Mitigation Strategies for Early-Age Shrinkage Cracking in Bridge Decks

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Full–Depth Shrinkage Cracking on Prestressed Girder Bridge

Restrained Shrinkage Cracking Test

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MITIGATION STRATEGIES FOR EARLY-AGE SHRINKAGE CRACKING IN BRIDGE DECKS

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16. ABSTRACT

Early-age shrinkage cracking has been observed in many concrete bridge decks in Washington State and elsewhere around the U.S. The cracking increases the effects of freeze-thaw damage, spalling, and corrosion of steel reinforcement, thus resulting in premature deterioration and structural deficiency of the bridges. In this study, the main causes of the early-age cracking in the decks are identified, and concrete mix designs as a strategy to prevent or minimize the shrinkage cracking are evaluated. Different sources (eastern and western Washington) and sizes of aggregates are considered, and the effects of paste content, cementitious materials (cement, fly ash, silica fume, slag), and shrinkage reducing admixture (SRA) are evaluated. A series of fresh, mechanical and shrinkage property tests were performed for each concrete mix. The outcomes of this study identify optimum concrete mix designs as appropriate mitigation strategies to reduce or eliminate early-age shrinkage cracking and thus help minimize shrinkage cracking in the concrete bridge decks, potentially leading to longer service life.

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EXECUTIVE SUMMARY

Early-age shrinkage cracking has been observed in many concrete bridge decks in Washington State and elsewhere around the U.S. The cracking increases the effects of freeze-thaw damage, spalling, and corrosion of steel reinforcement, thus resulting in premature deterioration and potential structural deficiencies in the bridges.

In this research, the main causes of the early-age cracking in the decks were identified, and concrete mix designs as a strategy to prevent or minimize the shrinkage cracking were evaluated. Different sources (i.e., eastern Washington and western Washington) and sizes (i.e., 1.5 in., 2 in. and 2.5 in.) of aggregates were considered, and the effects of paste content, cementitious materials (cement, fly ash, silica fume, slag), and shrinkage reducing admixture (SRA) were evaluated. A series of fresh, mechanical, and shrinkage property tests were performed for each concrete mix.

Based on the experimental evaluation of different mix designs conducted in this study, the following conclusions are obtained: (1) The use of SRA significantly reduces the free and restrained shrinkages of all concrete mixes using aggregates from Washington State; (2) The partial replacement of Portland cement by fly ash decreases the strength of concrete, and concrete containing fly ash cracks earlier than the corresponding concrete without fly ash; (3) Paste volume plays an important role in the free shrinkage of concrete, and concrete mixes with a smaller paste volume have a lower tendency for shrinkage cracking; (4) Concrete cracking resistance is the combined effects of both its flexural (tensile) strength and its free shrinkage property, and the concrete mix with an acceptable tensile strength and low free shrinkage strain is anticipated to have

relatively good cracking resistance; (5) High-range water-reducing admixtures have a significant effect on adjusting the workability of concrete; (6) When several chemicals are used in one concrete mix, it may be difficult to achieve the desired fresh concrete properties, such as air content; and (7) Both the size of coarse aggregates and the source of coarse aggregates play a very important role in the properties of concrete, and larger coarse aggregates reduce both the free shrinkage and restrained shrinkage properties and also minimize the paste content.

Based on the experimental program conducted in this study, the following recommendations are made to improve concrete mix design to mitigate shrinkage cracking in concrete: (1) SRA is recommended to be used in concrete mix to mitigate early-age shrinkage cracking in concrete bridge decks; (2) Adding fly ash or including more fly ash in the partial replacement of cement is not recommended due to its potential effect of lowering early-age strength; (3) Concrete designs with less paste volume are recommended to be used to increase the cracking resistance; (4) Coarse aggregates of as large a size as practical are recommended in construction; and (5) When several cementitious materials and chemical admixtures are used in the same concrete mix, trial batches are recommended to be evaluated before field applications.

In summary, the outcomes of this study identified optimum concrete mix designs as appropriate mitigation strategies to reduce or eliminate early-age shrinkage cracking and thus help minimize shrinkage-associated cracking in the concrete bridge decks, potentially leading to longer service life.

INTRODUCTION

PROBLEM STATEMENT

Early-age shrinkage cracking of concrete bridge decks is a common problem in the U.S. When the induced tensile stress is larger than the tensile strength of the concrete, cracking occurs (Figure 1). According to a survey conducted by Krauss and Rogalla (1996), more than 100,000 bridges in the U.S. experienced early-age transverse cracking problems (Figure 2).

The presence of early-age cracking in concrete bridge decks increases the effects of freeze-thaw damage, spalling due to sulfate and chloride penetration, and corrosion of steel reinforcement, thus resulting in premature deterioration and potential structural deficiencies in the bridges. A recent investigation by the Washington State Department of Transportation (WSDOT) found transverse, full-depth cracks (Figure 3) in the decks of all inspected bridges developed as a result of early-age concrete shrinkage (occurring within 48 hours after the deck concrete is poured). These cracks in the bridge decks provide an avenue for water, de-icing chemicals, sulfates, and other corrosive agents to penetrate into the concrete and substantially diminish the decks' service life. Concrete deck repair is expensive and can result in significant traffic delays. Accordingly, there is an urgent need to reduce the extent of this cracking and thereby prevent the premature deterioration. Even though the concrete materials, concrete mix designs, design specifications and construction technologies have changed over the years, shrinkage cracking still remains a significant problem and is prevalent in construction.

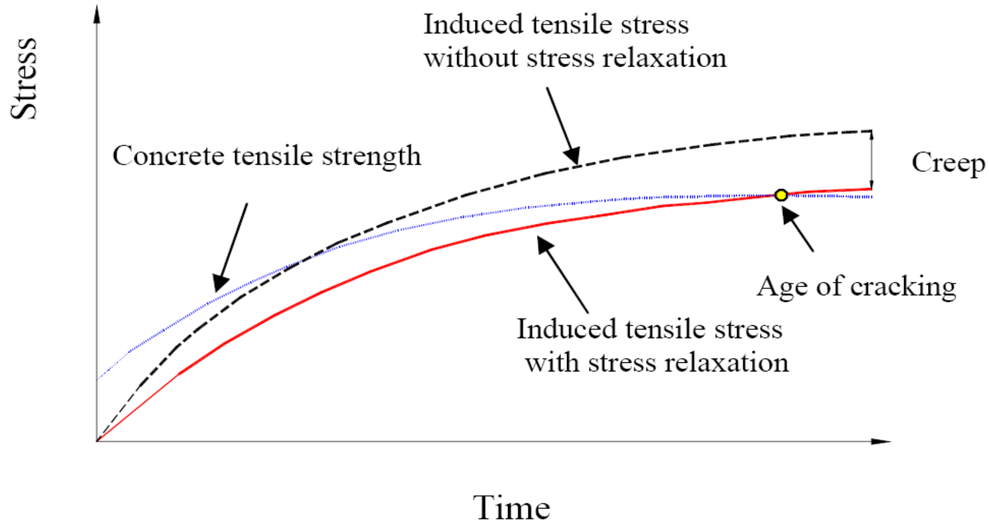


Figure 1 Mechanism of Cracking (from Neville 1996)

Figure 2 Early-age Shrinkage Cracking in Concrete Bridge Decks (Crowl and Sutak 2002)

Figure 3 Transverse, Full-depth Cracks that Developed in a Prestressed Girder Bridge within 48-hours of Pouring

RESEARCH OBJECTIVES

The objectives of the proposed study are five-fold: (1) to determine the primary causes of the transverse shrinkage cracking, (2) to identify appropriate mitigation strategies to reduce or eliminate early-age shrinkage cracking in the concrete bridge decks, (3) to evaluate current WSDOT concrete mix designs for their mechanical and shrinkage-related properties, (4) to develop and evaluate new concrete mix designs using local materials from Washington for their mechanical and shrinkage-related properties, and (5) to recommend improved mix designs and practices to mitigate early-age shrinkage cracking.

