline reading, friction test runs were conducted on the nonbeaded test markings adjacent to the beaded test markings. Six total friction test runs were conducted at the beginning of the test on aged PCC and aged HMA, as well as six more at the end of the tests. The friction readings from this test were equal to or surpassed the readings obtained from a previous study [4].

Table 14 shows the combined average friction test readings conducted at Test Site Two on aged PCC and Test Site Three on aged HMA. Data include surface material, bead type, and average friction value. A total of 36 friction test runs were conducted. Eighteen friction test runs were conducted at the beginning of the tests and 18 at the end of the tests. (See appendix D for additional data.)

Table 14. Average Friction Values on Aged PCC and Aged HMA

Surface Material		Bead Type					
		No Bead	Type I	Type III	Type IV	Manufacturer A	Manufacturer B
Aged PCC	Average Friction Value of μ	0.63	0.50	0.50	0.43	0.90	0.85
Aged HMA		0.57	0.64	0.60	0.59	0.70	0.72

SUBJECTIVE TEST.

Subjective data were collected in the form of questionnaires completed by the test subjects at Test Site Two on aged PCC. The responses regarding ease of detection and conspicuity were compiled into tables.

Figures 31 and 32 show comparisons of all test markings in relation to the questions, “Were the markings easy to detect?” and “Were the runway markings adequate in regards to conspicuity?” To display this information, a seven-point Likert scale was employed, where 1 implied “Totally Disagree” and 7 implied “Totally Agree.”

All the beaded test markings were deemed detectable by the test subjects on aged PCC. Responses indicated that Type IV and Manufacturer A retro-reflective beads were more easily detectable than Type I and Type III. In regard to conspicuity on aged PCC, Type IV retro-reflective beads were deemed most conspicuous, followed by Manufacturer A, then Type I and Type III, which were equivalent. Manufacturer B had little effect on conspicuity.

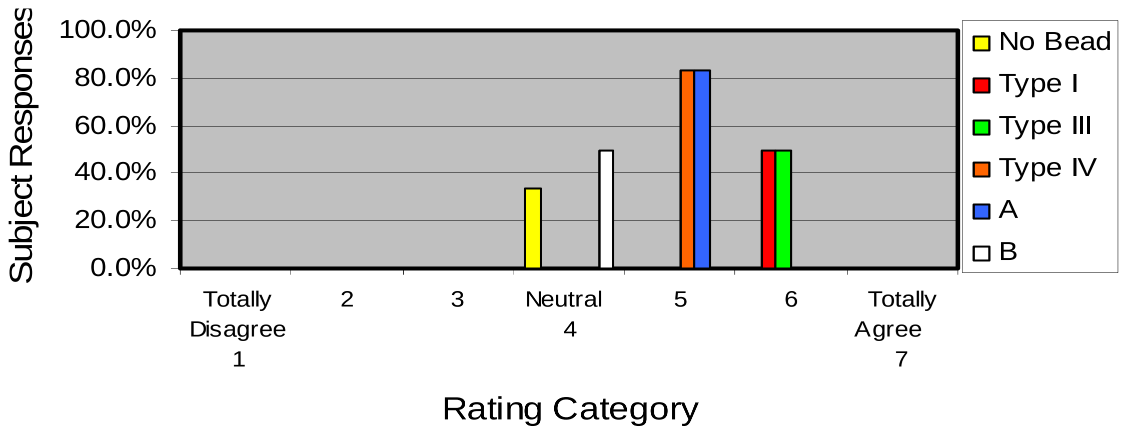

Figure 31. Test Subject Responses for Ease of Detection on Aged PCC

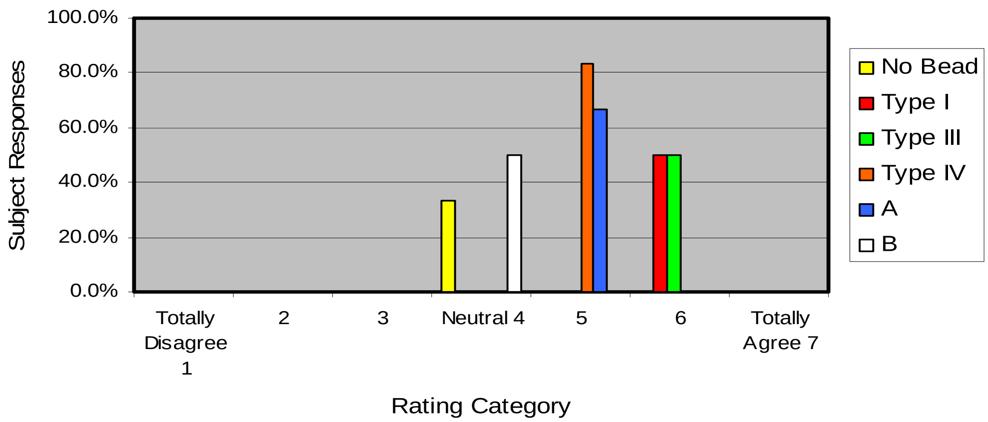

Figure 32. Test Subject Responses for Conspicuity of Markings on Aged PCC

CONCLUSIONS

This research validates previous research performed on Type I, Type III, and Type IV retro-reflective beads with respect to effectiveness for use on airport surface markings. No previous research was performed on the two newly proposed retro-reflective beads.

The initial application tests concerning coverage, water, and pull-off strength were deemed successful for all beads tested.

On new hot-mix asphalt (HMA), the test marking with Type IV retro-reflective beads remained conspicuous for the longest period of time. Type I, Type III, and Manufacturer B retro-reflective beads remained conspicuous for approximately half that time, and Manufacturer A for approximately one-quarter of that time.

All the approved retro-reflective beads proved suitable for use on aged HMA and aged Portland cement concrete (PCC) over a 1-year period. The proposed retro-reflective beads from Manufacturer A and Manufacturer B also proved suitable for use on aged HMA and aged PCC and could be considered acceptable for use on these surfaces.

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3. ASTM D 4541-02, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," ASTM International, West Conshohocken, Pennsylvania, 2002.

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6. ASTM E 2176-01, "Standard Test Method for Measuring the Coefficient of Retro-Reflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting," ASTM International, West Conshohocken, Pennsylvania, 2003.

7. ASTM D 2177-01, "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," ASTM International, West Conshohocken, Pennsylvania, 2003.

8. ASTM E 1551-93a, "Standard Specification for Special Purpose, Smooth—Tread Tire, Operated on Fixed Braking Slip Continuous Friction Measuring Equipment," ASTM International, West Conshohocken, Pennsylvania.

APPENDIX A—CHROMATICITY

Table A-1. Pass/Fail Rate of Test Markings Located at Test Site One on New Hot-Mix Asphalt

Marking Number	Bead Type	Paint Thickness (mil)	Pass	Fail
1	No bead	14	24	0
2	Type I	14	24	0
3	Type III	14	24	0
4	Type IV	18	24	0
5	Manufacturer A	25*	24	0
6	Manufacturer B	25*	24	0

*Manufacturer's recommendation

Table A-2. Pass/Fail Rate of Test Markings Located at Test Site Two on Aged Portland Cement Concrete

Marking Number	Bead Type	Paint Thickness (mil)	Pass	Fail
7	No bead	14	24	0
8	Type I	14	24	0
9	Type III	14	23	1
10	Type IV	18	24	0
11	Manufacturer A	25*	24	0
12	Manufacturer B	25*	23	1
13	No bead	14	24	0
14	Type I	14	23	1
15	Type III	14	24	0
16	Type IV	18	24	0
17	Manufacturer A	25*	24	0
18	Manufacturer B	25*	24	0

*Manufacturer's recommendation

Table A-3. Pass/Fail Rate of Test Markings Located at Test Site Three on Aged Hot-Mix Asphalt

Marking Number	Bead Type	Paint Thickness (mil)	Pass	Fail
19	No bead	14	24	0
20	Type I	14	24	0
21	Type III	14	24	0
22	Type IV	18	24	0
23	Manufacturer A	25*	24	0
24	Manufacturer B	25*	24	0
25	No bead	14	24	0
26	Type I	14	24	0
27	Type III	14	24	0
28	Type IV	18	24	0
29	Manufacturer A	25*	24	0
30	Manufacturer B	25*	24	0

*Manufacturer's recommendation

Table A-4. Initial Chromaticity Readings at Test Site One on New Hot-Mix Asphalt

Marking Number	Bead Type	Y = Depth Coordinate	x = Width Coordinate	y = Height Coordinate
1	No bead	33.66	0.4750	0.4474
2	Type I	34.85	0.4868	0.4408
3	Type III	34.00	0.4808	0.4384
4	Type IV	39.12	0.4868	0.4417
5	Manufacturer A	48.53	0.4857	0.4346
6	Manufacturer B	42.76	0.4917	0.4403

Table A-5. Initial Chromaticity Readings at Test Site Two on Aged Portland Cement Concrete

Marking Number	Bead Type	Y = Depth Coordinate	x = Width Coordinate	y = Height Coordinate
7	No bead	38.67	0.4856	0.4418
8	Type I	37.04	0.4885	0.4403
9	Type III	36.88	0.4849	0.4379
10	Type IV	39.58	0.4943	0.4382
11	Manufacturer A	37.07	0.4874	0.4352
12	Manufacturer B	41.25	0.4919	0.4382
13	No bead	41.28	0.4904	0.4399
14	Type I	35.60	0.4940	0.4388
15	Type III	35.57	0.4891	0.4358
16	Type IV	34.65	0.4911	0.4388
17	Manufacturer A	38.27	0.4886	0.4364
18	Manufacturer B	42.30	0.4958	0.4366

Table A-6. Initial Chromaticity Readings at Test Site Three on Aged Hot-Mixed Asphalt

Marking Number	Bead Type	Y = Depth Coordinate	x = Width Coordinate	y = Height Coordinate
19	No bead	35.94	0.4832	0.4379
20	Type I	27.73	0.4896	0.4364
21	Type III	34.30	0.4812	0.4364
22	Type IV	37.85	0.4880	0.4370
23	Manufacturer A	36.55	0.4859	0.4353
24	Manufacturer B	36.10	0.4819	0.4361
25	No bead	39.22	0.4884	0.4373
26	Type I	34.51	0.4940	0.4365
27	Type III	40.81	0.4900	0.4388
28	Type IV	32.73	0.4915	0.4353
29	Manufacturer A	33.18	0.4798	0.4294
30	Manufacturer B	37.09	0.4881	0.4377