REVIEW OF PREVIOUS RESEARCH

This literature review surveys past studies of shrinkage-related research, from which the causes of the early-age cracking in concrete bridge decks are identified and recommendations for appropriate strategies to prevent or minimize this cracking are suggested.

Shrinkage cracking of bridge deck can be affected by many different factors, including material properties, restraint types, construction methods, environmental conditions, etc. Many researchers have performed laboratory studies and literature reviews on shrinkage and cracking potentials of concrete using different kinds of methods. Also, the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM) provide test methods and specifications that can be used to analyze the behavior of concrete. In this section, the previous studies and test methods are reviewed.

TYPES OF SHRINKAGE

Generally there are three different kinds of shrinkage for concrete: plastic shrinkage, autogenous shrinkage and drying shrinkage. Plastic shrinkage and autogenous shrinkage happen at an early age of the concrete, while drying shrinkage takes place over a long period of time.

Plastic Shrinkage

Plastic shrinkage is caused by a rapid loss of water on the concrete surface before the concrete hardens. This loss of water can be caused by many reasons, such as evaporation or suction by a dry sub-base. In fresh concrete, the concrete materials have not formed into a solid matrix and are still surrounded by water. When too much water rapidly evaporates, the water that remains in the concrete will not be sufficient, and voids occur within concrete, leading to the occurrence of plastic shrinkage cracking.

According to Schaels and Hover (1988), environmental conditions, such as wind and temperature, have great influence on plastic shrinkage cracking of concrete. To reduce plastic shrinkage, the rate of water evaporation should be reduced. Therefore, when there are high wind speeds, concrete casting should be avoided, or wind breaks and fogging should be used to prevent water loss. Because water evaporation only happens at the surface, plastic shrinkage cracking only occurs at the surface, and it is usually small.

Autogenous Shrinkage

Autogenous shrinkage happens when the concrete begins to hydrate. It is caused by the self-desiccation of concrete during the hydration process due to lack of water in concrete that has a low water-cement ratio. Autogenous shrinkage is also usually small. However, for concrete using high-range-water-reducing admixture (HRWRA) and fine materials, such as silica fume, it may become an important factor leading to shrinkage cracking (Paillere et al. 1989).

To prevent autogenous shrinkage, low water-cement ratios are not preferred because there is not enough water for the cement to hydrate. When it is necessary to use a low water-cement ratio, other methods should be used to compensate for the lack of water in the concrete mix design.

Drying Shrinkage

Indicated by the pattern of early-age transverse cracking, drying shrinkage is associated with bridge decking shrinkage cracking (Krauss and Rogalla 1996). It is caused by loss of water in the hardened concrete. Drying shrinkage can be explained by three main mechanisms: capillary stress, disjoining pressure and surface tension, each of which plays an important role within a certain range of relative humidity (Mindess et al.

2003). Normally bridge decks will experience relative humidity from 45% to 90%, which is when the capillary stress mechanism plays the important role.

Many factors can directly affect the drying shrinkage of concrete, such as paste volume, water-cement ratio, aggregates type, environment conditions and curing methods. Of all these factors, paste volume is the most important one. Drying shrinkage will be greatly reduced if the paste volume is reduced (Xi et al. 2003; Tritsh et al. 2005; Darwin et al. 2007; Delatte et al. 2007).

Creep

While early-age cracking in bridge deck is mainly due to concrete shrinkage, creep helps to relax shrinkage. The study by Altoubat et al. (2001) found that the tensile creep relaxes the shrinkage stress by 50% and doubles the failure strain capacity. It is generally believed that creep will help reduce shrinkage of concrete, as shown in Figure 1.

EFFECT OF CONCRETE PROPERTIES ON DECK CRACKING

Paste Content and Water-to-cement Ratio

As aforementioned, paste content is a very important factor that affects the shrinkage behavior of bridge decks, since it leads to volume changes. Reducing paste content results in a decrease in free shrinkage (Bissonnette et al. 1999; Darwin et al. 2007). Water content plays two roles: increasing water content increases the shrinkage tendency of concrete and at the same time increases creep. Creep can help reduce shrinkage.

Decreasing the water-to-cement ratio can decrease drying shrinkage; at the same time, it increases autogenous shrinkage. Bissonnette et al. (1999) and Darwin et al.

(2007) stated that free shrinkage is not significantly influenced by the water-to-cement ratio. However, Weiss et al. (1999) concluded that the concrete with a low water-to-cement ratio may be more likely to develop early-age cracking due to increased autogenous shrinkage. Thus, there is no definitive conclusion of the effect of water-to-cement ratio to shrinkage. It is generally believed that a very high water-to-cement ratio will cause more shrinkage.

As a result, the cement content and the water-to-cement ratio are limited to reduce the risk of shrinkage cracking. Literature indicates that a reduced cement content should reduce cracking (Brown et al. 2001). The experimental study by Xi et al. (2003) suggested a concrete mix with a cement or cementitious material content of about 470 lb/yd^3 (279 kg/m^3) and water-to-cement ratio of about 0.4 as a possible optimum mix.

Cement Type

Cement type also plays an important role in shrinkage cracking of bridge decks, as the drying shrinkage of concrete is affected by the cement fineness. Finer cement particles generate greater heat of hydration and require a greater amount of water during the hydration process, which may lead to the increased risk of cracking in the concrete. As a result, Type II Portland cement is preferred to reduce cracking. Replacing Type I/II Portland cement with Type II Portland coarse-ground cement lowers the free shrinkage and shrinkage rate, and adding a shrinkage-reducing admixture (SRA) significantly reduces these values even further (Tritsch et al. 2005).

Aggregates Size and Type

The properties of concrete depend on cement paste and aggregates. In contrast to the cement paste, aggregates have much lower values of shrinkage and creep. When cement paste shrinks, aggregates provide restraint. Krauss and Rogalla (1996) found that aggregate type is the most significant factor affecting concrete cracking. It is generally believed that larger size aggregates decrease the cracking tendency of bridge decks. Large aggregates can form a rigid frame in the concrete, which prevents cement paste from shrinking freely. However, as bridge decks are becoming thinner, the optimized aggregate size to both resist shrinkage cracking and satisfy workability requirements should be evaluated. The properties of aggregates determine the amount of restraint that will be applied to cement paste.

Aggregate has the best restraint when it does not shrink at all. Burrows (1998) found that limestone aggregate has higher resistance to cracking than other types of aggregates. Also, the ratio of elastic moduli of aggregate and cement is important on the shrinkage of concrete. If the ratio of $E_{aggregate} / E_{cement}$ is higher, then the concrete has lower shrinkage potential (Troxell et al. 1958).

Air Content

Past literature shows no definite conclusion about the effect of air content on the shrinkage cracking of bridge decks (Xi et al. 2003). Schmitt and Darwin (1995) suggested that an air content of 6% by volume or more should be considered.