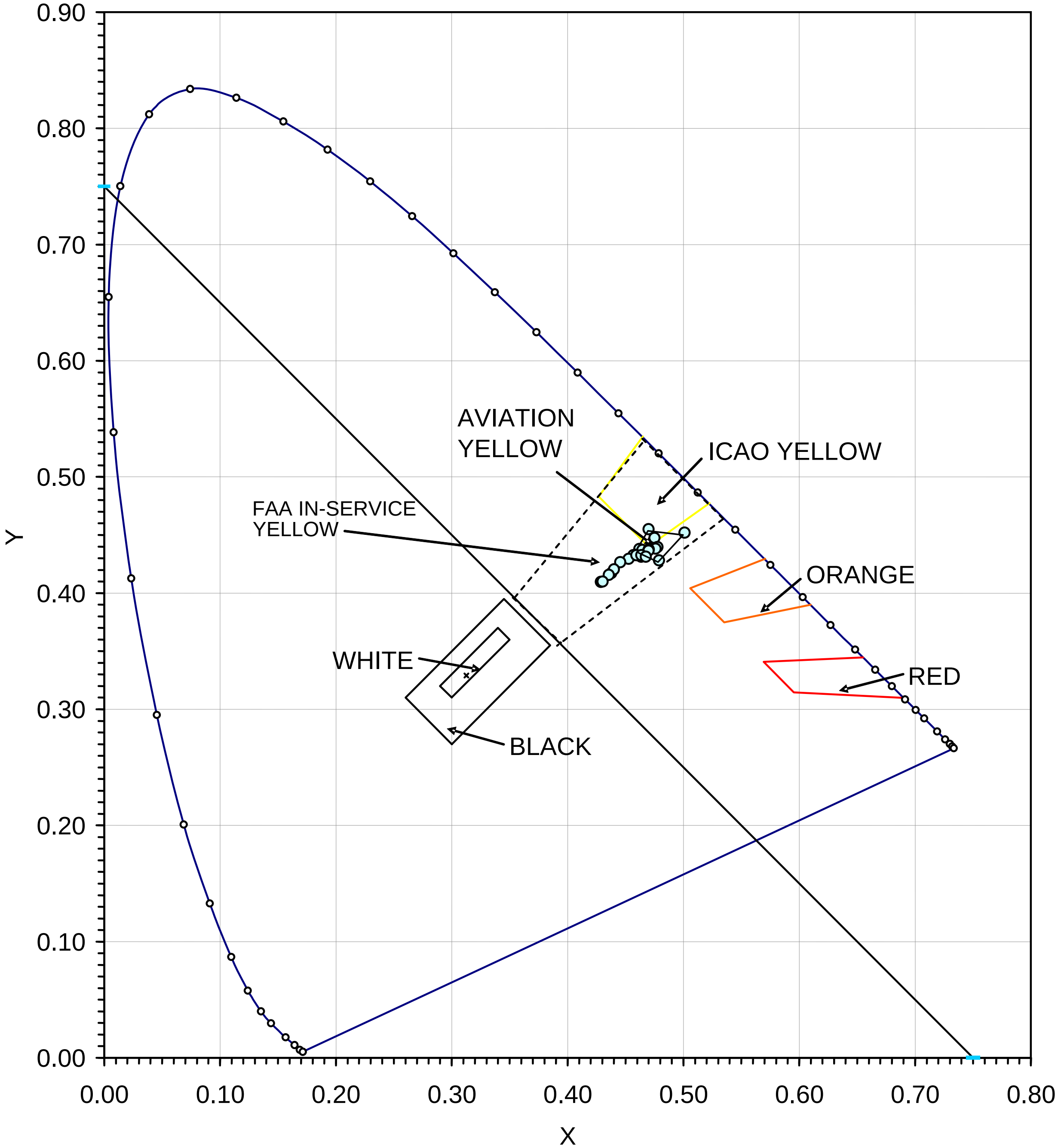

Figure A-1. Chromaticity Readings of No Bead on New Hot-Mix Asphalt

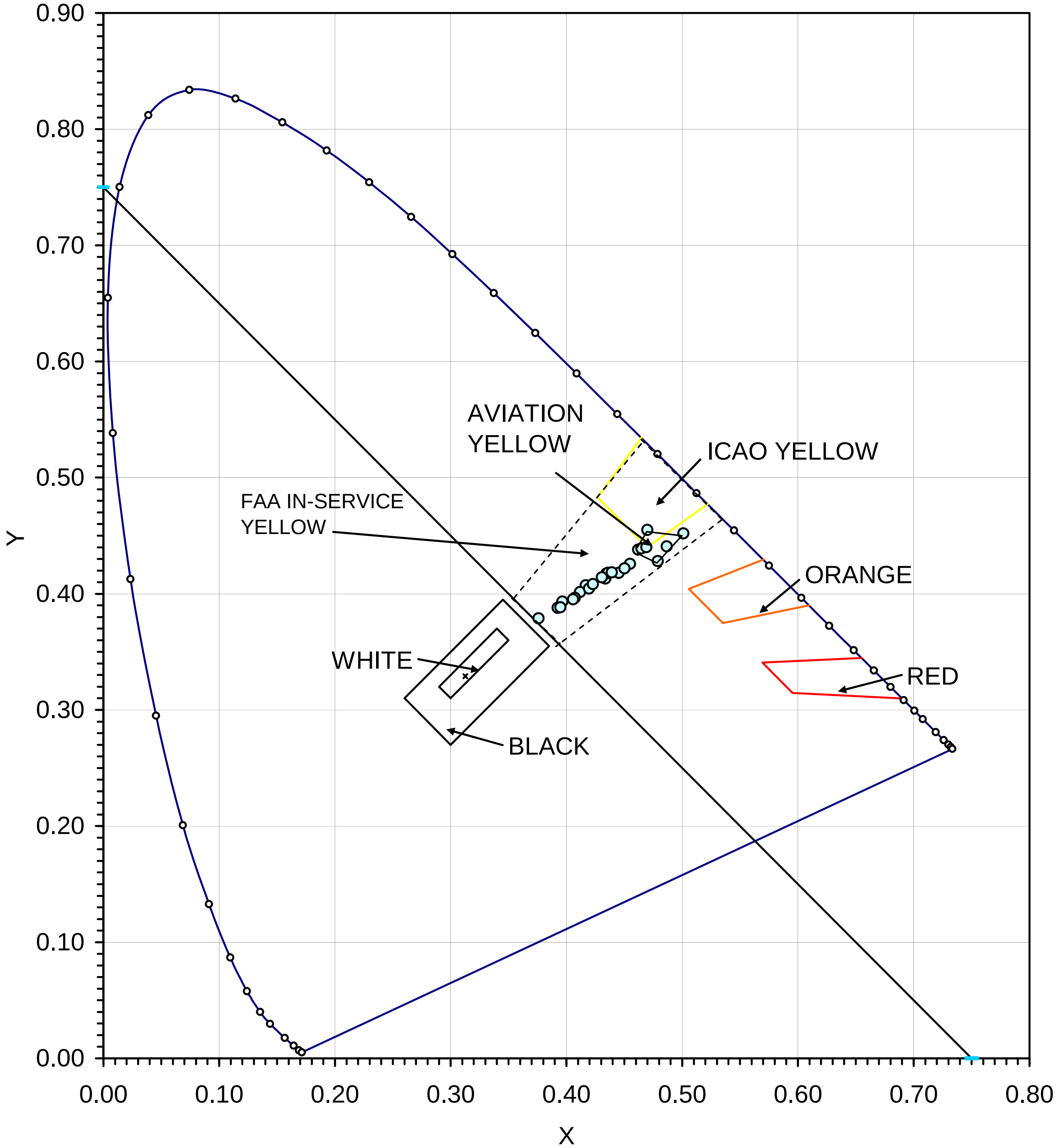

Figure A-2. Chromaticity Readings of Type I Bead on New Hot-Mix Asphalt

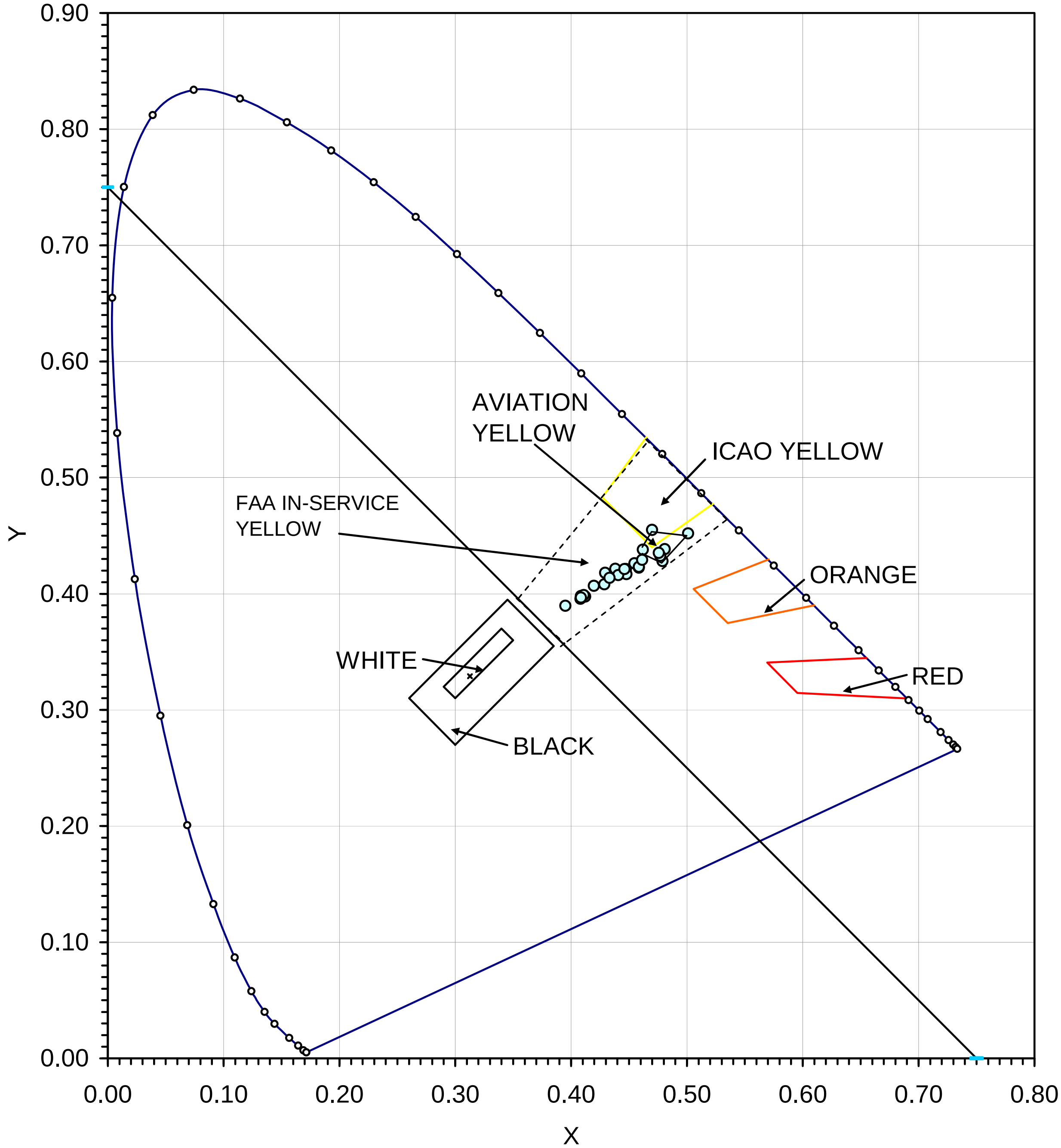

Figure A-3. Chromaticity Readings of Type III Bead on New Hot-Mix Asphalt

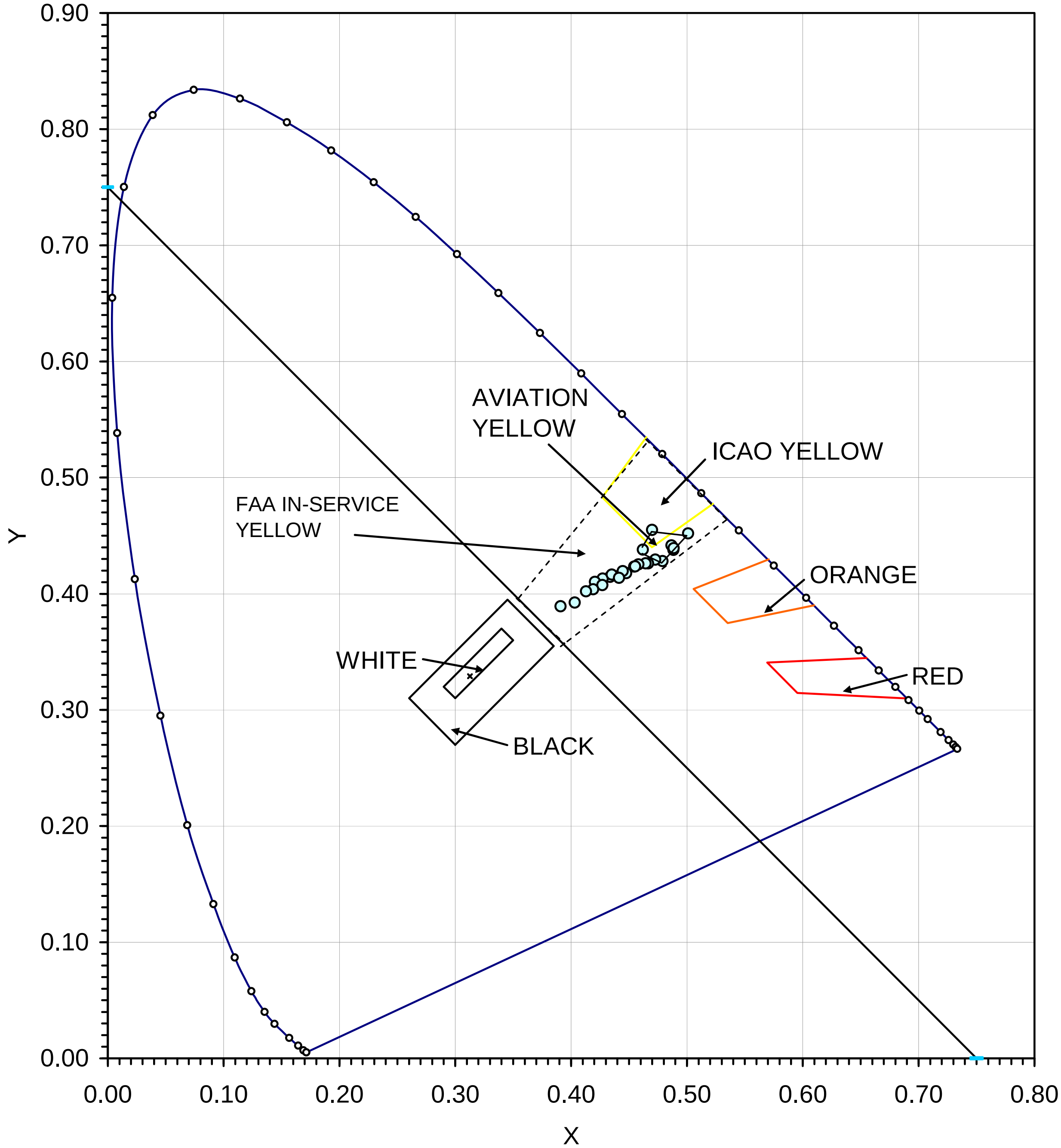

Figure A-4. Chromaticity Readings of Type IV Bead on New Hot-Mix Asphalt

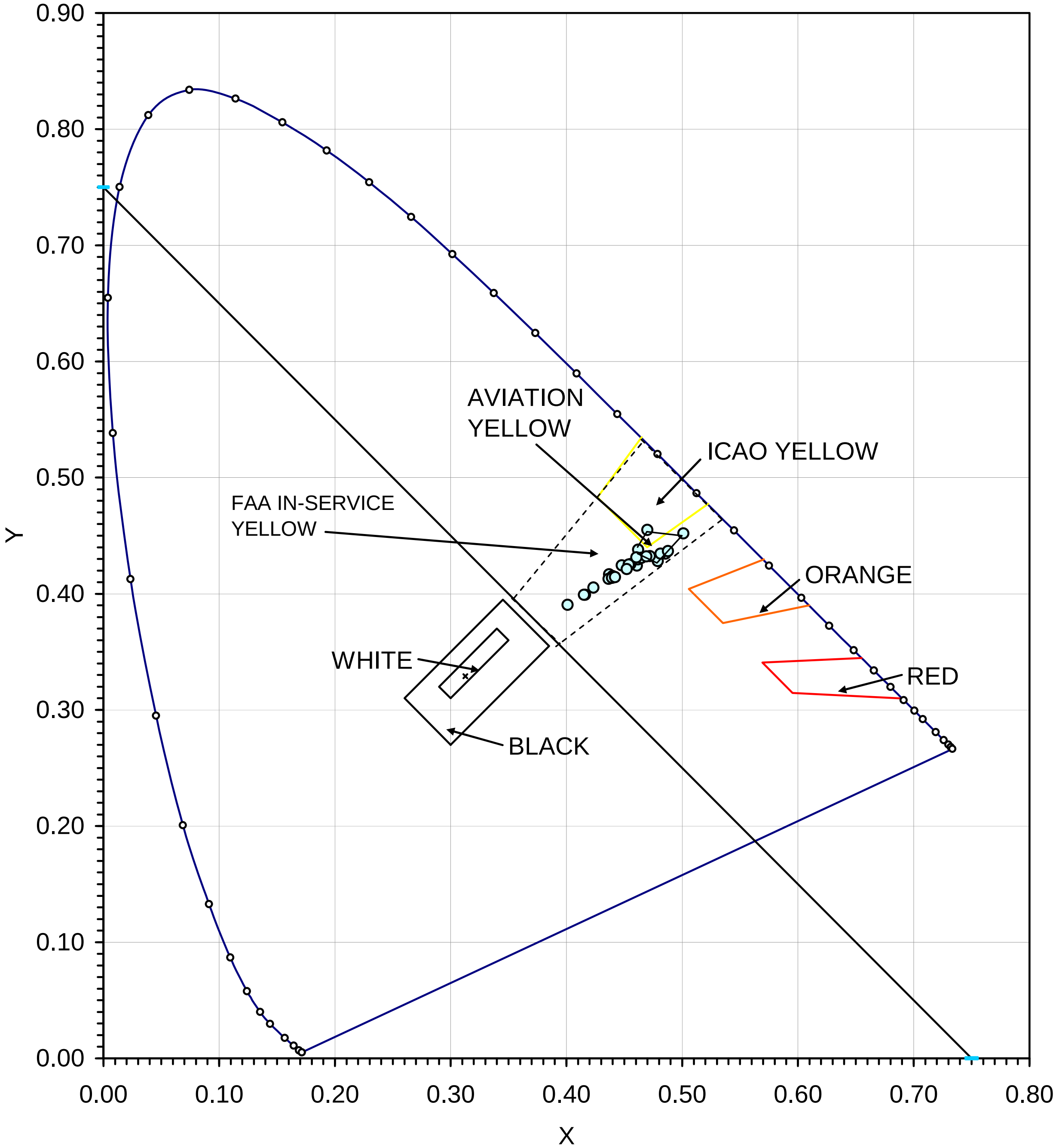

Figure A-5. Chromaticity Readings of Manufacturer A Bead on New Hot-Mix Asphalt

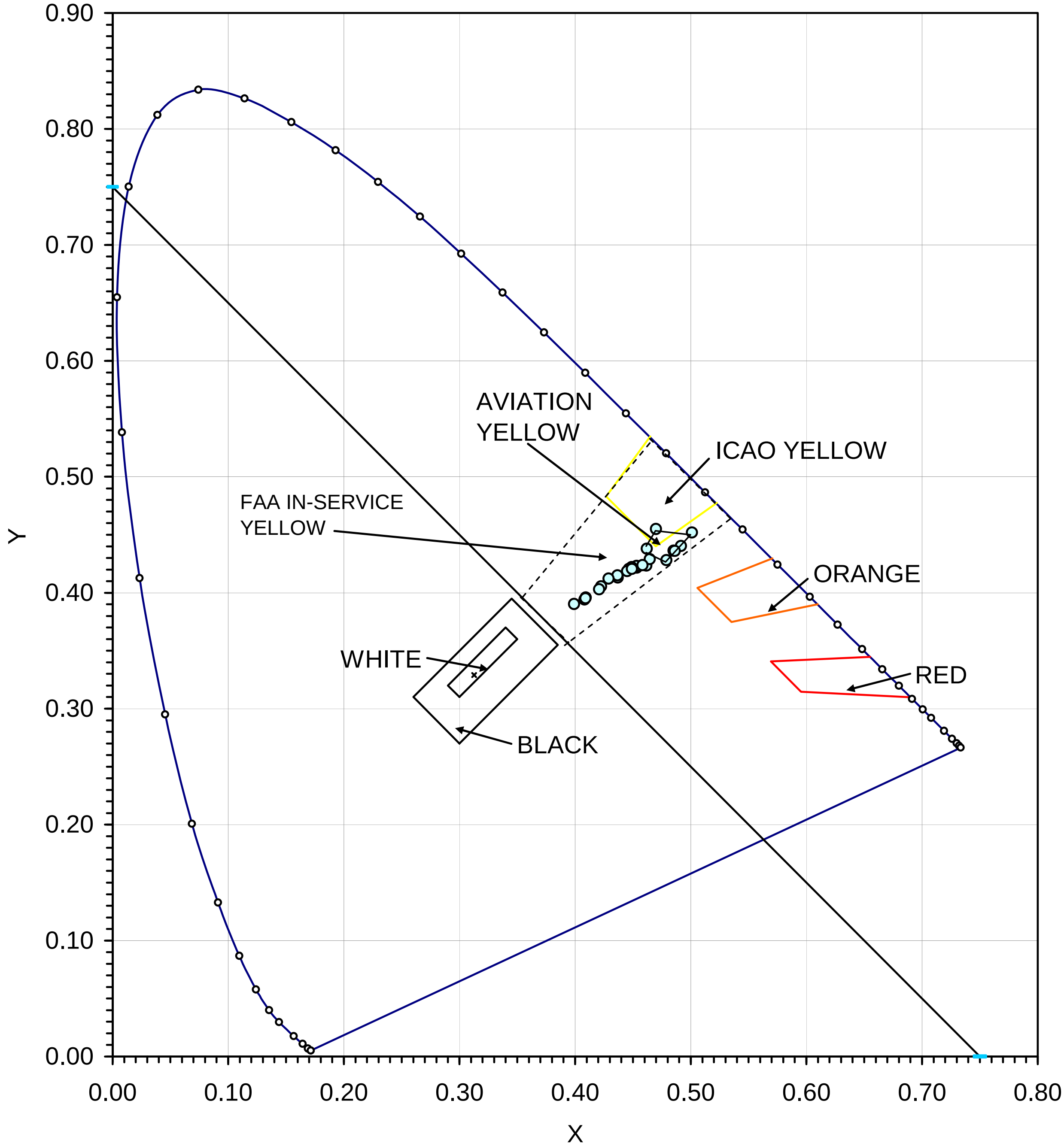

Figure A-6. Chromaticity Readings of Manufacturer B Bead on New Hot-Mix Asphalt

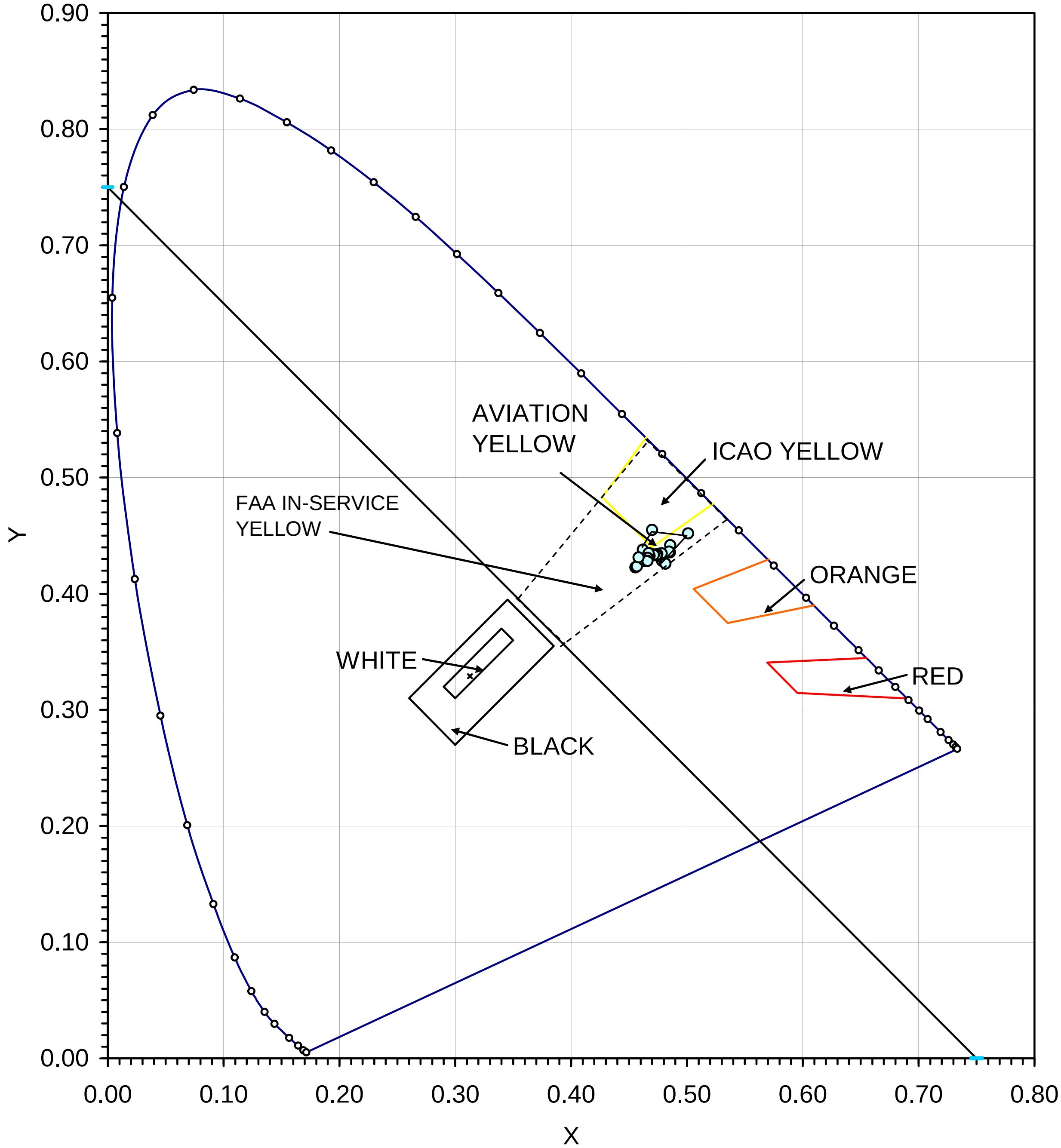