Slump

Slump is used as an indicator of concrete workability. If there is an excessive slump caused by a high water-to-cement ratio, the concrete will have high shrinkage. Krauss and Rogalla (1996) found that concrete mixes with a low water-to-cement ratio, low cement content, and low slump performed best. Generally, the slump of concrete is controlled within a reasonable range, and there is no definite relation between the change of slump and the change of cracking tendency of concrete.

SUPPLEMENTARY CEMENTITIOUS MATERIALS AND ADMIXTURES IN CONCRETE

Silica Fume

Silica fume is a pozzolanic material, and its particle size is about 1.0 µm. The use of silica fume in concrete can achieve a lower permeability, which is good for the durability issues of bridge decks. However, it has a high hydration heat so that it has a higher tendency of plastic shrinkage cracking. Autogenous shrinkage may be aggravated by the use of silica fume as well (Mindess et al. 2003).

NCHRP Report 410 “Silica Fume Concrete for Bridge Decks” concluded that cracking tendency of concrete was influenced by the addition of silica fume only when the concrete was improperly cured. When concrete is cured for 7 days under continuously moist conditions, there is no statistically significant effect of silica fume on the tendency of the concrete to exhibit early-age cracking. Darwin et al. (2007) stated that when cast with a high-absorption coarse aggregate, the addition of silica fume results in a reduction in shrinkage at all ages. Mazloom et al. (2004) studied the replacement of cement with 0%, 6%, 10%, and 15% of silica fume and concluded that the percentage of silica fume replacement did not have a significant influence on the total shrinkage of concrete, but the autogenous shrinkage increased as the increase of silica fume. Krauss and Rogalla (1996) contended that the effect on early-age shrinkage cracking of silica fume is still not clear. Thus, the moderate content of silica fume in a range of 6-8% by mass of cementitious materials in concrete was recommended. When silica fume is used, fog sprays or keeping moist after the placement of concrete is suggested for 7 days continuously (Schmitt and Darwin 1995).

Fly Ash

Fly ash is also a pozzolanic material. It is used to replace part of the Portland cement in the concrete mixture so that the rate of concrete hydration will slow down. Thus, the rate of early-age strength gain is also reduced, which may reduce early-age shrinkage cracking resistance. On the other hand, fly ash may improve workability, enhance the ultimate strength of concrete, and reduce the permeability of concrete. Breitenbucher and Mangold (1994) found that when the cement content of the concrete was lower than 573 lb/yd^3 (340 kg/m^3), fly ash did not significantly influence the cracking tendency during the first 4 or 5 days. However, Darwin et al. (2007) stated that when cast with a high-absorption coarse aggregate, the addition of fly ash increased initial shrinkage and only slightly reduced ultimate shrinkage.

The percentage replacement of fly ash for Portland cement should be evaluated during the application as different amounts of fly ash in a concrete mix affect the properties of the concrete, especially when a lower paste content is considered. Fly ash is now commonly used as an additive in concrete mixtures by many state DOTs.

Two types of fly ash are commonly used: Class F and Class C. Class F fly ash possesses pozzolanic properties but does not have self-cementing properties. Class C fly ash has both pozzolanic and self-cementing properties. The percentage replacement of Portland cement should be determined based on the specific cement being used in the mix (Xi et al. 2003).

Ground Granulated Blast-Furnace Slag (GGBFS)

Ground granulated blast-furnace slag (GGBFS) is added to Portland cement concrete to increase the concrete strength and durability. The use of GGBFS can improve the strength as well as the durability of concrete. NCHRP Report 566 "Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks" recommended that the addition of fly ash or GGBFS to the concrete has only a small effect on the cracking tendency of the concrete if the total cementitious volume is not changed. Cracking (drying shrinkage) may be reduced if the improved workability of the mixture containing the fly ash or GGBFS contributes to reduced water demand and reduced paste volume (Lawler et al. 2007).

Shrinkage-Reducing Admixtures

As discussed before, bridge decks will normally experience relative humidity from 45% to 90%, which is when the capillary stress mechanism plays an important role. Shrinkage-reducing admixtures (SRA) can lower the surface tension of pore water, thus reducing drying shrinkage.

Many researchers have found that the use of SRA in concrete reduced the shrinkage and cracking tendency (Shah et al. 1992; Brown et al. 2001; Tritsch et al. 2005; Brown et al. 2007). Weiss et al. (2002; 2003) stated that SRA significantly enhanced the cracking resistance of concrete by reducing the rate of shrinkage and the overall magnitude of shrinkage. SRA reduces the surface energy of the water so there is less tension to make the concrete shrink. However, research (Folliard and Berke 1997; Weiss et al. 2003) also found that SRA might cause a slight decrease in the compressive strength of concrete.

Fibers

When fibers are added to concrete, the properties of the concrete change in relation to the amount of fiber added. Steel fiber can improve the strength of concrete. Shah and Weiss (2006) stated that the inclusion of randomly distributed steel fibers can slightly delay the age of visible cracking. Because fibers act as restraint inside the concrete, they can reduce the amount of cracking (Sun et al. 2000; Banthia 2000). The fibers only play a role when cracking develops, and they are thus useful primarily for post-cracking control.

Other Factors Related to Shrinkage Cracking

***Restraint Type*:** After concrete hardens, the concrete deck endures restraint from both inside and outside the concrete. Because of the strong composite action between the concrete bridge deck and supporting girders, the outside supporting girders apply strong restraint to the concrete bridge deck, which constrains the shrinkage deformation of the deck. At the same time, the internal reinforcement of the concrete deck also restrains the shrinkage of the concrete and therefore the concrete deck experiences high tensile stress, which may lead to its cracking. French et al. (1999) found that bridge decks on simply-supported prestressed girders showed significantly less cracking than decks on continuous steel girders in their field study. Krauss and Rogalla (1996) found that decks supported by steel girders usually had higher risks of transverse deck cracking and higher tensile stresses than the ones with concrete girder construction. Rogalla et al. (1995) found that larger girder and closer spacing tended to be more prone to cracking. Thus, using smaller girder and wider spacing will reduce the cracking tendency.

***Construction Method*:** Construction method may have a very large influence on the early-age shrinkage cracking of concrete bridge decks. It is suggested that placing positive moment regions successively on one day and then after three days placing negative moment regions may minimize cracking (Issa 1999).

Finishing is also a factor that affects early-age bridge deck shrinkage cracking. The literature indicates that a delayed finishing could cause concrete to crack more easily (Krauss and Rogalla 1996).

Curing is an important factor that influences early-age bridge deck shrinkage cracking. Immediately after finishing, use of wet curing should be applied (Babaei and Purvis 1996).

***Environmental Conditions*:** Concrete should be placed during cool weather to reduce cracking, because the hydration reaction will be slowed down in low temperature, thus reducing the heat that is generated from the hydration process. Thermal stress is controlled to be small, which will help to reduce early-age thermal cracking. Other times that will increase the temperature in concrete during the hydration process should also be avoided, such as the time around noon. The study by French et al. (1999) recommended that the ambient air temperature ranged between highs of approximately 65 to 70 ^{o}F (18 to 21 ^{o}C) and lows of approximately 45 to 50 ^{o}F (7 to 10 ^{o}C).

When the wind is strong, windbreaks should be used to keep the concrete moist and prevent high evaporation of concrete surface water. Windbreaks or fogging should be used if the evaporation rate is more than 0.2 lb/ft^2/hr (9.576 Pa/hr).