Figure A-7. Chromaticity Readings of No Bead on Aged Portland Cement Concrete

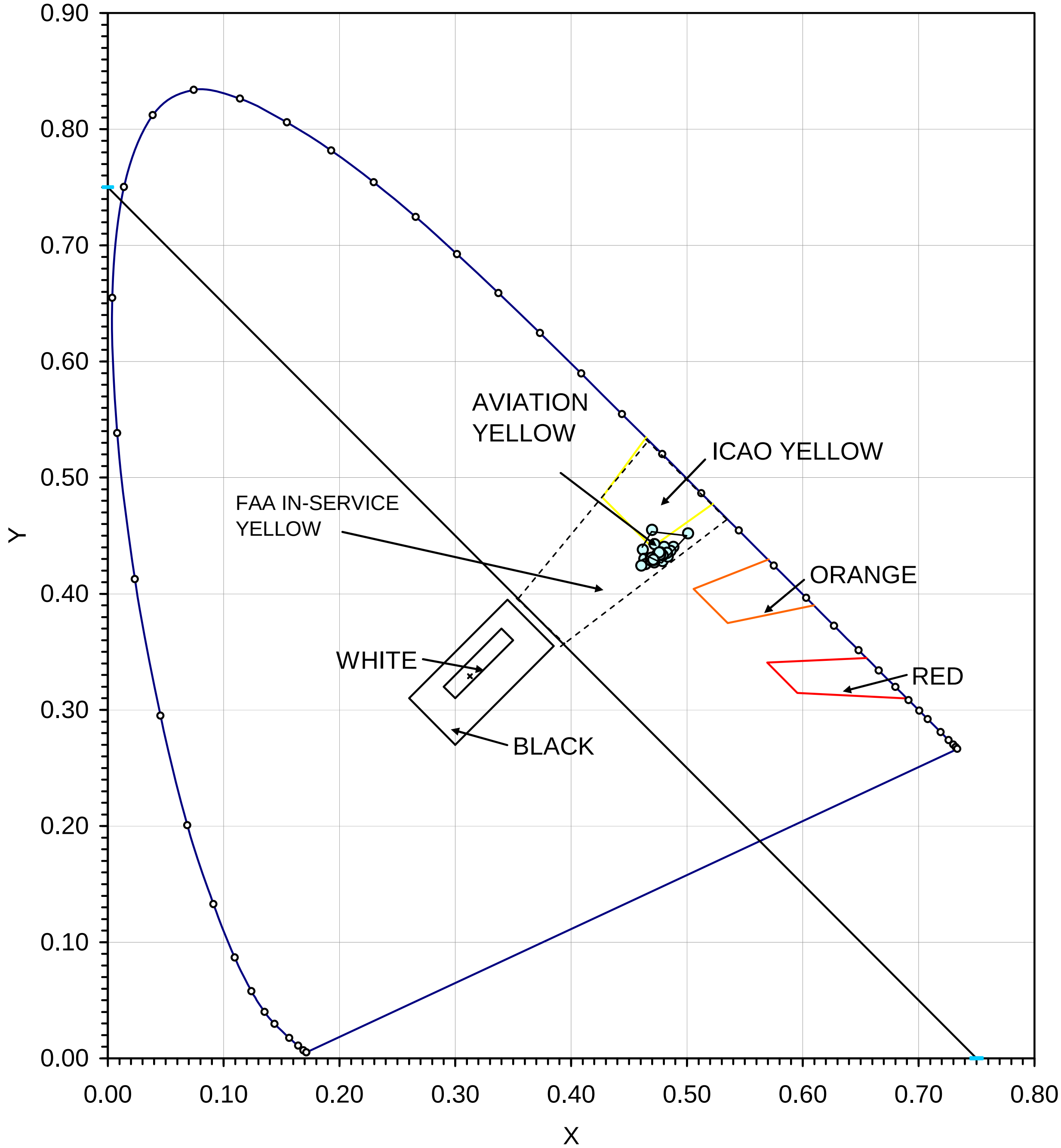

Figure A-8. Chromaticity Readings of Type I Bead on Aged Portland Cement Concrete

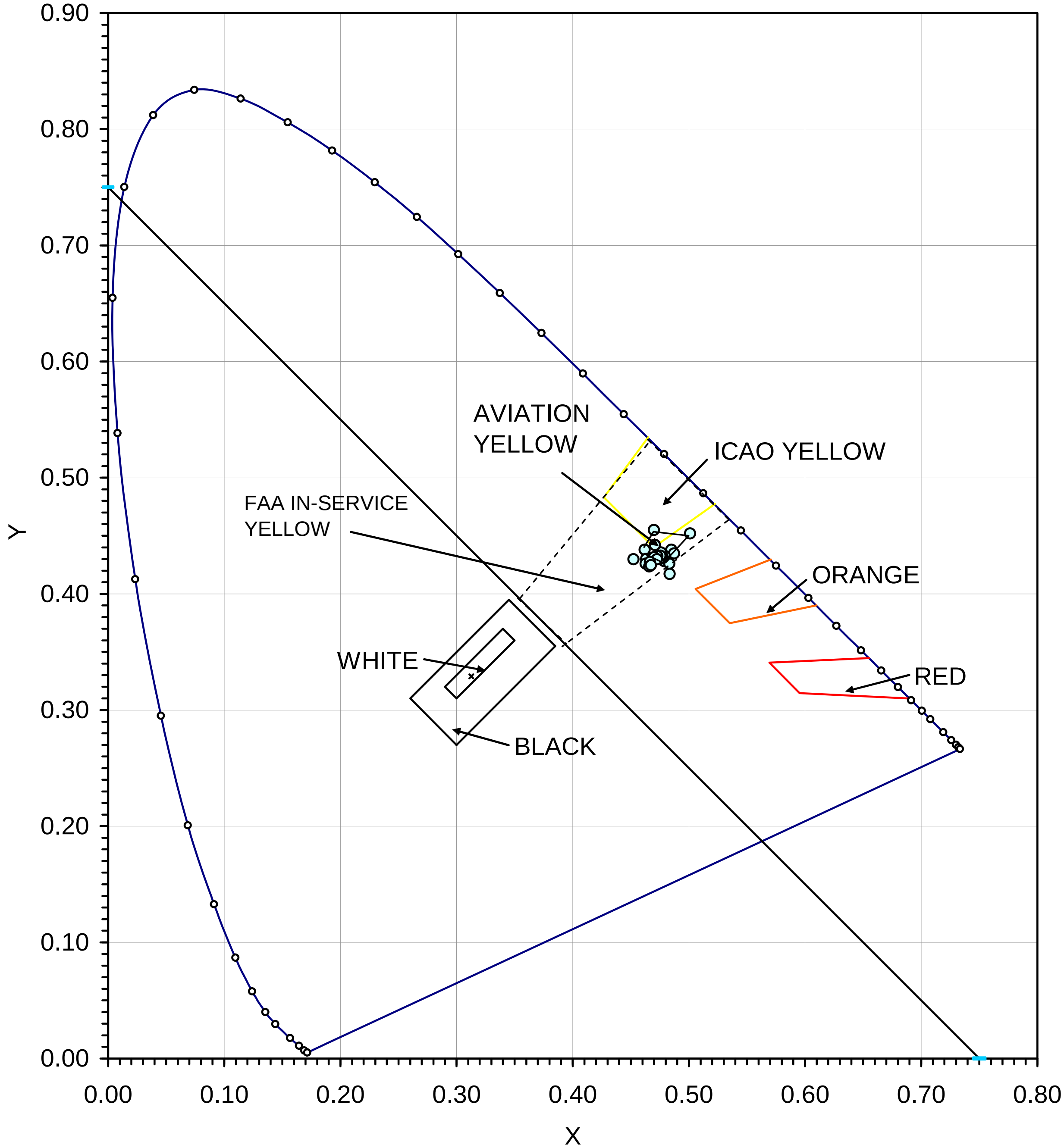

Figure A-9. Chromaticity Readings of Type III Bead on Aged Portland Cement Concrete

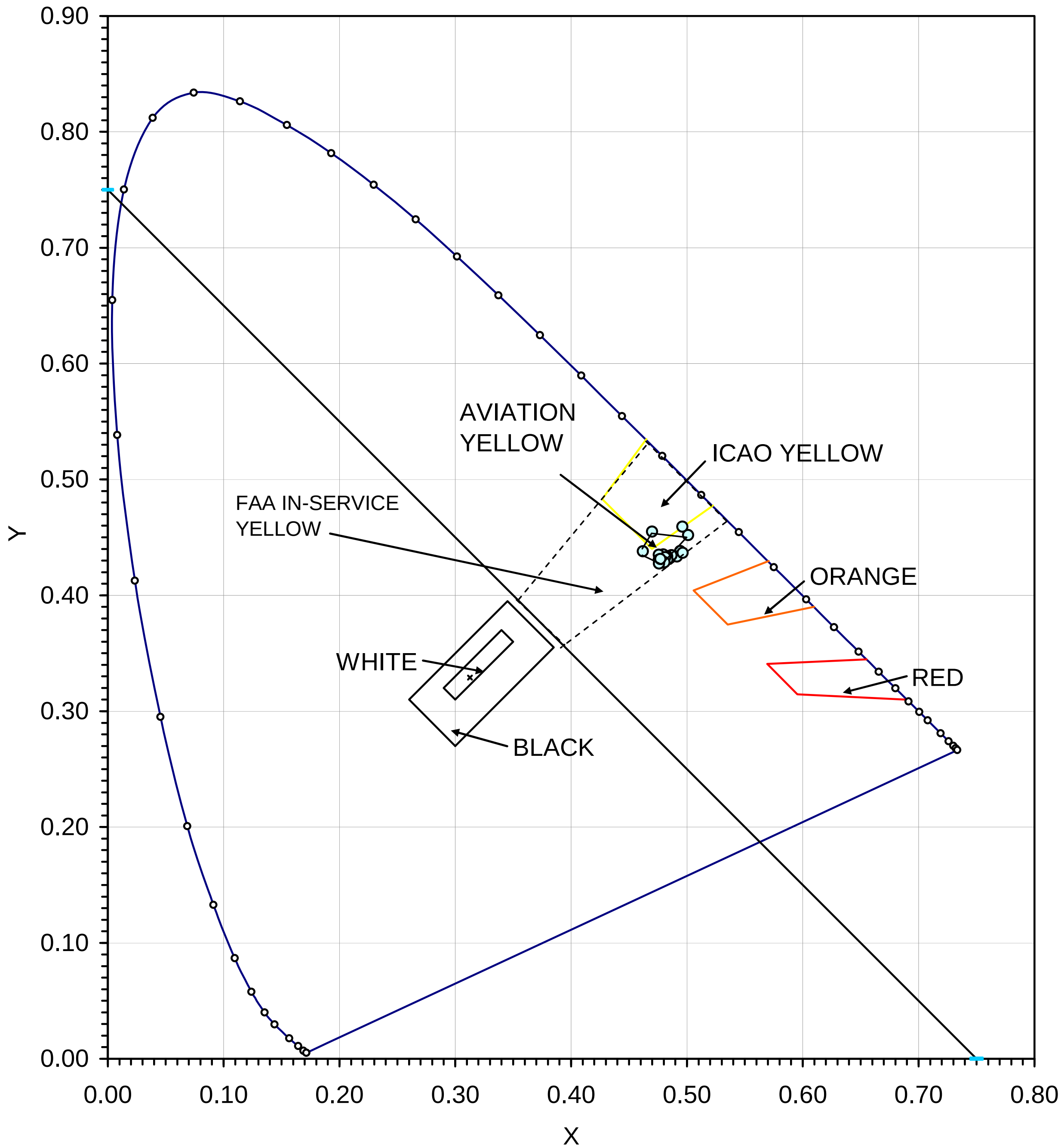

Figure A-10. Chromaticity Readings of Type IV Bead on Aged Portland Cement Concrete

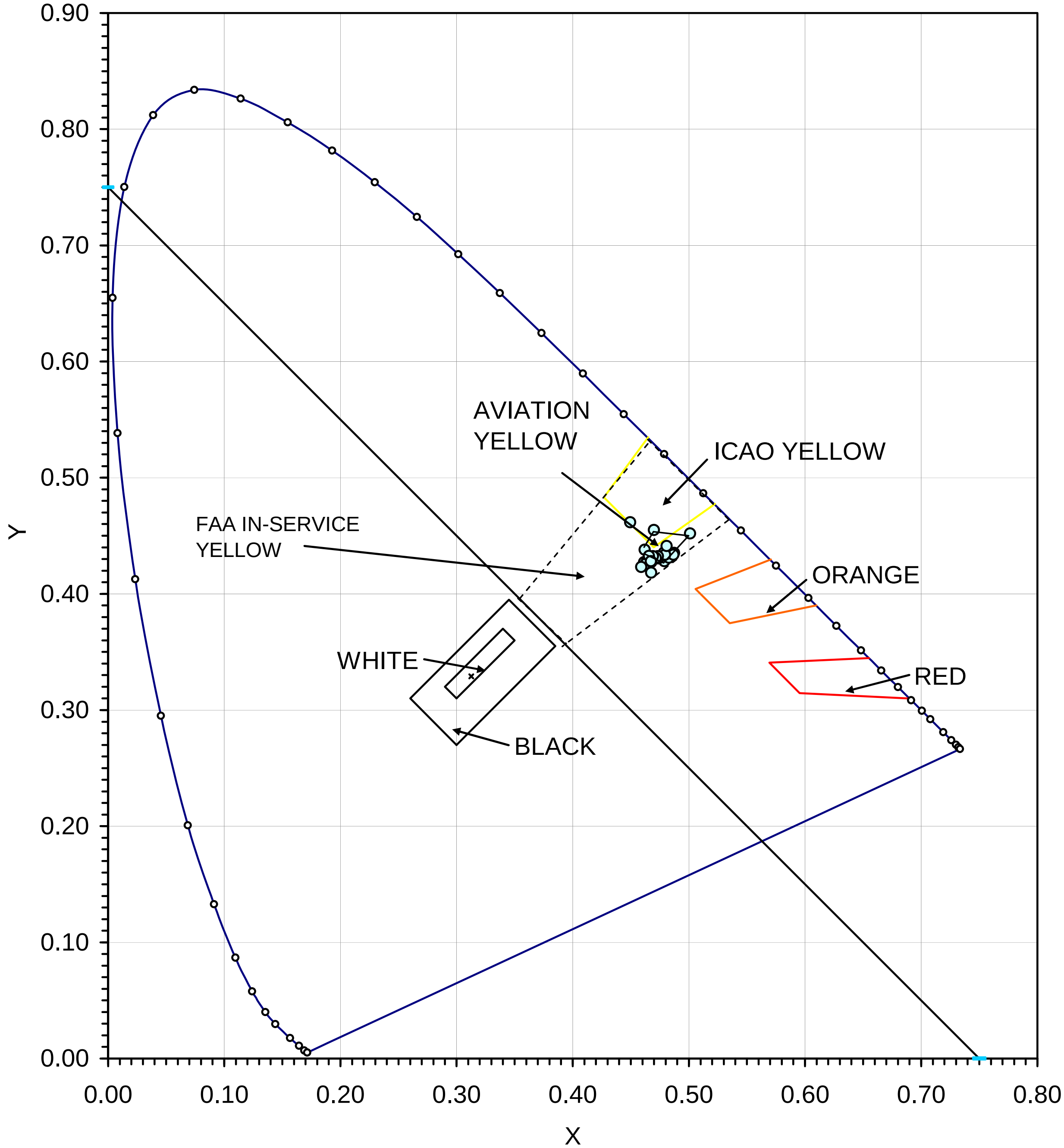

Figure A-11. Chromaticity Readings of Manufacturer A Bead on Aged Portland Cement Concrete

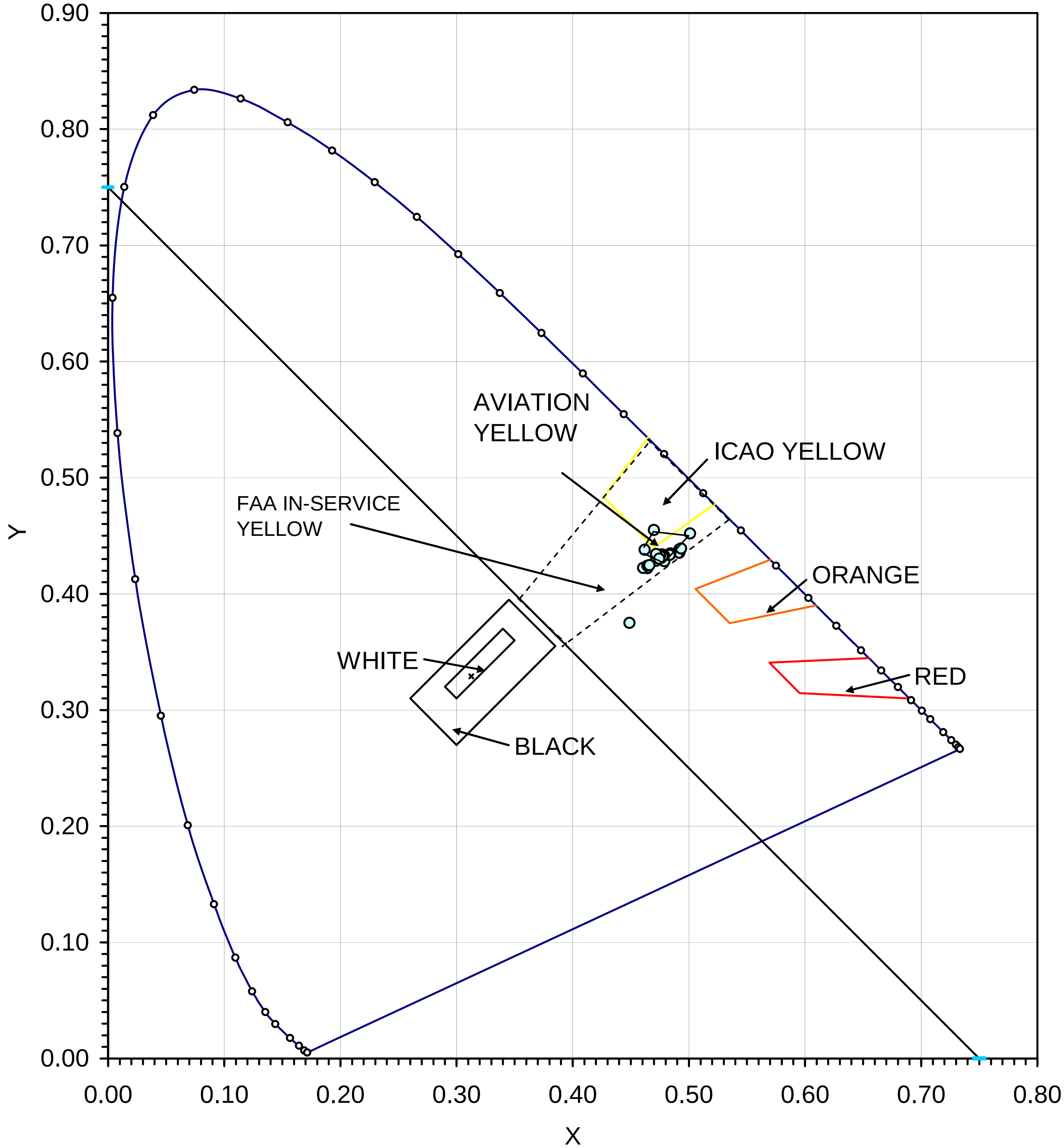

Figure A-12. Chromaticity Readings of Manufacturer B Bead on Aged Portland Cement Concrete