TEST METHODS

General Review on Test Methods of Concrete Shrinkage Cracking

Many researchers have developed different methods for evaluating the shrinkage cracking tendency of concrete using a wide range of test apparatus. Tritsch et al. (2005) divided these restrained shrinkage tests into three categories: plate tests, linear tests, and ring tests.

In the plate tests, flat concrete specimens were tested. Different researchers used different specimen dimensions and different test details. These specimens were usually thin, and the maximum aggregate sizes were small or no coarse aggregates were used. In some tests, the results were inconsistent and conflicted with each other. Free shrinkage tests were also considered as an addition to these restrained tests.

The linear test used specimens of rectangular cross section. Specimens of many different dimensions were used in these tests, such as 3.4 x 4.7 x 59 in. (8.5 x 12 x 150 cm) (Paillère et al. 1989) and 1.6 x 1.6 x 39.4 in. (40 x 40 x 1,000 cm) (Bloom and Bentur 1995). In these linear tests, one end of the concrete specimen is fixed, and the other end is connected to an instrument that applies and records the force that is required to keep the specimen in its original length. A companion specimen with the same dimension is also cast, with one end fixed and the other free to shrink, as a control specimen to the restrained one.

The ring test was used by many researchers to evaluate the shrinkage cracking tendency and behavior of concrete and cement-based materials under restraint. It is the most common test method used. Many different concrete rings were tested under a variation of restrained conditions. The dimensions of the concrete ring as well as the test procedure vary greatly from each other. More details on the ring test will be provided later.

Cracking Frame and Fracture Energy

Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les Constructions (RILEM) uses the cracking frame method as the standard test TC 119 for cracking evaluation. The cracking frame, as shown in Figure 4, was developed by Springenschmid (1994) after extensive research on the test methods for restrained shrinkage of concrete was conducted.

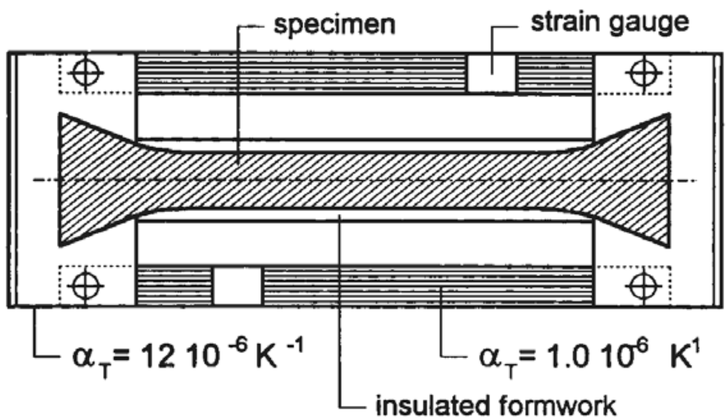


Figure 4 Cracking Frame (Springenschmid et al. 1994)

The cracking frame can be used for the contraction test as well as the expansion test of concrete, and the restraint stresses are recorded continuously. Comparing with the ring test, the cracking frame can represent the actual restraint conditions of the concrete bridge decks caused by the restraint from girders. As shown in Figure 4, the test is made up of a concrete beam and two surrounding steel bars in the longitudinal direction and also two steel cross-heads at each end. In the cracking frame, the concrete can be cooled to the surrounding temperature. It is first inspected for four days. If it does not crack in four days, its temperature is decreased at a fixed rate until cracking occurs. The temperature that cracking occurs is recorded as an indication of the cracking resistance property of the concrete mix in actual service conditions and the lower this temperature, the better the cracking resistance.

Fracture energy of concrete can be used to evaluate the drying shrinkage cracking property of concrete. Guo and Gilbert (2000) showed that the fracture energy could represent the actual amount of energy that is needed for a crack to occur upon unit area or fracture surface. In this test, a three-point bending test is performed upon a notched beam, and the displacement of the beam and corresponding applied load are recorded. By using the recorded load-displacement curve and some data reduction equations, the fracture energy of the beam can be calculated, from which the relation between the fracture energy and the cracking resistance behavior of the beam can be established.

Ring Test Method

As aforementioned, the ring test method is often used to evaluate the relative drying shrinkage cracking tendency of different concrete mixes under different conditions. The ring test restrains the concrete using a steel ring, thus inducing a stress in the surrounding concrete ring. When this stress becomes larger than the tensile strength of the concrete, the concrete ring will crack. The times that it takes for rings made of different concrete mixes to crack are recorded and then compared with each other. The longer it takes a concrete ring specimen to crack, the lower tendency of drying shrinkage cracking it has.

The ring test is simple and easy to conduct. Also, it evaluates most of the important factors that affect the drying shrinkage cracking tendency at one time. Furthermore, the cracking in the concrete ring is easily recognized and recorded. Therefore, the ring test method has become the most popular method for evaluating the restrained drying shrinkage of concrete.

Both the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing and Materials (ASTM) have developed a ring test as one of their standard tests, and they are:

- AASHTO T334-08. "Practice for Estimating the Crack Tendency of Concrete".
- ASTM C 1581-04. "Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage".

***AASHTO Ring Test*:** The AASHTO ring test is used to compare the relative restrained shrinkage cracking tendency of different concrete mix designs. It can be used to compare factors such as cement paste content and water-to-cement ratio, cement type, aggregate size and type, air content, slump and admixtures in concrete as related to the time and cracking relation of concrete. However, it does not take the specific restraint type, the construction method and environmental conditions into consideration, so it cannot predict the concrete cracking in actual service. The standard utilizes the apparatus shown in Figure 5.

The AASHTO standard inside steel ring has a wall thickness of 1/2 ± 1/64 in. (12.7 ± 0.4 mm), an outside diameter of 12 in. (305 mm), and a height of 6 in. (152 mm). However, structural steel pipe conforming to ASTM A501 or A53M/A53 12-in. extrastrong pipe with an outside diameter of 12 ¾ in. (324 mm) and wall thickness 1/2 in. (13 mm) may be used as a substitute. The outer ring can be made of 1/4 in. (6.4 mm) thick cardboard form tube (Sonotube) with an inside diameter of 18 in. (457 mm). Four strain gages are mounted on the inner surface of the steel ring at equidistant points at midheight. Data acquisition equipment shall be compatible with the strain instrumentation and automatically record each strain gage independently. Forms can be made of 24 in. by 24 in. x 5/8 in. (0.6 x 0.6 x 0.016 m) plywood or resin-coated (or polyethylene-coated) plywood sheet. Curing can be applied by using prewetted burlap covered with plastic.