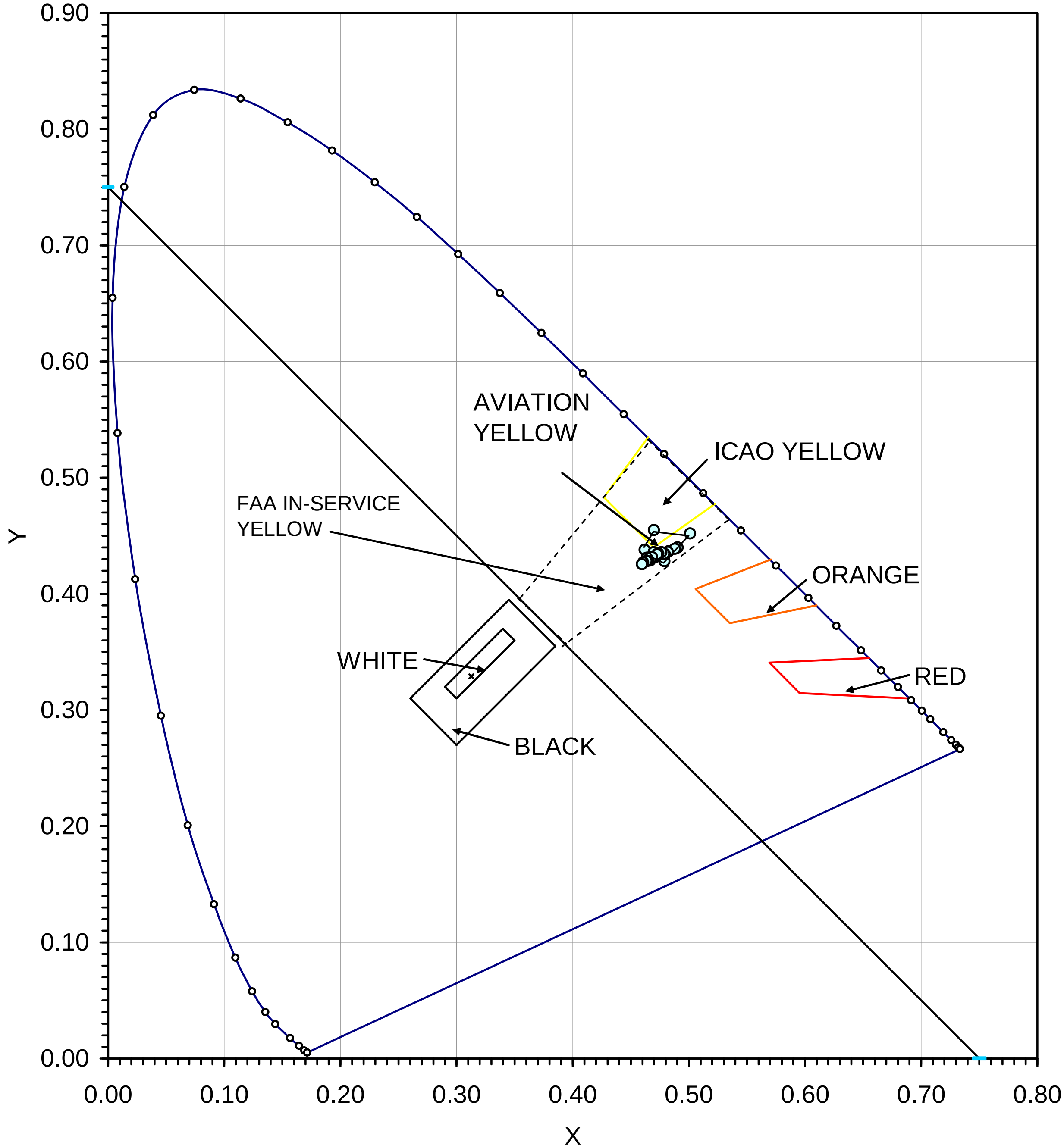

Figure A-13. Chromaticity Readings of No Bead on Aged Portland Cement Concrete

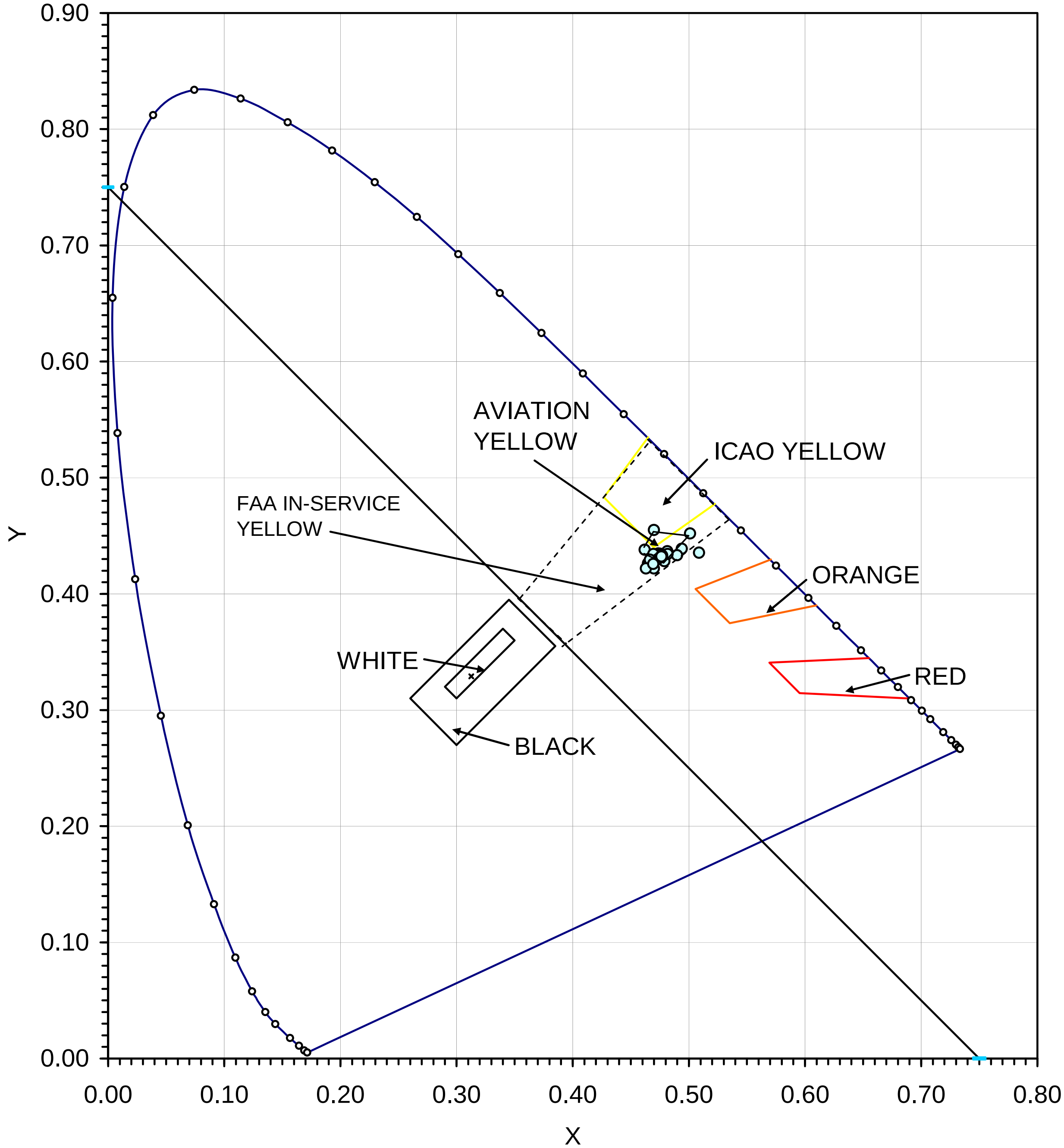

Figure A-14. Chromaticity Readings of Type I Bead on Aged Portland Cement Concrete

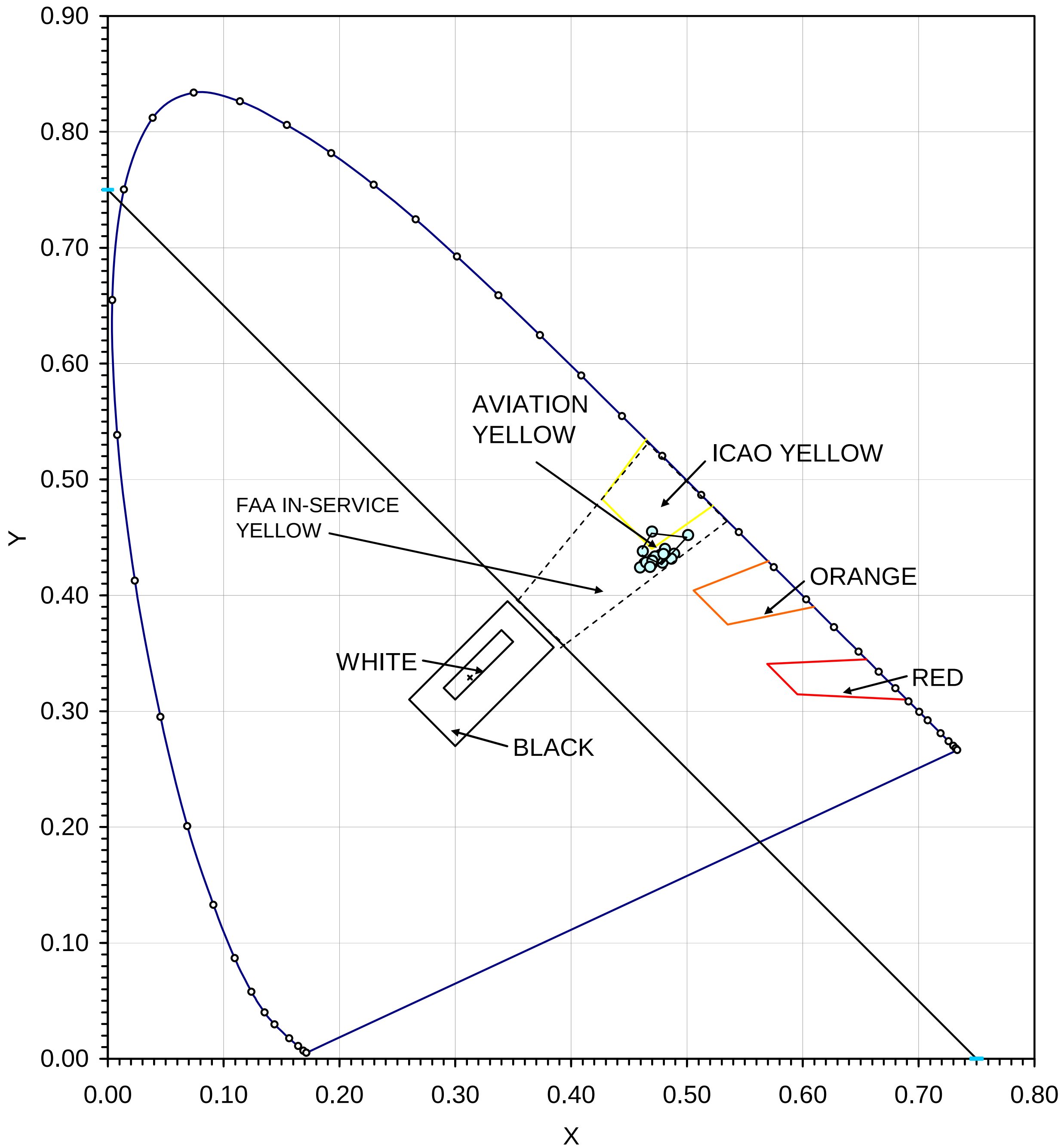

Figure A-15. Chromaticity Readings of Type III Bead on Aged Portland Cement Concrete

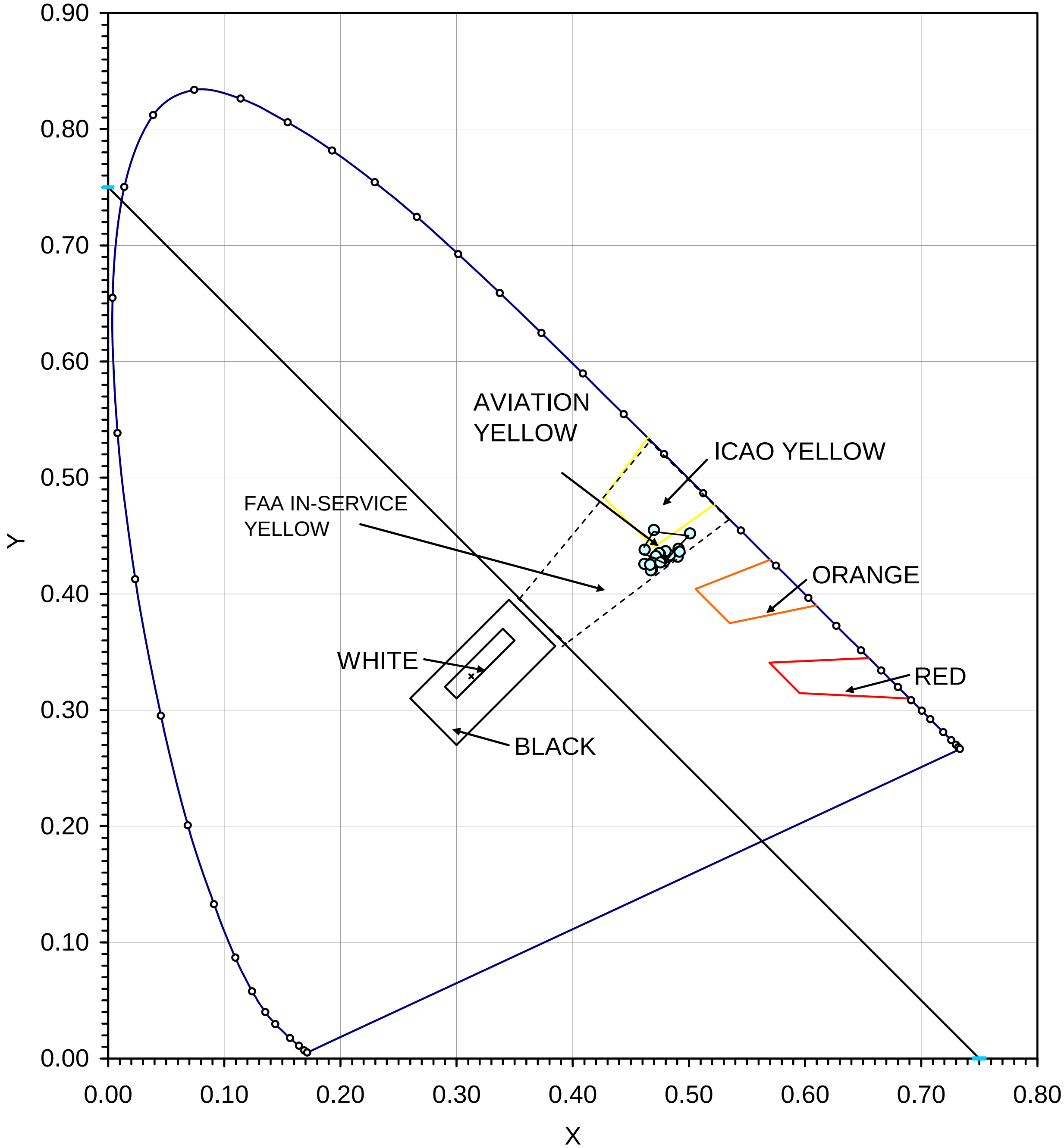

Figure A-16. Chromaticity Readings of Type IV Bead on Aged Portland Cement Concrete

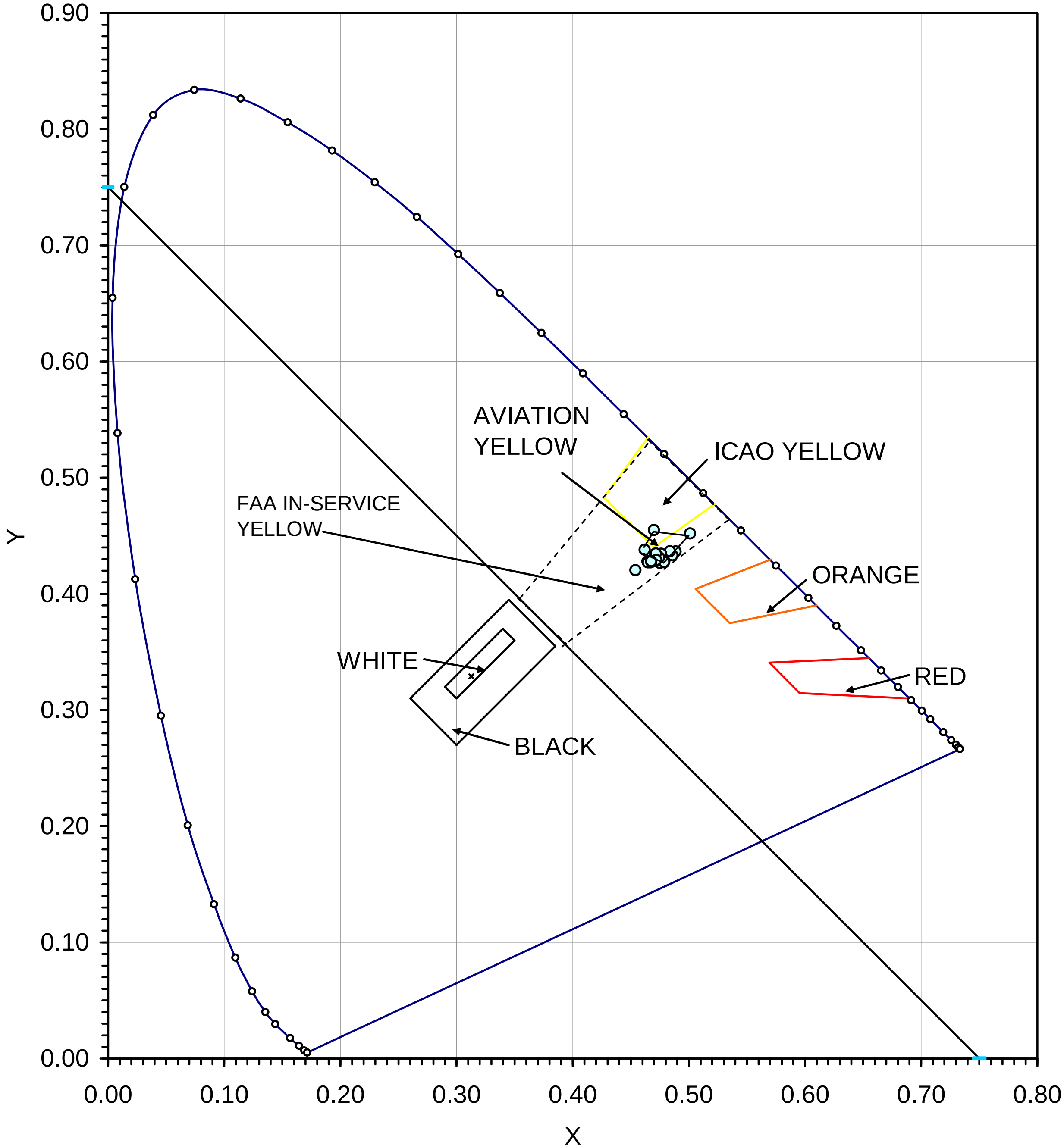

Figure A-17. Chromaticity Readings of Manufacturer A Bead on Aged Portland Cement Concrete