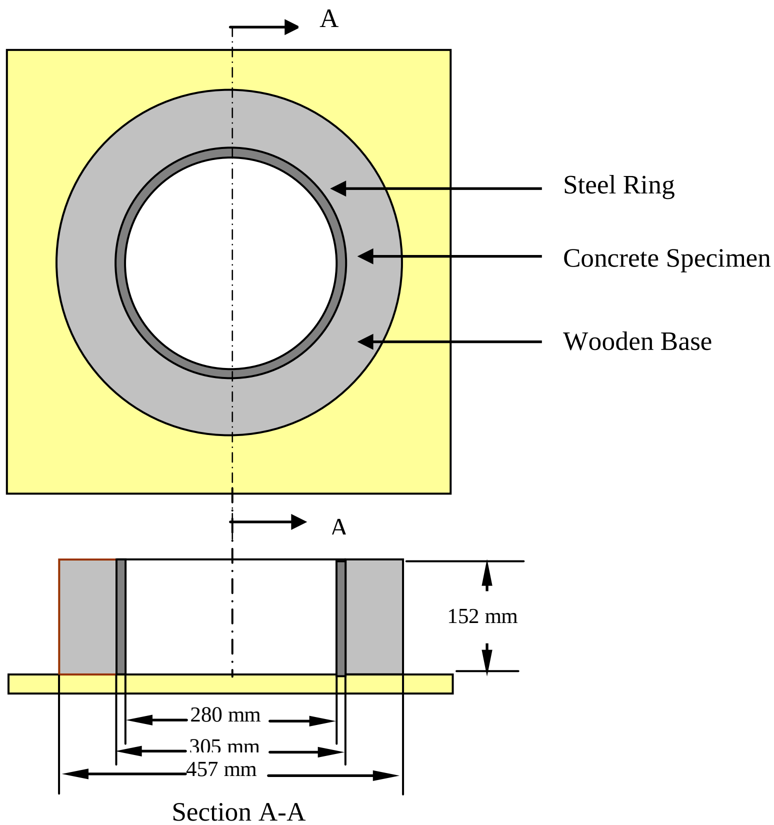


Figure 5 Diagrams of Ring Specimen (Reprinted from AASHTO T334-08)

The outer forms are removed at an age of 24±1 hr, and then the specimens are moved to the conditioning room with a constant air temperature of 73.5 ± 3.5 ^{o}F (23 ± 2

^{o}C) and 50 ± 5 % relative humidity. The time and strain from the strain gages are recorded every 30 minutes, and review of the strain and visual inspection of cracking is conducted every 2 or 3 days. A sudden strain decrease of more than 30 με in one or more strain gages usually indicates cracking. After the concrete ring cracks, the time and the cracking length and width on the exterior radial face are recorded.

***<u>ASTM Ring Test</u>*:** Similarly, the ASTM ring test is also used to evaluate the relative drying shrinkage cracking tendency of concrete under restraint. Slightly different from the AASHTO ring, the ASTM standard inside steel ring has a wall thickness of 0.50 ± 0.05 in. (13 ± 0.12 mm), an outer diameter of 13.0 ± 0.12 in. (330 ± 3.3 mm) and a height of 6.0 ± 0.25 in. (152 ± 6 mm). At least two electrical resistance strain gages are wired in a quarter-bridge configuration. Data acquisition system should be compatible with strain instrumentation and automatically record each strain gage independently with resolution ± 0.0000005 in./in. at intervals no greater than 30 minutes. The base can be made of epoxy-coated plywood or other non-absorptive and non-reactive surface. The outer ring can be made of PVC pipe or Steel outer ring or other, in accordance with F441, with 16.0 ± 0.12 in. (406 ± 3 mm) inside diameter and 6.0 ± 0.25 in. (152 ± 6 mm) height. The testing environment has the condition of 73.5 ± 3.5^{o}F (23.0 ± 2.0^{o}C) and 50 ± 4% relatively humidity. Ambient temperature and relatively humidity are recorded every day. A sudden decrease of more than 30 με in compressive strain in one or both strain gages indicates cracking. After the concrete ring cracks, the time and the cracking length and width on the exterior radial face are recorded. The specimen is monitored for at least 28 days after initiation of drying, unless cracking occurs prior to 28 days.

***Comparison between the AASHTO and ASTM Ring Tests*:** In general, both the AASHTO and the ASTM ring tests follow the same theory and procedures. However, there are some differences between the two methods. The main differences between them are the concrete ring dimensions and the maximum size of aggregates allowed. The AASHTO standard concrete ring is 3 in. (76.2 mm) thick, with an inner diameter of 12 in. (304.8 mm) and an outer diameter of 18 in. (457 mm), whereas the ASTM concrete ring is 1.5 in. (38.1 mm) thick, with an inner diameter of 13 in. (330.2 mm) and an outer diameter of 16 in. (406.4 mm). ASTM requires that the maximum size of aggregate should be less than 1/2 in. (12.7 mm), while there is no specific requirement in the AASHTO. Because the concrete ring is thicker in AASHTO than in ASTM, the AASHTO ring test allows evaluation of larger aggregate sizes. Also, the duration of the ASTM test is 28 days, while there is no specified duration in AASHTO. Because the AASHTO concrete ring is thicker, it will need more time to crack. Typically the AASHTO ring test may last for 56 days to 90 days (Delatte et al. 2007). The curing conditions are also slightly different between the two test methods.

***Effect of Geometry of the Ring Test*:** As mentioned previously, ring tests of many different dimensions have been conducted in the past, and the results were not the same. The dimensions play an important role in determining the properties of concrete mixes in the ring test. A finite element analysis was performed by Krauss and Rogalla (1996) on the ring test. Their analysis showed that when the inner steel rings have the thicknesses between 1/2 in. (12.7 mm) and 1 in. (25.4 mm), the stress and drying shrinkage tendency of concrete are not very different. A thinner inner steel ring induces larger steel stress, and a thicker inner steel ring induces larger concrete stress. Also, the concrete shrinkage stress reduces when the height of the concrete ring increases from 76 mm (3 in.) to 152 mm (6 in.). Thus, a thicker and shallower steel ring induces high stress in concrete as expected.

Delatte et al. (2007) compared the ring geometry using two sets of specimens. Both sets used two 16 in. (406.4 mm) and two 18 in. (457.2 mm) outer diameter concrete rings cast around inner steel ring of 12 in. (304.8 mm) diameter at the same time from the same mixture. From their study, they developed an equation for time-to-crack versus ratio of ring radii as:

$$\frac{R_o}{R_i} = -0.0025t^2 + 0.13t + 0.3188 \tag{1}$$

where R_o is the outside radius of concrete ring; R_i is the inside radius of the concrete ring; and t is the time to crack.

Summary of Test Methods

As reviewed in this section, several test methods have been developed for measuring the drying shrinkage cracking tendency of specimens consisting of different concrete mixes or other different conditions. Among these methods, the ring test method is simple and easy to conduct, and it can be used to compare most of the factors that affect the cracking tendency of concrete at the same time. Also, it is easier for the concrete to develop visual cracks. Because of these merits, the ring test method was adopted by many researchers. However, it should be noted that the ring test method only reflects the relative cracking tendency of concrete with different mixes and different conditions, and it cannot represent the concrete in actual service life.

The ring test method will be adopted in this study. The AASHTO ring method (AASHTO T334-08) will be considered using structural pipe with an outside diameter of 12¾ in. (323.9 mm). The AASHTO ring test for this study produces a concrete ring thickness of 2.625 in. (66.5 mm). The ASTM ring test produces concrete rings of 1.5 in. (38.1 mm), which limited the maximum size of aggregate to be 1/2 in. (12.7 mm). In this study, aggregates with maximum nominal size of 1.5 in. (38.1 mm) or larger will be considered.

OTHER RELATED WORK

Folliard and Berke (1997) evaluated the effect of shrinkage-reducing admixture (SRA) on high-performance concrete properties. The mechanical properties, free shrinkage and restrained shrinkage cracking were investigated. For the restrained ring test, a concrete ring with 2 in. (50.8 mm) thickness and 6 in. (152.4 mm) height was cast around a steel pipe with inner diameter of 10 in. (254.0 mm) and outer diameter of 12 in. (304.8 mm). Then, the specimens were put into drying condition of 20^oC and 50% RH. Free shrinkage concrete prisms with dimensions of 3 x 3 x 11.2 in. (76.2 x 76.2 x 284.5 mm) were also evaluated. Their study concluded that the use of SRA greatly reduced drying shrinkage cracking in laboratory ring specimens, despite concrete containing SRA having lower early strengths than companion mixtures without SRA.