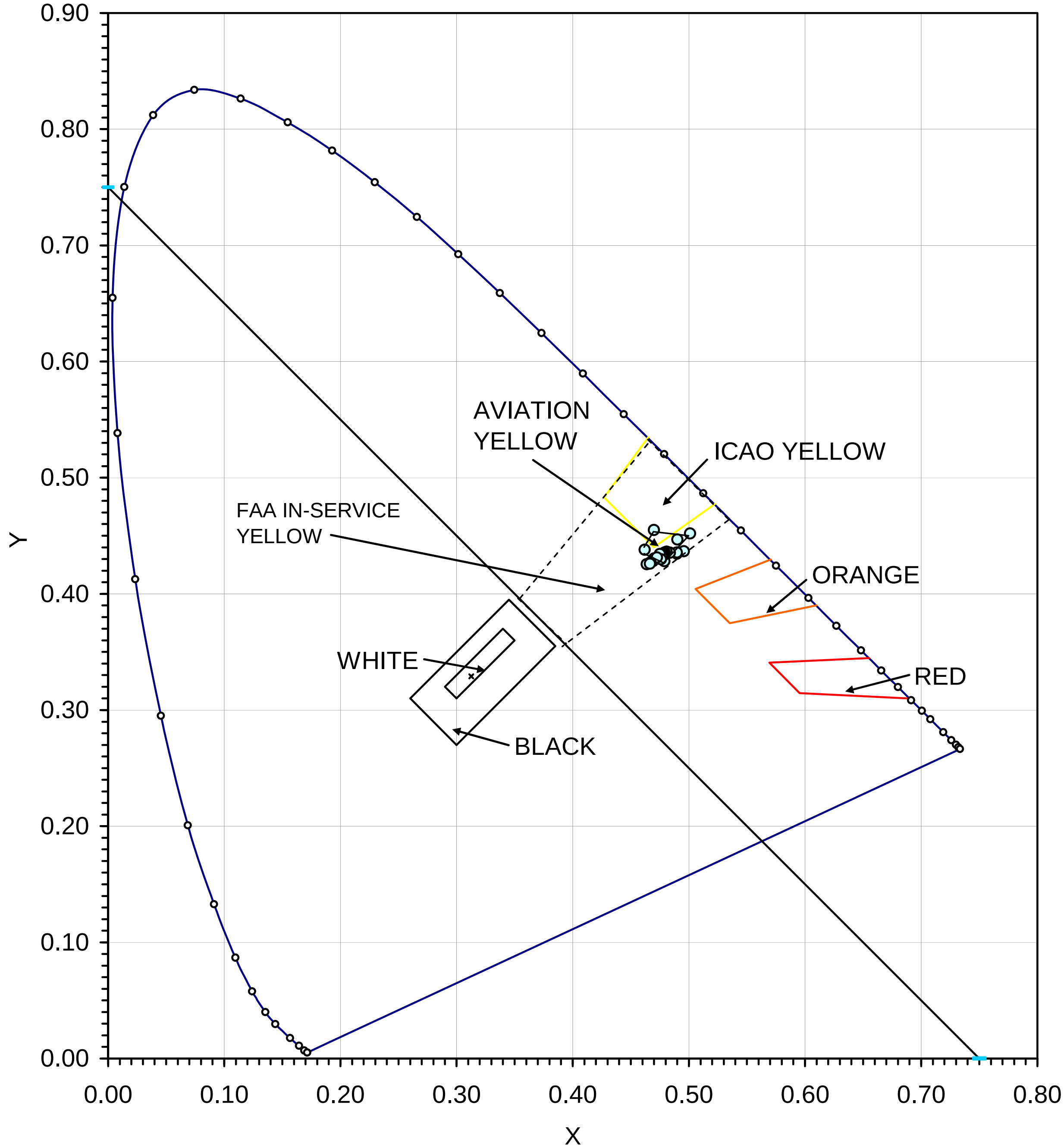

Figure A-18. Chromaticity Readings of Manufacturer B Bead on Aged Portland Cement Concrete

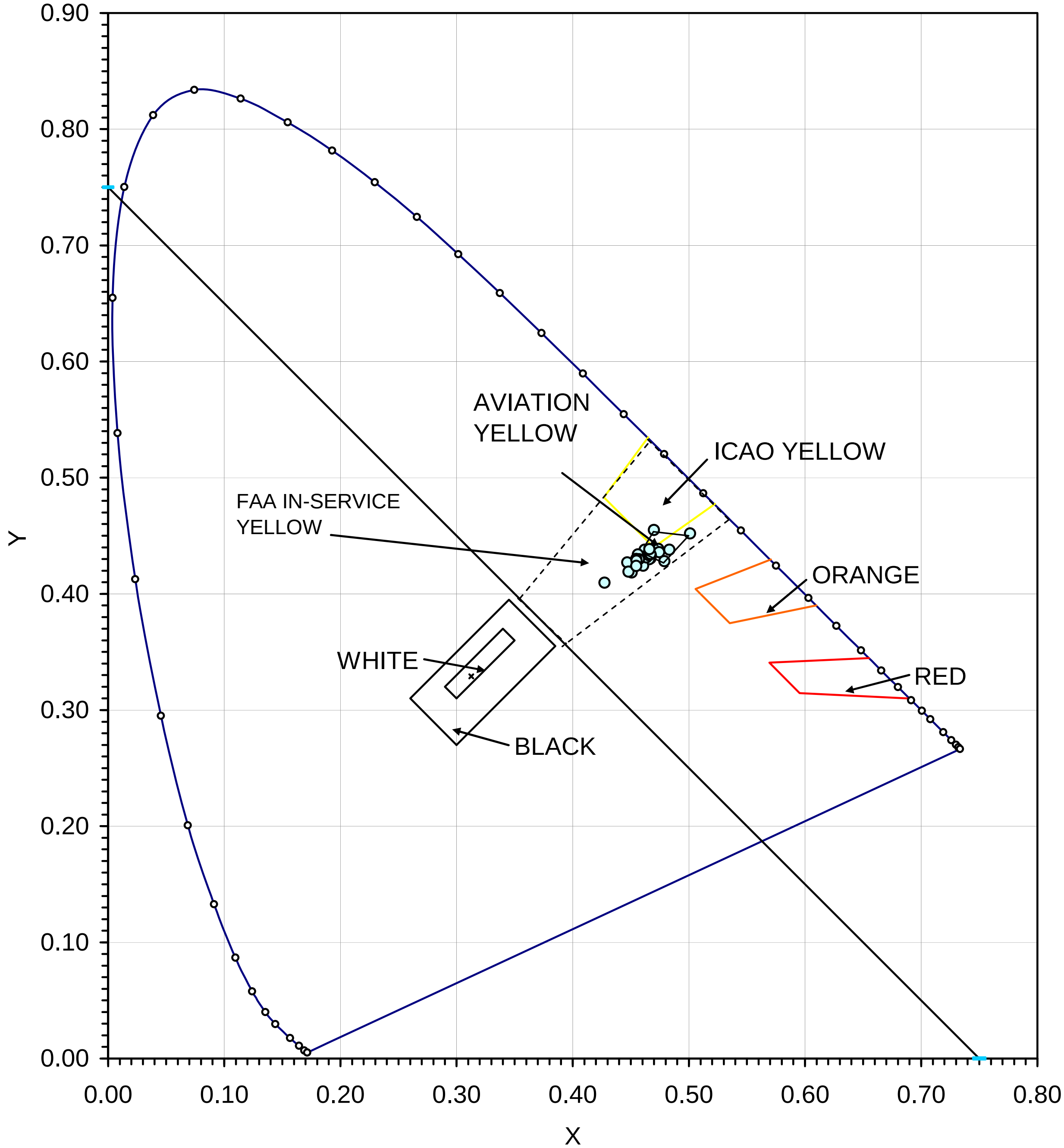

Figure A-19. Chromaticity Readings of No Bead on Aged Hot-Mix Asphalt

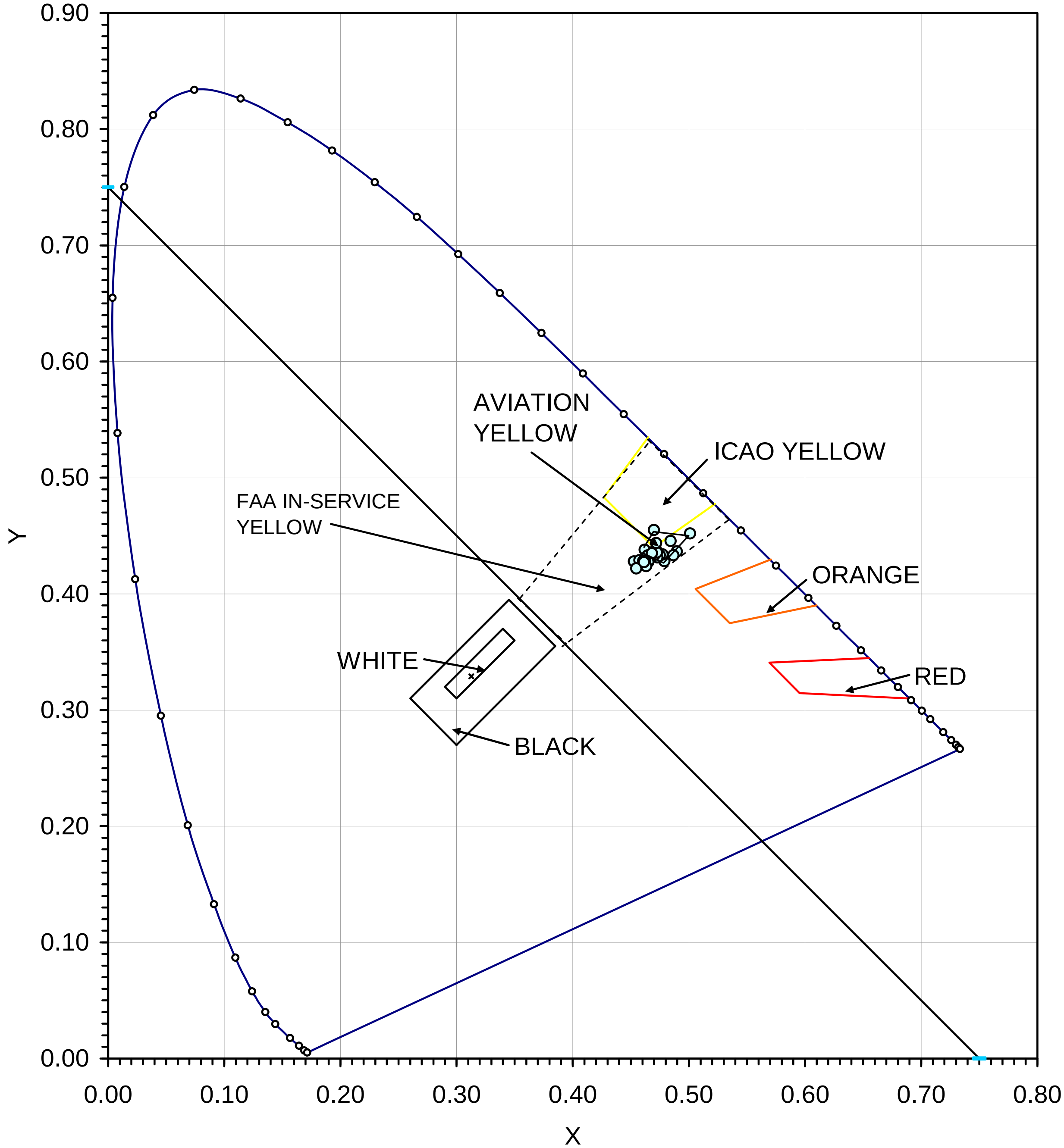

Figure A-20. Chromaticity Readings of Type I Bead on Aged Hot-Mix Asphalt

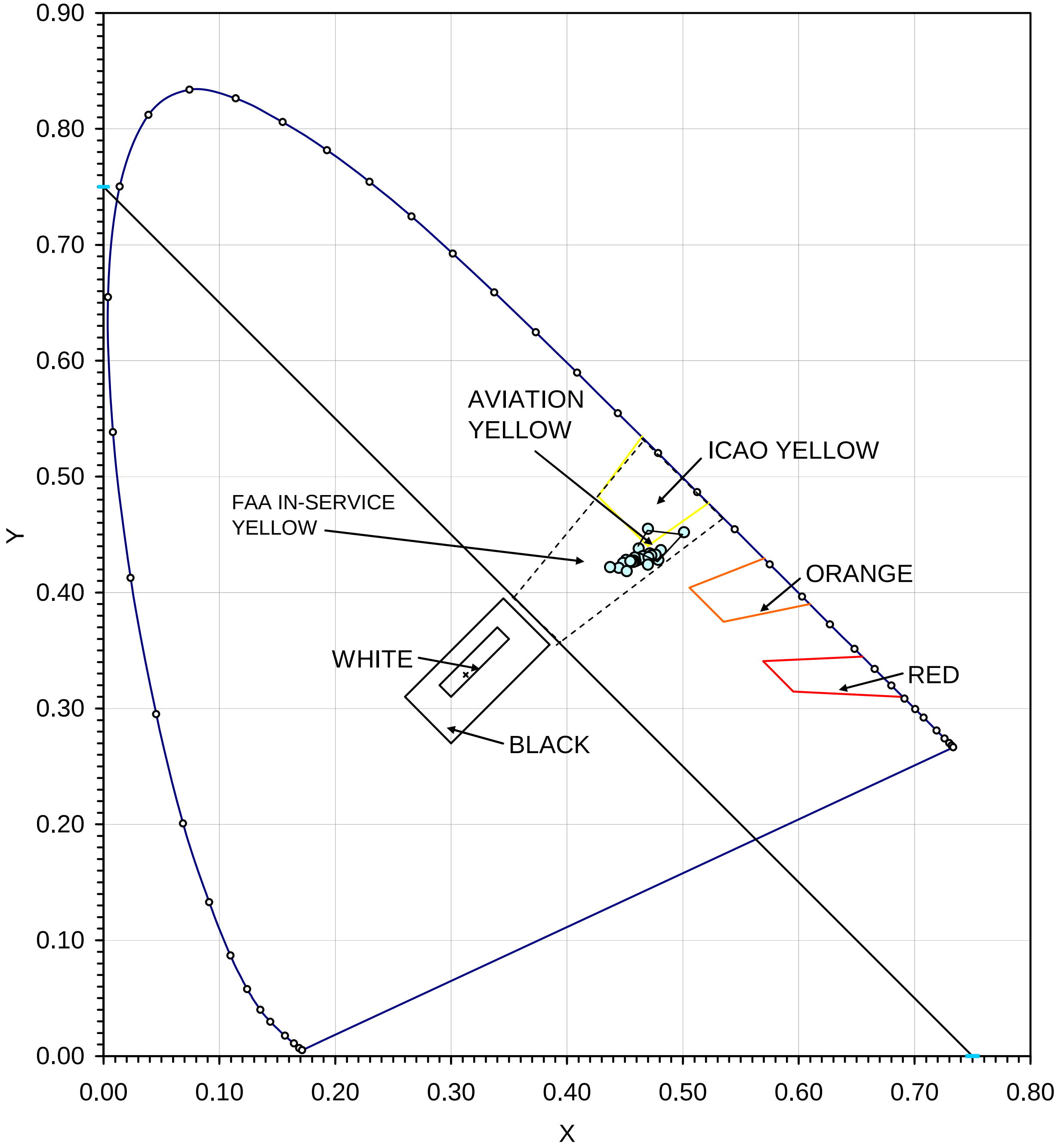

Figure A-21. Chromaticity Readings of Type III Bead on Aged Hot-Mix Asphalt

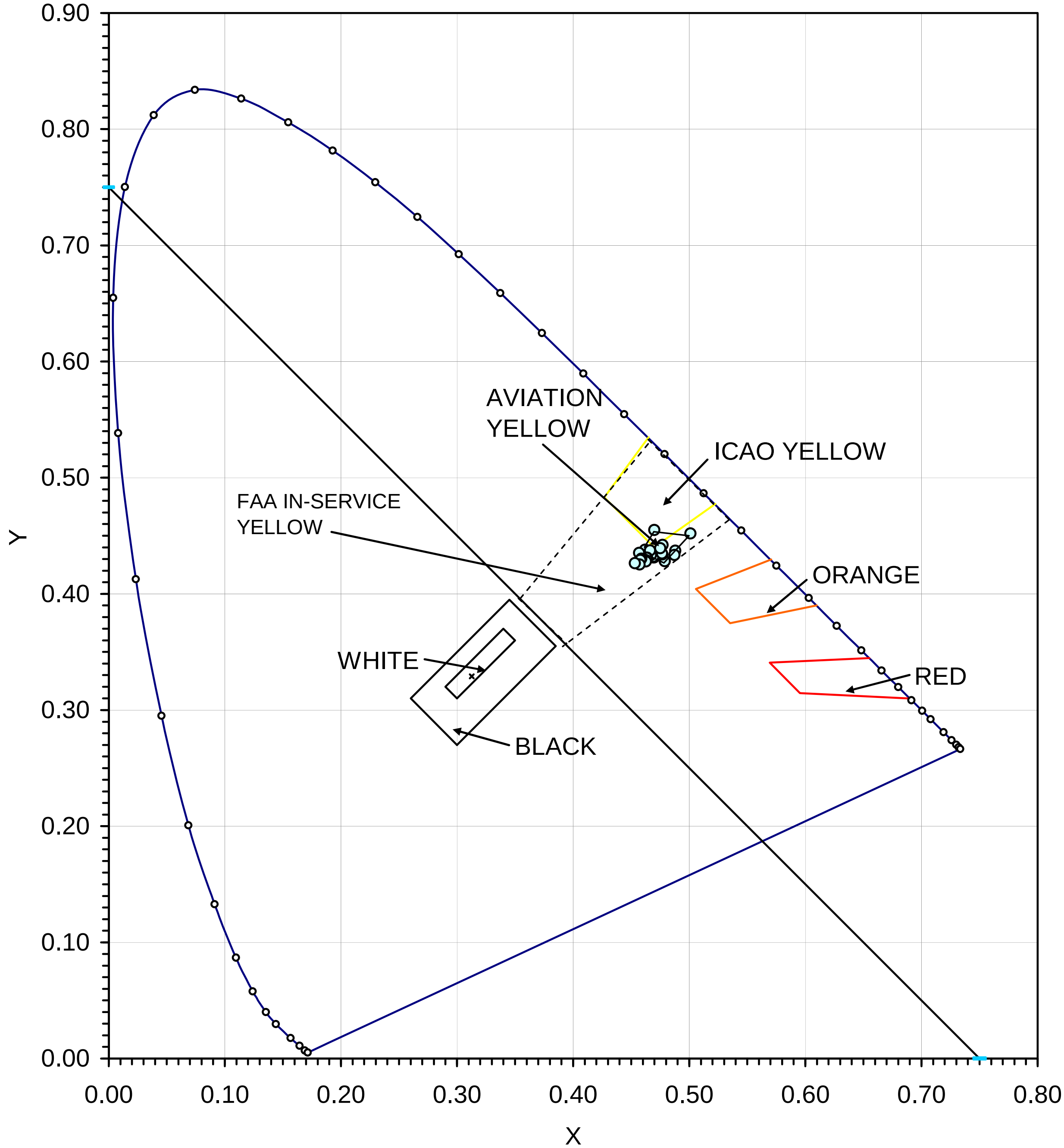

Figure A-22. Chromaticity Readings of Type IV Bead on Aged Hot-Mix Asphalt

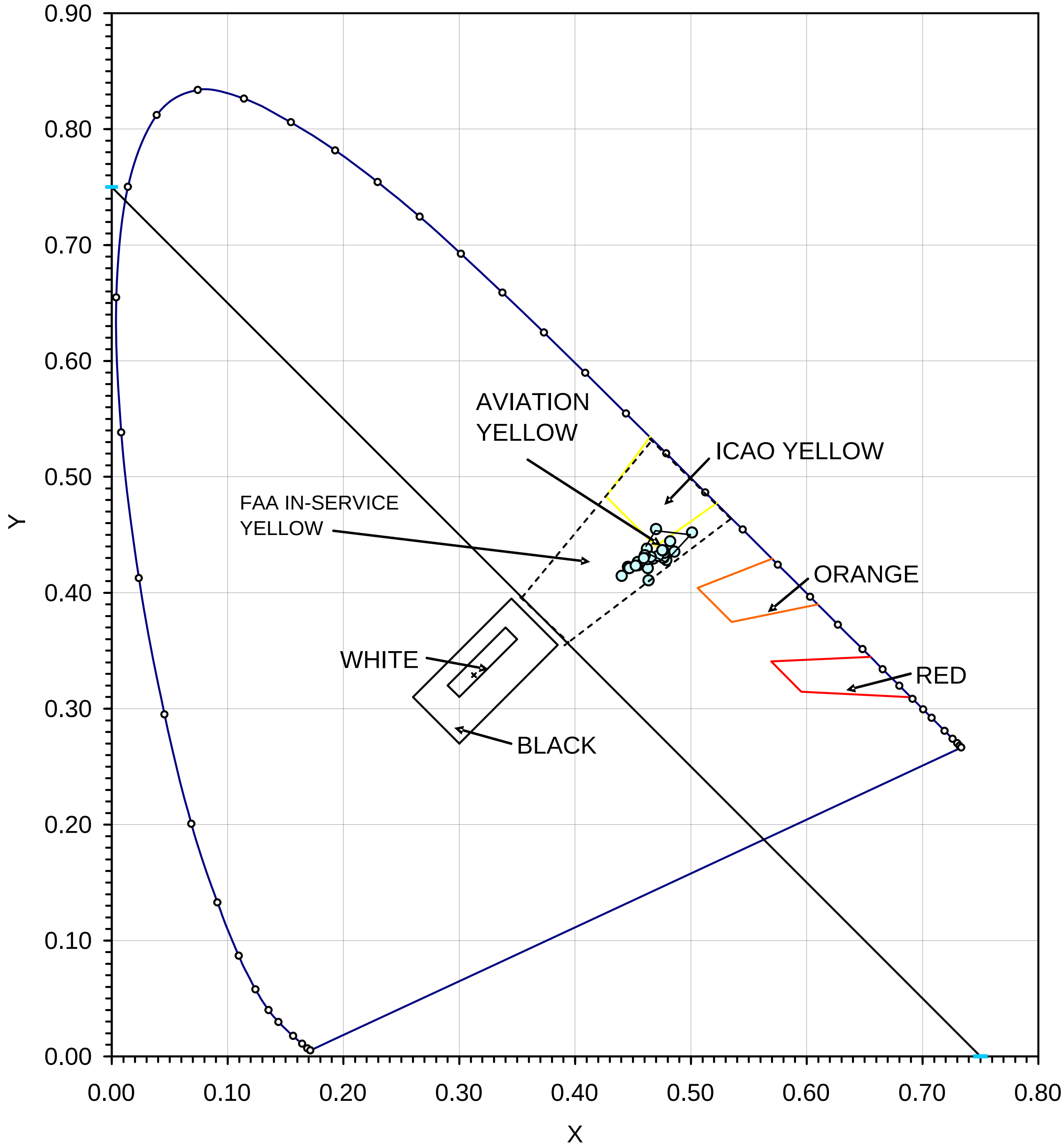

Figure A-23. Chromaticity Readings of Manufacturer A Bead on Aged Hot-Mix Asphalt

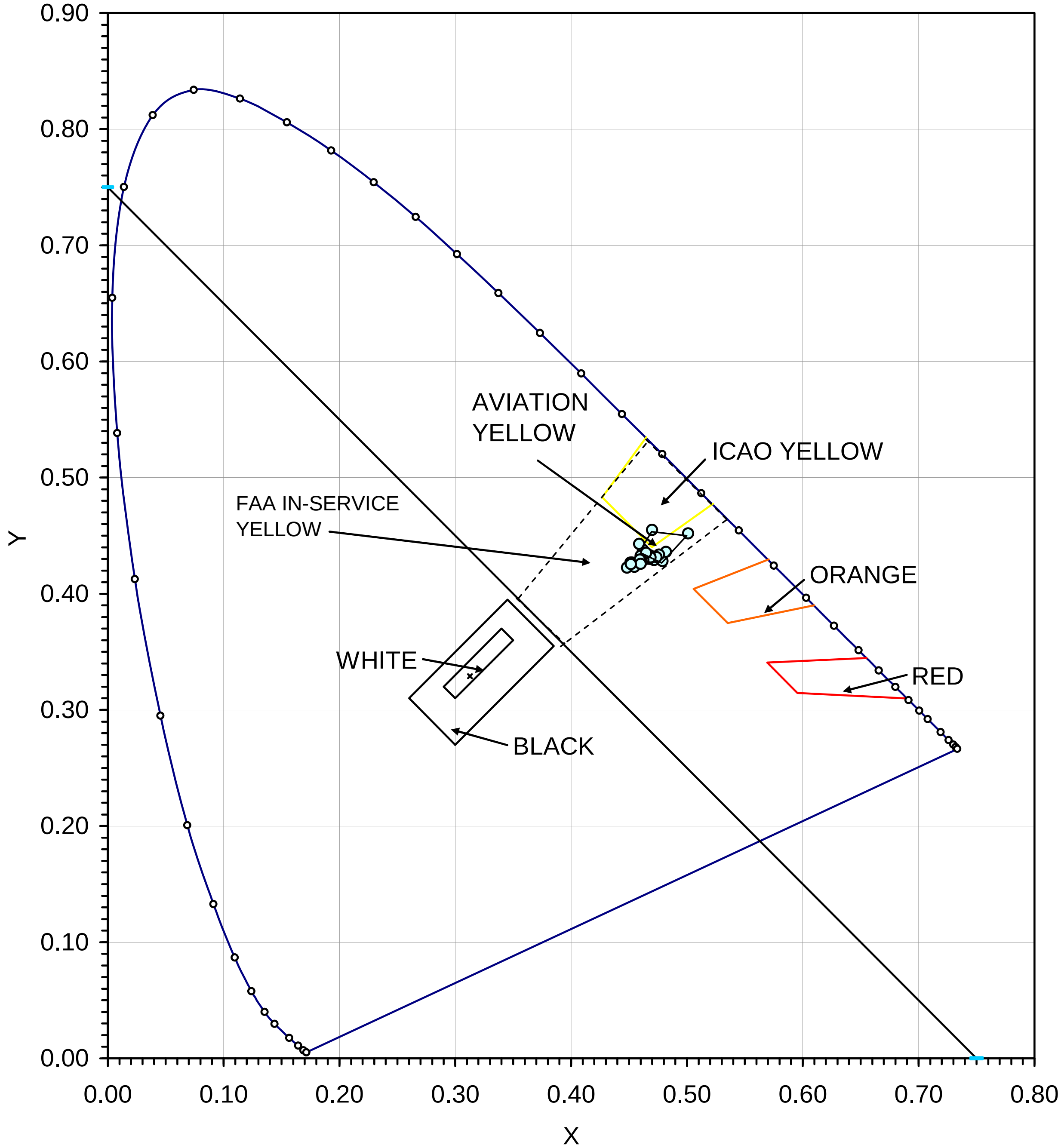

Figure A-24. Chromaticity Readings of Manufacturer B Bead on Aged Hot-Mix Asphalt