Xi et al. (2001) studied the development of optimal concrete mix design for bridge decks. Four different tests (i.e., compressive strength, rapid chloride permeability, restrained ring, and free shrinkage) were performed to evaluate the properties of concrete. The AASHTO ring test was adopted with modification. Two concrete rings of 6 in. (152.4) height with 12 in. (304.8 mm) inner and 18 in. (457.2 mm) outer diameters were cast for each concrete mix. After one day of curing, the specimens were put in the lab with temperature of $72^{o}F$ ($22^{o}C$) and relative humidity of 35%. Two concrete beams of 3 x 3 x 12 in. (76.2 x 76.2 x 304.8 mm) were made for the free shrinkage test for drying shrinkage test. Their study included two phases. Eighteen mix designs were formulated in Phase I to get some viable mixes that satisfied the requirements. Phase II was to finalize the mix designs from Phase I to be used in the field. It was found that cracking was related to the cement content. A proper increase of coarse aggregate could reduce cracking potentially; Class F fly ash had better cracking resistance than Class C fly ash.

Tritsch et al. (2005) evaluated the shrinkage and cracking behavior of concrete using the restrained ring and free shrinkage tests. Their study was made of a series of preliminary tests and three test programs. The steel ring had a thickness of 1/2 in. (13 mm) with an outside diameter of 12 in. (304.8 mm). The concrete ring specimens were 3 in. (76.2 mm) or 2 in. (50.8 mm) thick. Both the steel and concrete rings were 3 in. (76.2 mm) tall. In each program, the concrete was exposed to drying condition of about $70^{o}F$ ($21^{o}C$) and 50% relative humidity. Free shrinkage specimens of 3 x 3 x 11 in. (76.2 x 76.2 x 279.4 mm) dimension were also cast. Their concrete mix design included a typical mix from both the Kansas DOT and Missouri DOT and seven laboratory mixes. The results showed that the ultimate free shrinkage increased as the paste content of concrete increased. Adding a shrinkage-reducing admixture (SRA) significantly decreased the free shrinkage and shrinkage rate. Early-age free shrinkage was reduced by increasing the curing time, although curing time did not have influence on the restrained shrinkage rate at the start of drying. Surface-to-volume ratio influenced shrinkage in the way that the increase of surface-to-volume ratio caused the increase of free shrinkage and restrained shrinkage. Of the 39 restrained rings in their study, only the Missouri DOT mix cracked, which had the highest paste content and highest shrinkage rate of all. As a result of this study, they recommended that a concrete mix with lower paste content should be used; the shrinkage-reducing admixtures (SRA) can be used to reduce shrinkage cracking.

Gong (2006) at West Virginia University investigated the cracking behavior of high-performance concrete using the restrained ring test, the fracture test and the numerical analysis method. He used the AASHTO ring specimen test to study the restrained cracking characteristics of different concrete mixtures. The steel ring had inside and outside diameters of 11 in. (279.4 mm) and 12 in. (304.8 mm), respectively. The outside diameter of the concrete was 18 in. (457.2 mm). The heights of both steel ring and concrete ring were 6 in. (152.4 mm). Free shrinkage and mechanical properties, such as direct tensile strength, compressive strength, and modulus of elasticity, were also studied. They concluded that the AASHTO ring test could capture the cracking onset of high-performance concrete with reasonable accuracy. The test results showed that under the same conditions, gravel (from two different sources in the local region (WV): Dulles Bottom, Joe Lucas Dredge, WV and Apple Grove Plant) generally had better cracking resistance than limestone. High cementitious materials and low water-to-cementitious-materials (w/cm) ratio led to earlier cracking.

Delatte et al. (2007) studied the effect of using high-absorptive materials to improve internal curing of low permeability concrete to reduce shrinkage cracking using free shrinkage and restrained ring tests. Besides field observation, they conducted experimental research in four phases: concrete mixtures using traditional Ohio DOT materials and mixture designs, concrete mixtures using high absorption fine lightweight aggregate, concrete mixtures using coarse aggregate with a larger nominal size in a blended mixture, and field testing. For the restrained ring test, they used a 13 in. (330.2 mm) outside diameter steel tube acted as restraint, which has a thickness of 1/2 in. (12.7 mm). The diameter of the outer form for the concrete ring was either 16 in. (406.4 mm) or 18 in. (457.2 mm) with a height of 6 in. (152.4 mm). The outer form was removed 24 hours after casting. Specimens were moved to an environmental chamber at a temperature of $22^{o}C$ and a relative humidity of 50%. Two strain gages were mounted at opposite mid-height of the inner surface of the steel ring to monitor the strain development. The unrestrained or free shrinkage specimens were 3 x 3 x 10 in. (76.2 x 76.2 x 254.0 mm) beams. Two sets of beams were made, one set kept in water bath and the other at the environmental chamber. Their research concluded that the strongest effect on cracking was to replace a small maximum size coarse aggregate of 3/8 in. (9.5 mm) (#8) with a blend of maximum size coarse aggregates of 1 in. (25.4 mm) (#57) and 3/8 in. (9.5 mm) (#8). Increasing the coarse aggregate absorption level from low to medium was less effective in reducing shrinkage cracking. The introduction of lightweight aggregate for internal curing also had less effect on shrinkage cracking. Thus, the use of a larger size aggregate (e.g., 1 in. (25.4 mm) of #57) or a blend of sizes was recommended for reducing shrinkage cracking of bridge decks.

In summary, a review on the types of shrinkage, effects of concrete properties and cementitious materials on shrinkage resistance, and test methods on shrinkage resistance evaluation is provided. A recent ACI Report (2010) on “Early-Age Cracking: Causes, Measurement, and Mitigation” (ACI 231R-10) also provided detailed reviews of the causes of thermal- and moisture-related deformation and cracking, test methods for assessing shrinkage and thermal deformation properties, and mitigation strategies for reducing early-age cracking.

POTENTIAL CAUSES OF EARLY-AGE SHRINKAGE CRACKING

Several state DOTs have conducted studies (Xi et al. 2001; Folliard et al. 2003; Delatte et al. 2007) on early-age cracking in concrete bridge decks and identified potential causes and remedies. Based on a review of these previous studies, the early-age shrinkage cracking in concrete bridge decks can be caused by a number of mechanisms, including one or more of the following:

- Delay in curing, wind, low humidity and hot weather causing plastic shrinkage.
- High strength or high-performance decks with low water-cementitious material ratio resulting in autogenous shrinkage due to self-desiccation.
- Improper mix design with high cement content or high quantity of water, resulting in high drying shrinkage.
- Restraint from deep longitudinal girders and their connections (e.g., shear studs) increasing the restrained shrinkage stresses.
- Low tensile strength resulting in less resistance to cracking.
- High modulus of elasticity of concrete causing high stresses for a given shrinkage strain.
- Low creep properties that do not allow for stress relaxation.
- Temperature differential between the newly-placed deck and supporting girders with different shrinkage rates causing induced stress in concrete.

- High curing temperatures causing excessive evaporation of water.

REMEDIES FOR ENHANCING SHRINKAGE CRACKING RESISTANCE

To reduce and/or eliminate shrinkage cracks, a variety of strategies were proposed in the previous studies (Xi et al. 2001; Folliard et al. 2003; Delatte et al. 2007), and they include:

- Improved curing practices to prevent excessive loss of water due to evaporation (e.g., using continuous fogging and wind breaks in construction immediately after finishing).
- Internal curing strategies (Delatte et al. 2007) - (a) Using an optimized combination of coarse aggregate gradation (e.g., replacing a small maximum size coarse aggregate with a blend of small and large aggregates); (b) Utilizing high absorption aggregate (e.g., absorption level > 1%); (c) Replacing fine aggregate with light weight aggregate (LWA) with high water absorption; and (d) Employing super absorbent polymer particles (SAP) as an alternative to moderately absorptive aggregate or expanded shale structural lightweight aggregate particle replacement.
- Improved mix designs and reduced paste content (mixture proportion optimization) with locally-available materials (e.g., decreasing the volume of water and cement and maintaining an air content above 6%). Use of larger size aggregates with optimized gradation to reduce the need of water and cementitous materials in concrete.
- Modified bridge design methods to reduce the shrinkage restraint.

- Addition of single or hybrid fibers (specific fiber types and mix combinations need to be matched to achieve the desired characteristics) to increase the bonding strength of concrete to resist concrete shrinkage cracking.
- Incorporation of shrinkage-reducing admixtures (SRA). SRA reduces the surface tension of water and were found to reduce concrete free shrinkage greatly by many researches. Currently, SRA has not been used in concrete bridge decks in Washington State. SRA will be evaluated with local Washington State materials in this study.
- If SRA and/or synthetic fibers are used in the mix design, a compatibility study is needed. As a chemical additive, SRA may cause changes in the mechanical properties of concrete, such as flexural strength, compressive strength, etc.
- Inclusion and recognition of the effects of fly ash (C and F), slag, and silica fume on potential early-age shrinkage reduction or augment. The replacement of cement using fly ash will slow down the hydration process of concrete, and it may reduce the early-age strength of concrete.

Based on the above remedies, the improvement of concrete mix designs is considered in this study as a viable strategy to mitigate the early-age shrinkage cracking. Several factors in the mix designs, including paste content, supplementary cementitious materials (admixtures) (fly ash, silica fume, slag), SRA, size and type of aggregates, will be investigated in order to arrive at optimized mix designs with improved early-age shrinkage cracking resistance properties.

MATERIALS AND SELECTION OF CONCRETE MIX DESIGNS

The primary goal of this study is to develop and evaluate different concrete mix designs using various sizes of aggregates, different cementitious and admixture material proportions, and different sources of aggregates to identify the concrete mix designs that will have the best shrinkage cracking resistance as well as good mechanical properties. In the following sections, the materials used in this study and the design of the concrete mixes are elaborated.

MATERIALS

Cementitious Materials

The cementitious materials, including Portland cement, fly ash (FA), silica fume (SF), and slag (SL), were provided by Lafarge NA – PNW District. The properties and chemical contents are listed in Table 1.

Table 1 Properties and Chemical Contents of Cementitious Materials

	Cement	Fly Ash	Silica Fume	Slag
Specific Gravity	3.15	2.04	2.2	2.89
SiO_2, %	20	53.3		
Al_2O_3, %	4.6	23.1		
Fe_2O_3, %	3.3	3.4		
CaO, %	64.6	10		
MgO, %	0.8	1.1		
SO_3, %	2.7	0.1		
Loss on Ignition, %	2.6	0.4		
Limestone, %	3			

Aggregates

Coarse aggregates from eastern Washington (EW) and from western Washington (WW) were used in this study. EW coarse aggregates were provided by Central Pre-Mix Concrete Company in Spokane, WA, and four different maximum sizes of coarse aggregates were considered: nominal sizes of 2.5 in., 2.0 in., 1.5 in., and 3/8 in. The gradations of the EW coarse aggregates are presented in Table 2. The specific gravities are listed in Table 3.

Table 2 Eastern Washington Coarse Aggregate Gradations (Sieve Analysis)

	Eastern Washington 3/8" Pea Gravel	Eastern Washington 1.5"	Eastern Washington 2"	Eastern Washington 2.5"
Sieves	Cumulative % Passing	Cumulative % Passing	Cumulative % Passing	Cumulative % Passing
2-1/2"				100
2"				91.7
1-1/2"		100	100	22.5
1-1/4"		94.8	73.8	6.2
1"		64.4	28.2	0.8
3/4"		11.4	3.1	0.2
5/8"		2.8	0.6	
1/2"	100	1.3	0.4	
3/8"	98.5	0.6	0.2	
1/4"	67.8			
#4	37.3			
#8	3.0			
#16	0.4			

The WW coarse aggregates were provided by Glacier NW, Seattle, WA. The gradations of WW aggregates are listed in Table 4, and their specific gravities are given in Table 5.

Table 3 Specific Gravity of Eastern Washington Aggregates

Aggregates	EW 2.5"	EW 2"	EW 1.5"	EW 3/8"	Sand
Specific Gravity	2.7	2.7	2.7	2.67	2.65

Table 4 Western Washington Coarse Aggregate Gradations (Sieve Analysis)

	Western Washington 3/8" Pea Gravel	Western Washington 1.5"	Western Washington 2"	Western Washington 2.5"
Sieves	Cumulative % Passing	Cumulative % Passing	Cumulative % Passing	Cumulative % Passing
2-1/2"				100
2"			100	92 - 100
1-1/2"		100	95 - 100	95 - 100
1-1/4"		91.6		
1"		48	35 - 70	35 - 70
3/4"		2.4		
5/8"		0.6	10 - 30	10 - 30
1/2"	100	0.5		
3/8"	86.4	0.4		
5/16"	64.6	0.1		
1/4"	38.5			
#4	13.9		0 - 5	0 - 5
#8	0.7			
#16	0.2			
#200	0.1			

Table 5 Specific Gravities of Western Washington Coarse Aggregates

Aggregates	WW 2.5"	WW 2"	WW 1.5"	WW 3/8"
Specific Gravity	2.7	2.7	2.7	2.67

Fine aggregate was provided by Central Pre-Mix Concrete Company in Spokane, WA. The fine aggregate meets Class 1 WSDOT Sand requirements. The specific gravity of fine aggregate is also listed in Table 3, and the detailed gradation is listed in Table 6.

Table 6 Fine Aggregate Gradation (Sieve Analysis)

	Fine Aggregate	
Sieves	Individual % Retained	Cumulative % Passing
3/8"	0	100
1/4"	0.5	99.5
#4	1.8	97.7
#8	13.4	84.3
#16	23.3	61
#30	18.8	42.2
#50	24.5	17.7
#100	13.6	4.1
#200	1.9	2.2

<u>Chemical Admixtures</u>

Three types of chemical admixtures were used: air entraining admixture (AEA), shrinkage reducing admixture (SRA), and high-range water reducing admixture (HRWRA).

DARAVAIR 1000 air-entraining admixture from Grace Construction Products was used to produce proper air content in all the concrete mixes. According to the information from the manufacturer, it is based on a high-grade saponified rosin formulation and chemically similar to vinsol-based products. The amount of AEA for each mix was determined based on the recommended addition rate from the product instructions and adjusted according to measurements made on the fresh batch of concrete.

An ADVA 190 high-range water-reducing admixture from Grace Construction Products was used to achieve the desired slump value as well as to reduce the water content in all concrete mixes. It is a polycarboxlate-based admixture specifically designed for concrete industry. The amount of HRWRA for each mix was also determined based on the product instructions and adjusted according to measurements made on the fresh batch of concrete.