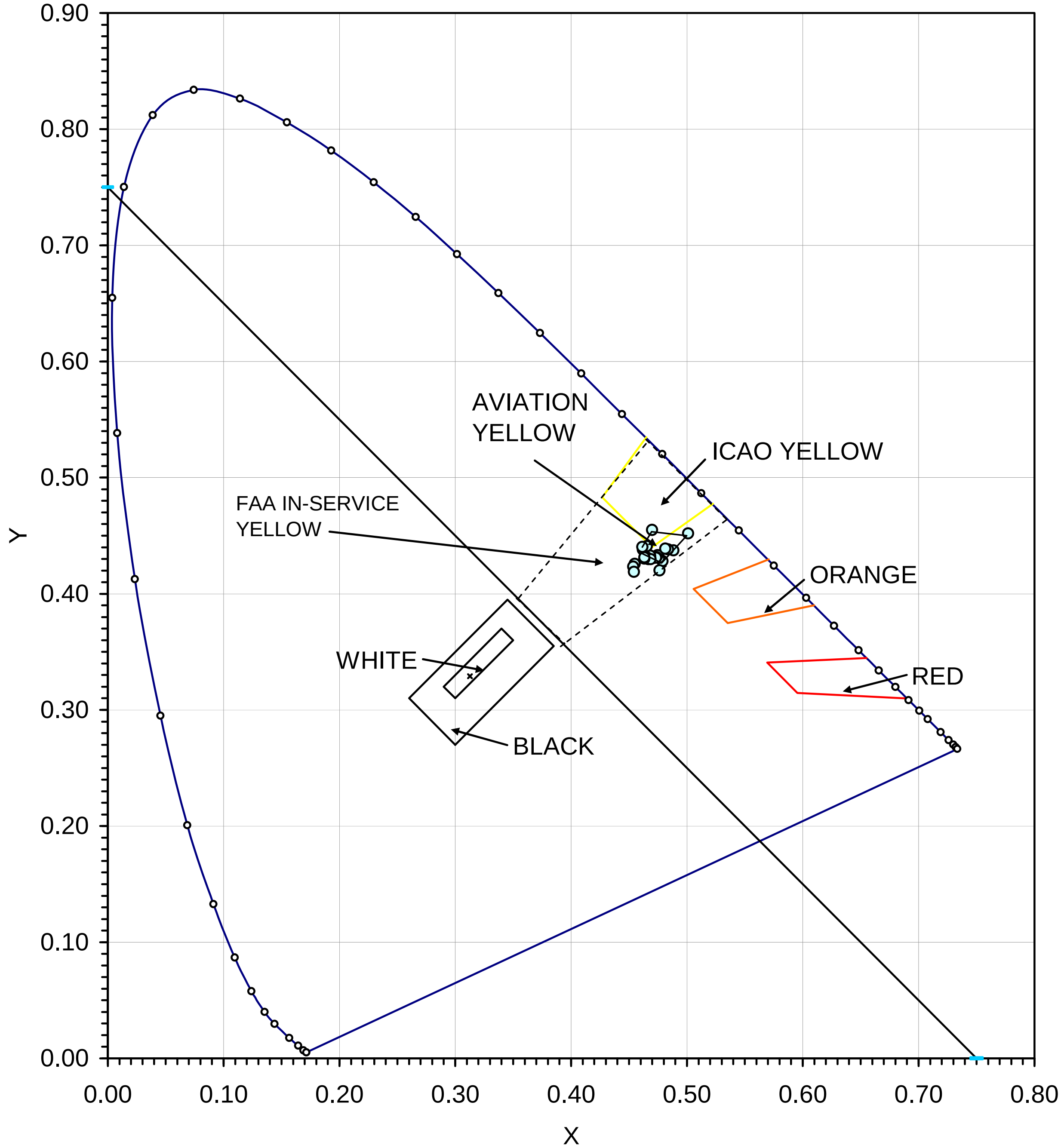

Figure A-25. Chromaticity Readings of No Bead on Aged Hot-Mix Asphalt

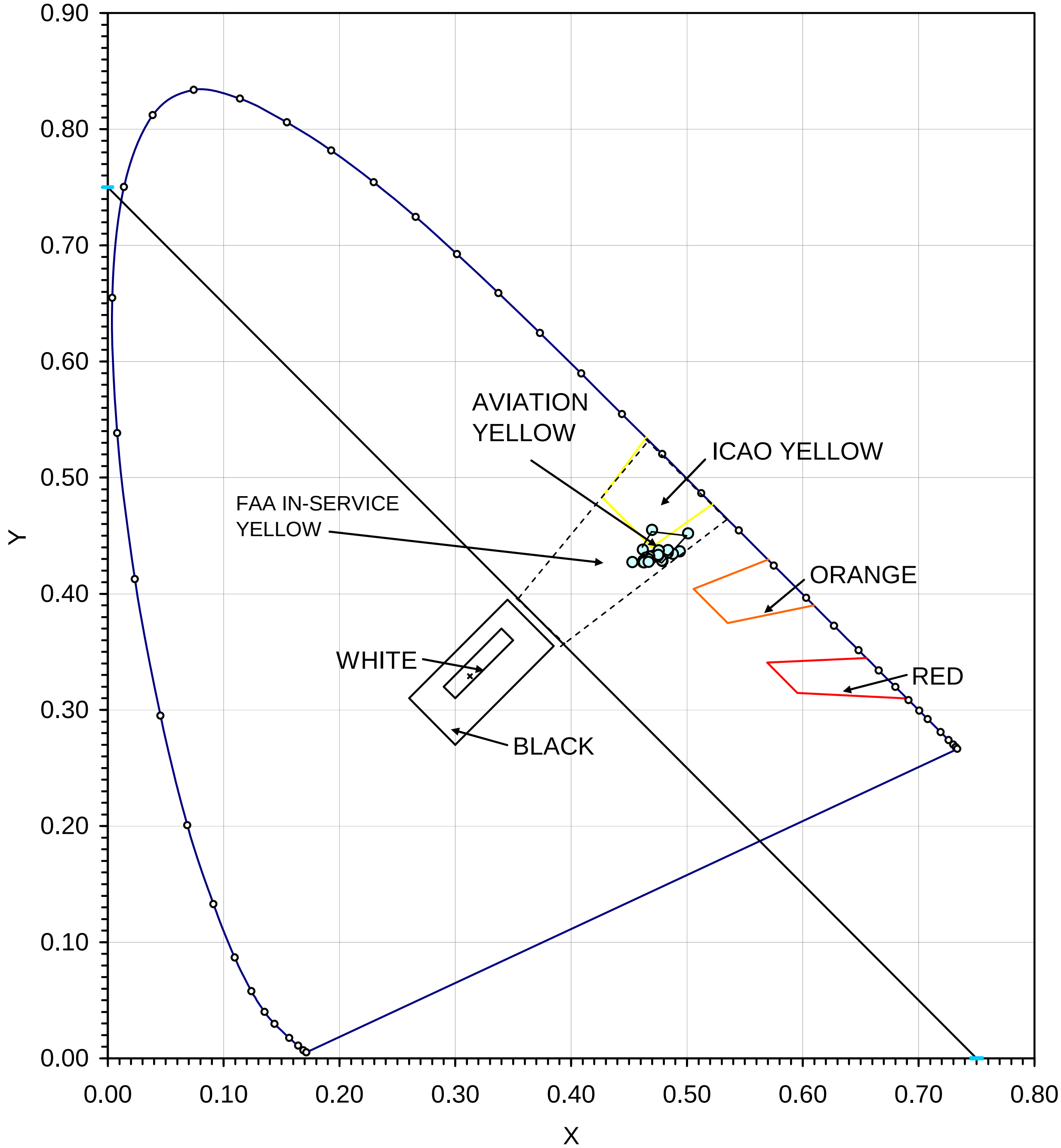

Figure A-26. Chromaticity Readings of Type I Bead on Aged Hot-Mix Asphalt

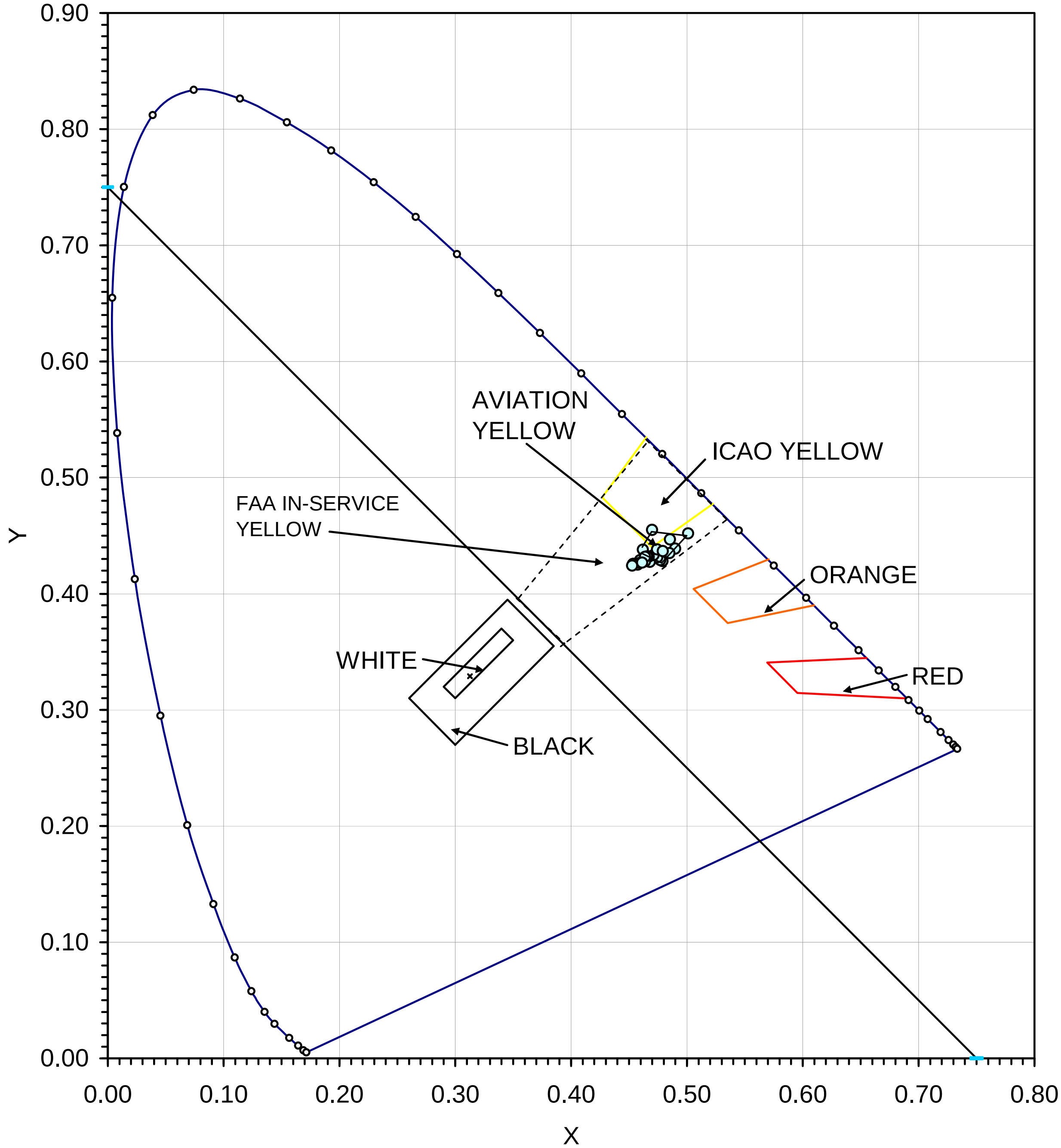

Figure A-27. Chromaticity Readings of Type III Bead on Aged Hot-Mix Asphalt

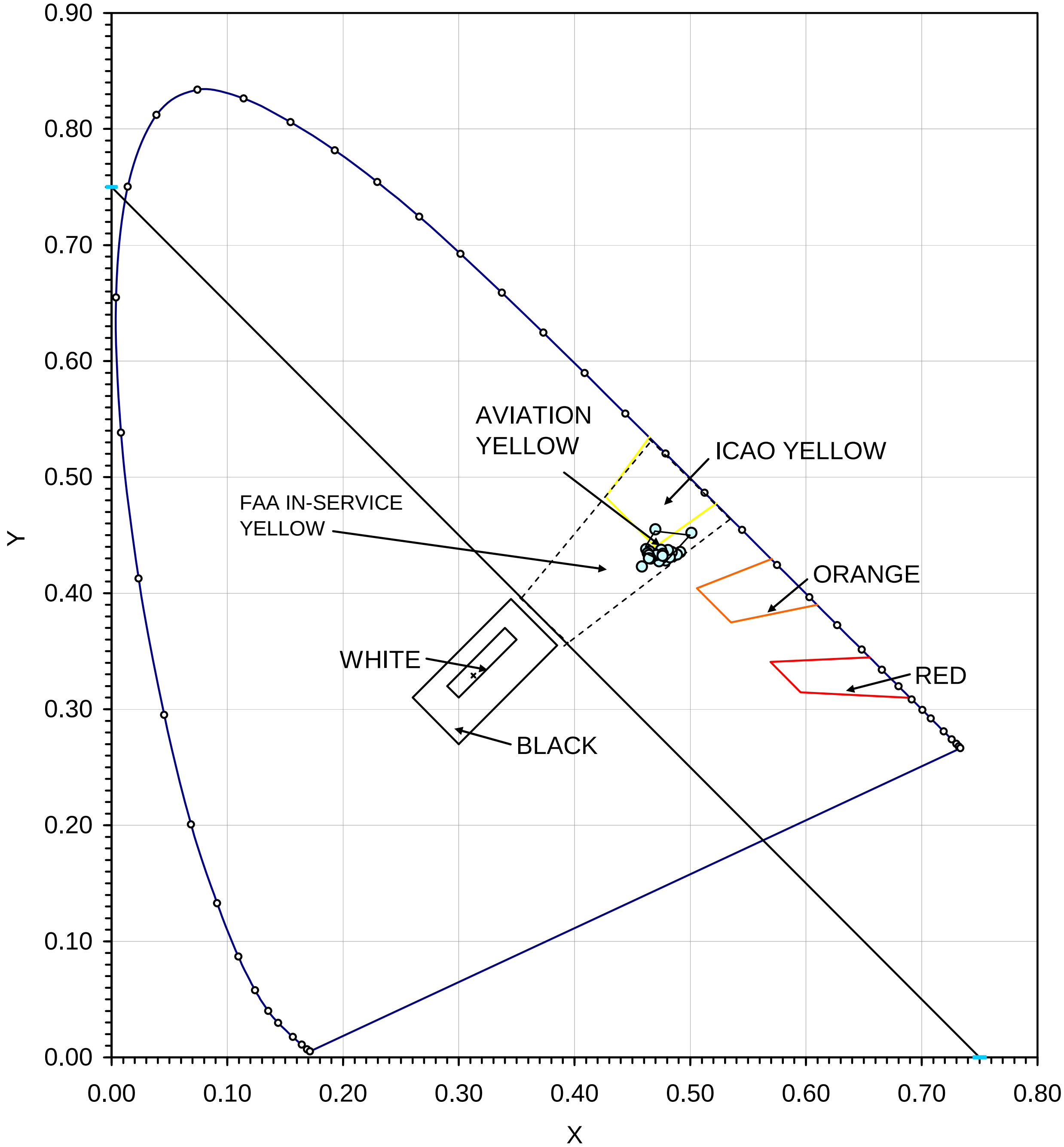

Figure A-28. Chromaticity Readings of Type IV Bead on Aged Hot-Mix Asphalt

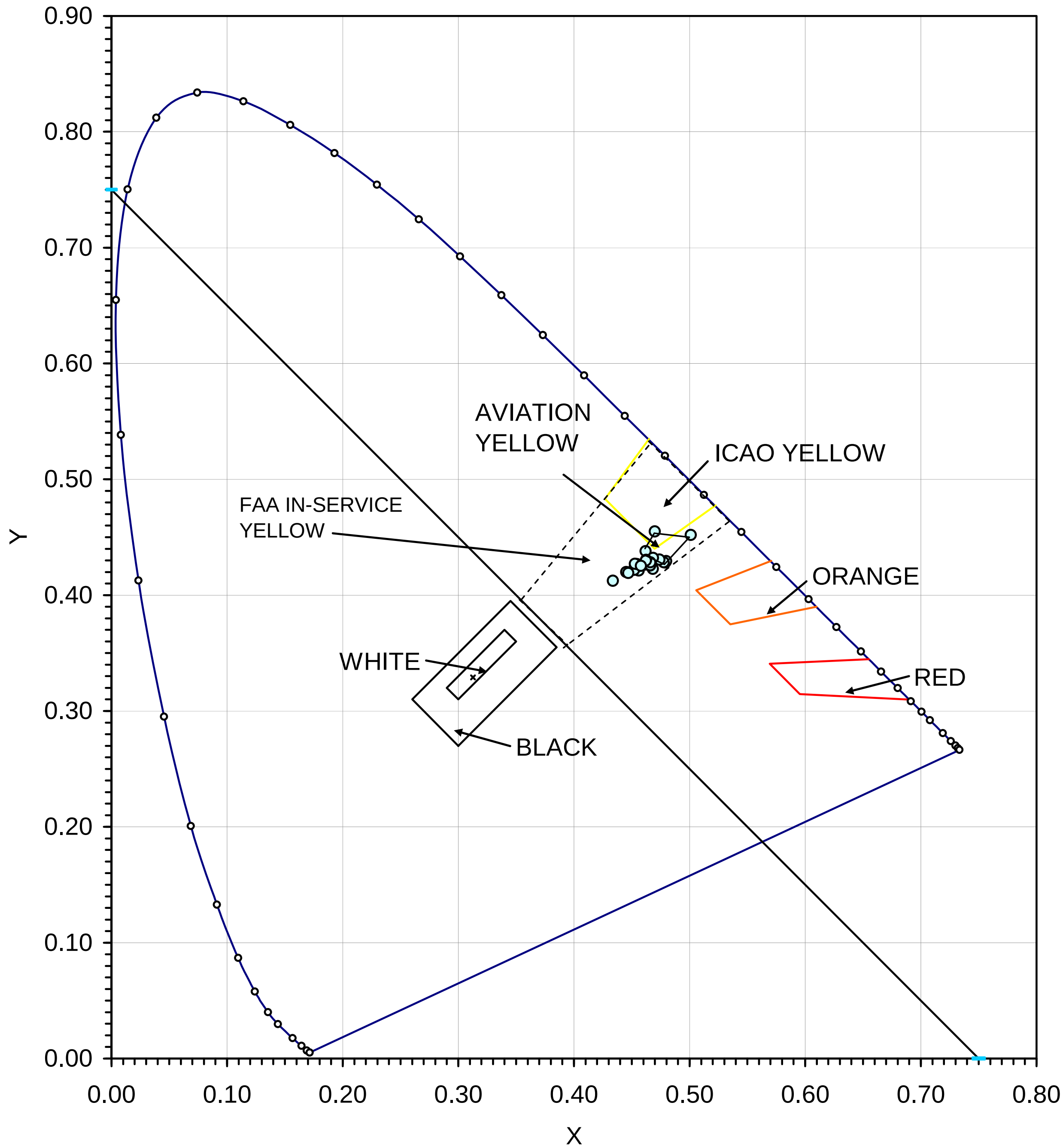

Figure A-29. Chromaticity Readings of Manufacturer A Bead on Aged Hot-Mix Asphalt

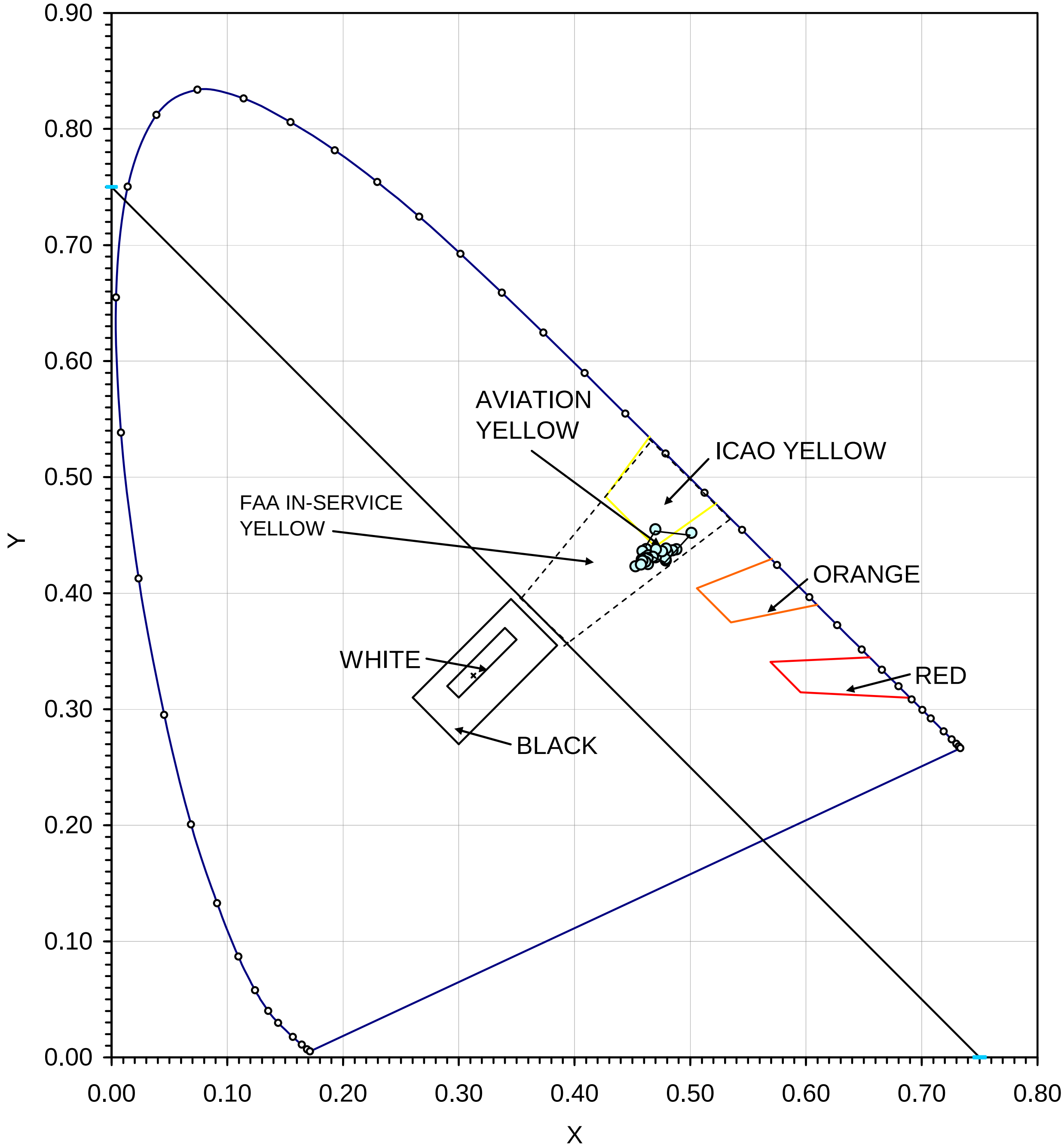

Figure A-30. Chromaticity Readings of Manufacturer B Bead on Aged Hot-Mix Asphalt

APPENDIX B—WATER TESTS

SURFACE MATERIAL—NEW HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
1	No Bead	14	12	14	12
	14 mil	10	10	12	

Skidabrader Water Test	8 Seconds

Continuous Wetting Tests	
Seconds	$mcd/m^2/lx$
Initial	8
10	7
20	9
30	6
40	8
50	8
60	9

2-Liter Recovery Test	
Minutes	$mcd/m^2/lx$
Initial	6
1	9
2	9
3	10
4	11
5	11
6	12

Figure B-1. Water Tests of No Bead Marking on New Hot-Mix Asphalt

SURFACE MATERIAL—HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
2	Type I	102	144	3	85
	14 mil	92	69	100	

Skidabrader Water Test	13 Seconds
Continuous Wetting Tests	
Seconds	mcd/m²/lx
Initial	8
10	9
20	8
30	9
40	8
50	8
2-Liter Recovery Test	
Minutes	mcd/m²/lx
Initial	9
1	19
2	21
3	23
4	22
5	22
6	22

Figure B-2. Water Tests of Type I Bead Marking on New Hot-Mix Asphalt

SURFACE MATERIAL—HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
3	Type III	239	249	217	176
	14 mil	125	71	152	

Skidabrader Water Test	11 Seconds
Continuous Wetting Tests	
Seconds	mcd/m²/lx
Initial	8
10	9
20	8
30	9
40	8
50	8
2-Liter Recovery Test	
Minutes	mcd/m²/lx
Initial	5
1	3
2	5
3	5
4	4
5	6
6	5
7	4
8	5
9	6
10	6
11	5
12	6
13	6

Figure B-3. Water Tests of Type III Bead Marking on new Hot-Mix Asphalt

SURFACE MATERIAL—HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
4	Type IV	31	144	214	166
	18 mil	175	252	179	
	Skidabrader Water Test		10 Seconds		
	Continuous Wetting Tests				
	Seconds		$mcd/m^2/lx$		
	Initial		11		
	10		9		
	20		9		
	30		8		
	40		8		
	2-Liter Recovery Test				
	Minutes		$mcd/m^2/lx$		
	Initial		4		
	1		7		
	2		10		
	3		9		
	4		9		
	5		9		

Figure B-4. Water Tests of Type IV Bead Marking on New Hot-Mix Asphalt

SURFACE MATERIAL—HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
5	Manufacturer A	31	23	56	46
	25 mil	54	24	86	
	Skidabrader Water Test		9 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m²/lx		
	Initial		9		
	10		9		
	20		10		
	30		10		
	40		9		
	2-Liter Recovery Test				
	Minutes		mcd/m²/lx		
	Initial		1		
	1		3		
	2		3		
	3		6		
	4		4		
	5		4		
	6		4		

Figure B-5. Water Tests of Manufacturer A Bead Marking on New Hot-Mix Asphalt

SURFACE MATERIAL—HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
6	Manufacturer B	45	33	2	46
	25 mil	40	68	87	

Skidabrader Water Test	5 Seconds
Continuous Wetting Tests	
Seconds	$mcd/m^2/lx$
Initial	10
10	10
20	10
2-Liter Recovery Test	
Minutes	$mcd/m^2/lx$
Initial	3
1	2
2	3
3	5
4	6
5	5
6	6
7	6
8	6

Figure B-6. Water Tests of Manufacturer B Bead Marking on New Hot-Mix Asphalt

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
7	No Bead	40	35	21	33
	14 mil	39	42	18	

Skidabrader Water Test	7 Seconds
Continuous Wetting Tests	
Seconds	$mcd/m^2/lx$
Initial	16
10	13
20	16
30	12
40	16
50	11
60	12
70	11
2-Liter Recovery Test	
Minutes	$mcd/m^2/lx$
Initial	1
1	9
2	14
3	18
4	23
5	28
6	32
7	33
8	33
9	35
10	34

Figure B-7. Water Tests of No Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
8	Type I	143	175	178	143
	14 mil	156	136	70	
	Skidabrader Water Test		11 Seconds		
	Continuous Wetting Tests				
	Seconds		$mcd/m^2/lx$		
	Initial		16		
	10		21		
	20		9		
	30		18		
	40		11		
	50		10		
	60		11		
	70		11		
	2-Liter Recovery Test				
	Minutes		$mcd/m^2/lx$		
	Initial		34		
	1		79		
	2		116		
	3		141		
	4		164		

Figure B-8. Water Tests of Type I Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings ($mcd/m^2/lx$)			Average
9	Type III	371	443	424	404
	14 mil	399	395	393	
	Skidabrader Water Test		7 Seconds		
	Continuous Wetting Tests				
	Seconds		$mcd/m^2/lx$		
	Initial		25		
	10		13		
	20		14		
	30		17		
	40		15		
	50		18		
	60		13		
	70		24		
	80		31		
	90		23		
	100		27		
	110		26		
	120		26		
	2-Liter Recovery Test				
	Minutes		$mcd/m^2/lx$		
	Initial		37		
	1		56		
	2		59		
	3		64		
	4		97		
	5		117		
	6		135		
	7		149		
	8		171		
	9		193		
	10		221		
	11		265		
	12		361		
	13		440		

Figure B-9. Water Tests of Type III Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m^2/lx)			Average
10	Type IV	329	267	247	272
	18 mil	338	297	151	

Skidabrader Water Test	6 Seconds
Continuous Wetting Tests	
Seconds	mcd/m^2/lx
Initial	13
10	14
20	11
30	13
40	11
50	12
60	11
70	11
2-Liter Recovery Test	
Minutes	mcd/m^2/lx
Initial	2
1	36
2	68
3	81
4	95
5	112
6	110
7	113
8	126
9	154
10	162
11	176
12	187
13	202
14	212
15	223
16	233
17	245
18	255
19	274
20	287

Figure B-10. Water Tests of Type IV Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

<table>
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<tr><td>11</td><td>Manufacturer A</td><td>512</td><td>314</td><td>98</td><td rowspan="2">325</td></tr>
<tr><td></td><td>25 mil</td><td>350</td><td>526</td><td>149</td></tr>
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<tr><td></td><td colspan="4">2-Liter Recovery Test</td><td></td></tr>
<tr><td></td><td colspan="2">Minutes</td><td colspan="2">mcd/m²/lx</td><td></td></tr>
<tr><td></td><td colspan="2">Initial</td><td colspan="2">3</td><td></td></tr>
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Figure B-11. Water Tests of Manufacturer A Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED PORTLAND CEMENT CONCRETE
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
12	Manufacturer B	572	700	418	584
	25 mil	656	622	535	
	Skidabrader Water Test		5 Seconds		
	Continuous Wetting Tests				
	Seconds	mcd/m²/lx	Seconds	mcd/m²/lx	
	Initial	19	80	25	
	10	27	90	29	
	20	25	100	32	
	30	19	110	20	
	40	28	120	33	
	50	32	130	33	
	60	26	140	30	
	70	35			
	2-Liter Recovery Test				
	Minutes	mcd/m²/lx	Minutes	mcd/m²/lx	
	Initial	22	15	124	
	1	54	16	135	
	2	64	17	141	
	3	85	18	159	
	4	90	19	176	
	5	92	20	211	
	6	95	21	254	
	7	97	22	342	
	8	100	23	406	
	9	103	24	447	
	10	105	25	457	
	11	108	26	455	
	12	110	27	455	
	13	113	28	454	
	14	115	29		

Figure B-12. Water Tests of Manufacturer B Bead Marking on Aged Portland Cement Concrete

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
19	No Bead	43	56	32	46
	14 mil	36	90	17	
	Skidabrader Water Test		7 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m²/lx		
	Initial		10		
	10		10		
	20		12		
	30		13		
	40		11		
	50		11		
	60		11		
	2-Liter Recovery Test				
	Minutes		mcd/m²/lx		
	Initial		0		
	1		20		
	2		27		
	3		30		
	4		32		
	5		35		
	6		37		
	7		42		
	8		47		

Figure B-13. Water Tests of No Bead Marking on Aged Hot-Mix Asphalt

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
20	Type I	181	209	215	192
	14 mil	201	235	110	
	Skidabrader Water Test		5 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m²/lx		
	Initial		12		
	10		13		
	20		12		
	30		12		
	40		12		
	2-Liter Recovery Test				
	Minutes		mcd/m²/lx		
	Initial		2		
	1		42		
	2		57		
	3		66		
	4		85		
	5		109		
	6		133		
	7		179		
	8		239		

Figure B-14. Water Tests of Type I Bead Marking on Aged Hot-Mix Asphalt

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
21	Type III	443	433	488	498
	14 mil	534	597	491	
	Skidabrader Water Test		6 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m²/lx		
	Initial		16		
	10		12		
	20		12		
	30		13		
	40		12		
	50		13		
	60		13		
	2-Liter Recovery Test				
	Minutes		mcd/m²/lx		
	Initial		11		
	1		131		
	2		183		
	3		212		
	4		255		
	5		330		
	6		474		
	7		506		

Figure B-15. Water Tests of Type III Bead Marking on Aged Hot-Mix Asphalt

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m^2/lx)			Average
22	Type IV	213	254	253	250
	18 mil	236	293	252	
	Skidabrader Water Test		4 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m^2/lx		
	Initial		11		
	10		11		
	20		15		
	30		14		
	40		15		
	50		15		
	2-Liter Recovery Test				
	Minutes		mcd/m^2/lx		
	Initial		3		
	1		32		
	2		53		
	3		74		
	4		94		
	5		113		
	6		142		
	7		180		
	8		215		
	9		225		
	10		226		
	11		227		
	12		227		

Figure B-16. Water Tests of Type IV Bead Marking on Aged Hot-Mix Asphalt

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m²/lx)			Average
23	Manufacturer A	432	449	308	365
	25 mil	369	435	198	
	Skidabrader Water Test		4 Seconds		

Continuous Wetting Tests	
Seconds	mcd/m²/lx
Initial	30
10	32
20	30
30	34
40	30
50	26
60	35
70	24
80	64
90	22
100	26
110	23
120	37
130	29
140	21
150	21

2-Liter Recovery Test	
Minutes	mcd/m²/lx
Initial	47
1	145
2	166
3	174
4	179
5	184
6	186
7	185
8	185

Figure B-17. Water Tests of Manufacturer A Bead Marking on Aged Hot-Mix Asphalt

SURFACE MATERIAL—AGED HOT-MIX ASPHALT
12-Inch-Wide by 6-Foot-Long Edge Line

Marking No.	Yellow	Retro-Reflective Readings (mcd/m^2/lx)			Average
24	Manufacturer B	354	379	312	351
	25 mil	363	338	359	
	Skidabrader Water Test		3 Seconds		
	Continuous Wetting Tests				
	Seconds		mcd/m^2/lx		
	Initial		14		
	10		17		
	20		15		
	30		15		
	40		18		
	50		16		
	60		21		
	70		17		
	80		17		
	90		17		
	2-Liter Recovery Test				
	Minutes		mcd/m^2/lx		
	Initial		22		
	1		70		
	2		79		
	3		85		
	4		92		
	5		112		
	6		209		
	7		267		
	8		308		
	9		355		

Figure B-18. Water Tests of Manufacturer B Bead Marking on Aged Hot-Mix Asphalt

APPENDIX C—RETRO-REFLECTIVITY

Table C-1. Average Retro-Reflectivity Readings of Test Markings at Test Site One on New Hot-Mix Asphalt

Marking Number	Bead Type	AUG 2008	SEP 2008	OCT 2008	NOV 2008	DEC 2008	JAN 2009	FEB 2009	MAR 2009	APR 2009	MAY 2009	JUN 2009
1	No bead	30	12	11	14	17	18	15	20	19	23	19
2	Type I	199	94	82	58	60	70	59	53	54	55	46
3	Type III	599	222	119	149	67	85	68	47	64	59	55
4	Type IV	356	122	139	92	82	119	98	97	76	86	67
5	A	352	47	20	35	41	34	30	33	26	29	27
6	B	367	64	71	39	70	61	57	43	70	62	49

*Readings measured in mcd/m^2/lx per month and year

Table C-2. Average Retro-Reflectivity Readings of Test Markings at Test Site Two on Aged Portland Cement Concrete

Marking Number	Bead Type	Readings measured in mcd/m^2/lx per Month and Year										
		AUG 2008	SEP 2008	OCT 2008	NOV 2008	DEC 2008	JAN 2009	FEB 2009	MAR 2009	APR 2009	MAY 2009	JUN 2009
7	No bead	39	35	36	39	38	39	41	41	40	39	39
8	Type I	174	195	186	190	182	163	173	113	195	147	170
9	Type III	601	466	435	566	439	404	367	318	386	355	347
10	Type IV	363	303	314	376	315	336	364	310	319	339	298
11	A	303	422	388	233	325	334	399	254	360	366	416
12	B	510	595	636	579	602	634	743	538	609	547	535
13	No bead	37	36	35	37	36	37	40	39	39	38	36
14	Type I	202	172	179	200	177	182	181	170	181	172	164
15	Type III	445	350	392	433	351	400	398	316	288	329	343
16	Type IV	381	322	359	365	313	372	380	294	375	364	325
17	A	347	417	591	214	348	478	464	306	298	355	435
18	B	312	406	535	267	363	543	452	375	432	362	351

*Readings measured in mcd/m^2/lx per month and year

Note 1. Snow event prior to February 2009 readings. Approximately 1000 gallons of potassium acetate applied to airfield areas.

Note 2. Snow event prior to March 2009 readings. Approximately 2000 gallons of potassium acetate applied to airfield areas.

Table C-3. Average Retro-Reflectivity Readings of Test Markings at Test Site Three on Aged Hot-Mix Asphalt

Marking Number	Bead Type	Readings measured in mcd/m²/lx per Month and Year										
		AUG 2008	SEP 2008	OCT 2008	NOV 2008	DEC 2008	JAN 2009	FEB 2009	MAR 2009	APR 2009	MAY 2009	JUN 2009
19	No bead	52	58	44	80	41	74	42	31	41	36	31
20	Type I	206	222	228	206	118	196	129	149	145	165	144
21	Type III	442	510	471	438	215	398	159	130	133	145	145
22	Type IV	211	228	243	259	209	233	182	129	131	119	128
23	A	259	384	302	233	193	257	136	109	117	109	118
24	B	222	401	286	249	239	272	149	169	159	156	167
25	No bead	34	25	25	34	19	29	30	24	27	26	25
26	Type I	239	210	189	226	144	198	173	117	146	129	132
27	Type III	774	552	570	585	328	578	294	151	215	184	219
28	Type IV	325	278	252	331	257	327	266	174	240	219	173
29	A	348	400	449	315	353	408	111	122	114	179	191
30	B	223	312	255	249	231	347	176	146	167	186	171

*Readings measured in mcd/m^2/lx per month and year

Note 1. Snow event prior to February 2009 readings. Approximately 1000 gallons of potassium acetate applied to airfield areas.

Note 2. Snow event prior to March 2009 readings. Approximately 2000 gallons of potassium acetate applied to airfield areas.

APPENDIX D—FRICTION TESTS

Table D-1. Bare Pavement Friction Test Runs at Test Site Two on Aged Portland Cement Concrete

September 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
1	Bare pavement	0.61	36	7	Bare pavement	0.62	41
2	Bare pavement	0.54	40	14	Bare pavement	0.62	37
3	Bare pavement	0.53	41	21	Bare pavement	0.61	39
Bare pavement average friction: 0.56 µ				Bare pavement average friction: 0.56 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 39 mph			

Table D-2. Bare Pavement Friction Test Runs at Test Site Three on Aged Hot-Mix Asphalt

September 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
4	Bare pavement	0.84	43	7	Bare pavement	0.89	43
5	Bare pavement	0.84	41	14	Bare pavement	0.90	37
6	Bare pavement	0.84	40	21	Bare pavement	0.92	42
Bare pavement average friction: 0.84 µ				Bare pavement average friction: 0.90 µ			
Average vehicle speed: 41 mph				Average vehicle speed: 41 mph			

Table D-3. Friction Test Runs of Marking 13 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
1	No beads	0.58	41	1	No beads	0.65	38
7	No beads	0.67	37	8	No beads	0.60	40
13	No beads	0.64	39	15	No beads	0.60	36
Marking number 13 average friction: 0.63 µ				Marking number 13 average friction: 0.63 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 39 mph			

Table D-4. Friction Test Runs of Marking 14 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
2	Type I	0.49	39	2	Type I	0.55	36
8	Type I	0.51	41	9	Type I	0.47	40
14	Type I	0.52	37	16	Type I	0.50	37
Marking number 14 average friction: 0.50 µ				Marking number 14 average friction: 0.50 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 39 mph			

Table D-5. Friction Test Runs of Marking 15 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
3	Type III	0.48	40	3	Type III	0.62	37
9	Type III	0.52	38	10	Type III	0.52	40
15	Type III	0.49	37	17	Type III	0.48	40
Marking number 15 average friction: 0.50 µ				Marking number 15 average friction: 0.50 µ			
Average vehicle speed: 38 mph				Average vehicle speed: 38 mph			

Table D-6. Friction Test Runs of Marking 16 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
4	Type IV	0.44	37	4	Type IV	0.59	38
10	Type IV	0.43	39	11	Type IV	0.43	38
16	Type IV	0.42	38	18	Type IV	0.42	38
Marking number 16 average friction: 0.43 µ				Marking number 16 average friction: 0.43 µ			
Average vehicle speed: 38 mph				Average vehicle speed: 38 mph			

Table D-7. Friction Test Runs of Marking 17 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)
5	Manufacturer A	0.87	37	5	Manufacturer A	0.83	37
11	Manufacturer A	0.93	37	12	Manufacturer A	0.80	40
17	Manufacturer A	0.91	36	19	Manufacturer A	0.80	40
Marking number 17 average friction: 0.90 μ				Marking number 17 average friction: 0.90 μ			
Average vehicle speed: 37 mph				Average vehicle speed: 37 mph			

Table D-8. Friction Test Runs of Marking 18 on Aged Portland Cement Concrete

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)
6	Manufacturer B	0.85	38	6	Manufacturer B	0.83	39
12	Manufacturer B	0.86	41	13	Manufacturer B	0.85	39
18	Manufacturer B	0.83	38	20	Manufacturer B	0.80	40
Marking number 18 average friction: 0.85 μ				Marking number 18 average friction: 0.85 μ			
Average vehicle speed: 39 mph				Average vehicle speed: 39 mph			

Table D-9. Friction Test Runs of Marking 25 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of μ	Average Vehicle Speed (mph)
19	No beads	0.67	41	6	No beads	0.48	42
25	No beads	0.64	40	8	No beads	0.49	39
31	No beads	0.54	42	15	No beads	0.55	34
Marking number 25 average friction: 0.62 μ				Marking number 25 average friction: 0.51 μ			
Average vehicle speed: 41 mph				Average vehicle speed: 38 mph			

Table D-10. Friction Test Runs of Marking 26 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
20	Type I	0.69	41	4	Type I	0.63	41
26	Type I	0.64	37	10	Type I	0.66	41
32	Type I	0.57	39	17	Type I	0.65	39
Marking number 26 average friction: 0.63 µ				Marking number 26 average friction: 0.65 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 40 mph			

Table D-11. Friction Test Runs of Marking 27 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
21	Type III	0.65	38	2	Type III	0.62	42
27	Type III	0.61	40	12	Type III	0.56	42
33	Type III	0.53	39	19	Type III	0.59	41
Marking number 27 average friction: 0.60 µ				Marking number 27 average friction: 0.59 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 42 mph			

Table D-12. Friction Test Runs of Marking 28 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
22	Type IV	0.84	42	5	Type IV	0.55	41
28	Type IV	0.48	44	9	Type IV	0.54	39
34	Type IV	0.59	41	16	Type IV	0.51	37
Marking number 28 average friction: 0.64 µ				Marking number 28 average friction: 0.53 µ			
Average vehicle speed: 42 mph				Average vehicle speed: 39 mph			

Table D-13. Friction Test Runs of Marking 29 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
23	Manufacturer A	0.86	40	3	Manufacturer A	0.53	43
29	Manufacturer A	0.86	40	11	Manufacturer A	0.59	40
35	Manufacturer A	0.76	41	18	Manufacturer A	0.60	42
Marking number 29 average friction: 0.83 µ				Marking number 29 average friction: 0.57 µ			
Average vehicle speed: 40 mph				Average vehicle speed: 42 mph			

Table D-14. Friction Test Runs of Marking 30 on Aged Hot-Mix Asphalt

August 2008				June 2009			
Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)	Test Run Number	Bead Type	Average Friction Value of µ	Average Vehicle Speed (mph)
24	Manufacturer B	0.91	40	1	Manufacturer B	0.57	40
30	Manufacturer B	0.89	39	13	Manufacturer B	0.55	41
36	Manufacturer B	0.80	39	20	Manufacturer B	0.60	41
Marking number 30 average friction: 0.87 µ				Marking number 30 average friction: 0.57 µ			
Average vehicle speed: 39 mph				Average vehicle speed: 41 mph			

APPENDIX E—COVERAGE TESTS

Table E-1. Coverage Test Results at Test Site One on New Hot-Mix Asphalt

Marking Number	Bead Type	Paint Coverage (%)
1	No bead	100
2	Type I	100
3	Type III	100
4	Type IV	100
5	Manufacturer A	100
6	Manufacturer B	100

Table E-2. Coverage Test Results at Test Site Two on Aged Portland Cement Concrete

Marking Number	Bead Type	Paint Coverage (%)
7	No bead	100
8	Type I	100
9	Type III	100
10	Type IV	100
11	Manufacturer A	100
12	Manufacturer B	100
13	No bead	100
14	Type I	100
15	Type III	100
16	Type IV	100
17	Manufacturer A	100
18	Manufacturer B	100

Table E-3. Coverage Test Results at Test Site Three on Aged Hot-Mix Asphalt

Marking Number	Bead Type	Paint Coverage (%)
19	No bead	100
20	Type I	100
21	Type III	100
22	Type IV	100
23	Manufacturer A	100
24	Manufacturer B	100
25	No bead	100
26	Type I	100
27	Type III	100
28	Type IV	100
29	Manufacturer A	100
30	Manufacturer B	100