Eclipse Plus shrinkage-reducing admixture (SRA) from Grace Construction Products was added to some of the concrete mixes to reduce concrete drying shrinkage. Eclipse Plus decreases drying shrinkage by reducing the surface tension of water, which causes a force pulling in on the walls of the pores in concrete. The amount of SRA added to each mix was also determined based on its recommended amount and adjusted according to measurements made on the fresh batch of concrete. When Eclipse Plus shrinkage-reducing admixture (SRA) was added, the same amount of water was taken out of each mix.

Factors Considered for Mix Design

In order to develop the concrete mix designs to evaluate for mitigating shrinkage cracking, a number of factors in the mix designs were considered, based on the information in the review of previous research.

First, the mix designs incorporated different selections and proportions of cementitious materials and chemicals. Supplementary cementitious materials (SCMs), such as fly ash (FA), silica fume (SF), and slag (SL), are used by many DOTs to partially replace Portland cement in a concrete mix. Single replacements of cement by one single SCM were evaluated. To further reduce the cement content, replacement of cement by combinations of two different SCMs was also performed. Based on the information from the literature review, the single replacement of cement by weight was selected as 20% for fly ash or slag, and 4% for silica fume.

Second, larger sizes of aggregates were also considered in the mix designs to reduce paste content as suggested by the literature review and to reduce the shrinkage cracking tendency of concrete. As suggested by the WSDOT, aggregates with nominal maximum size of 1.5 in. (38.1 mm) were used to replace the current WSDOT standard practice of limiting the nominal maximum size aggregates to 1 in. (25.4 mm). When larger sizes of aggregates are used, the paste content of concrete mix designs are correspondingly reduced compared with small size aggregates. In this study, nominal maximum sizes of aggregates of 1.5 in. (38.1 mm), 2.0 in. (50.8 mm), and 2.5 in. (63.5 mm) were evaluated, along with two sources of aggregates, i.e., Eastern and Western Washington aggregates.

Shrinkage reducing admixture (SRA) was also used as suggested by the literature review to reduce the drying shrinkage of concrete.

MIX DESIGNS

The mix designs investigate in this study (a total of 28) were developed based on procedures given in ACI 211.1-91 along with the University of Kansas (KU) mix design (so called "KU Mix") program (Zhuang 2009). ACI 211.1-91 is only capable of obtaining the mix design with one size coarse aggregate; in contrast, the KU Mix program is able to include the effects of larger sizes of aggregates and a combination of different sizes of aggregates. The KU Mix program developed by the researchers at University of Kansas (http://www.silicafume.org/ku-mix.html) is based on Microsoft Excel to design concrete mixes, and it includes a function for aggregate optimization. By combining the ACI 211.1-91 and the KU Mix program, the mix designs considered for this study were developed and are summarized in Tables 7 and 8 along with the benchmark mix designs from the WSDOT (Table 9).

Table 7 Mix Designs with Different Supplementary Cementitious Materials

Mixture	Cement (lb/yd^3)	FA (lb/yd^3)	SF (lb/yd^3)	Slag (lb/yd^3)	Paste (%)	#4 (lb/yd^3)	#8 (lb/yd^3)	Sand (lb/yd^3)	w/cm	Air (%)	Water (lbs)
EW	550	0	0	0	23.43	1161	1177	759	0.4	8	220
EW-SF-SRA	462	0	22	0	20.79	1154	969	1087	0.4	8	193.6
EW-FA-SRA	440	110	0	0	24.54	1160	1192	697	0.4	8	220
EW-FA-SL-SRA	330	110	0	110	24.72	1159	1194	686	0.4	8	220
EW-FA	440	110	0	0	24.54	1160	1192	697	0.4	8	220
EW-FA-SF-SRA	352	110	22	0	21.9	1187	1205	772	0.4	8	193.6
WW-SRA	550	0	0	0	23.43	1017	811	1259	0.4	8	220
WW-SL-SRA	440	0	0	110	23.61	1016	813	1250	0.4	8	220
WW	550	0	0	0	23.43	1017	812	1260	0.4	8	220
WW-SF-SRA	462	0	22	0	20.79	1044	822	1342	0.4	8	193.6
WW-FA-SRA	440	110	0	0	24.54	1014	821	1203	0.4	8	220
WW-FA-SL-SRA	330	110	0	110	24.72	1013	822	1194	0.4	8	220
WW-FA	440	110	0	0	24.54	1014	821	1204	0.4	8	220
WW-FA-SF-SRA	352	110	22	0	21.9	1041	832	1286	0.4	8	193.6

Note: EW – Eastern Washington Coarse Aggregates, SRA – Shrinkage Reducing Admixtures, SL – Slag , SF – Silica Fume, FA – Fly Ash, and WW – Western Washington Coarse Aggregates. Paste percentage is based on mix volume.

Table 8 Mix Designs with Different Sources and Sizes of Coarse Aggregates

Mixtures	Cement (lb/yd^3)	2.5" Aggregate (lb/yd^3)	2" Aggregate (lb/yd^3)	3/8" Aggregate (lb/yd^3)	Sand (lb/yd^3)	w/cm	Air Content (%)	Water (lbs)
EW 2"	525	-	1072.6	850	1240	0.4	8	210
EW 2.5"	500	1125	-	850	1240	0.4	8	200
WW 2"	525	-	1072.6	850	1240	0.4	8	210
WW 2.5"	500	1125	-	850	1240	0.4	8	200

Table 9 Control Mix Designs from the WSDOT

Mixtures	Cement (lb/yd^3)	Fly Ash (lb/yd^3)	Silica fume (lb/yd^3)	Slag (lb/yd^3)	3/4" Aggregate (lb/yd^3)	Sand (lb/yd^3)	w/cm	Air Content (%)	Water (lbs)
WSDOT	660	75	-	-	1730	1250	0.34	6.5	250
LD-WSDOT	564	-	-	-	1830	1270	0.48	4.8	270

Note: WSDOT mix is with the aggregate from eastern Washington (EW); LD-WSDOT mix is with the aggregate from western Washington (WW) of relatively normal or low degradation (LD) gradation

EXPERIMENTAL TESTING PROGRAM

In order to evaluate the factors in the concrete mix designs that affect the shrinkage cracking of concrete, a number of tests are conducted. According to the condition of the concrete when it is being tested, these tests can be grouped into two categories: (1) fresh concrete tests and (2) hardened concrete tests.

Fresh concrete property tests evaluate the following properties of concrete: air content, slump, and unit weight. The hardened concrete property tests are further divided into two sub-categories. The first category pertains to the mechanical properties at different ages, such as the compression strength of concrete, the flexural strength of concrete, and the modulus of elasticity of concrete. The second category is the drying shrinkage of concrete, which include the free shrinkage and the restrained shrinkage. Depending on the importance of other properties and applications, some additional tests (e.g., permeability, freeze/thaw, scaling) may also be conducted for the finalized candidate mixture(s) with the best shrinkage cracking resistance in order to develop a concrete mix performance matrix. For each concrete mix, the tests considered in this study are summarized in Table 10 along with their ASTM and AASHTO standard test method designations.

Table 10 Fresh and Hardened Property Tests

Properties of Concrete	Test Methods
Fresh Properties of Concrete	
Air content	ASTM C 231/AASHTO T 152
Slump	ASTM C 143/AASHTO T 119
Unit Weight	ASTM C 138
Hardened Properties of Concrete	
Compression Strength of Concrete	ASTM C 39/AASHTO T 22
Flexural Strength of Concrete	ASTM C 78/AASHTO T97
Splitting Tensile Strength of Concrete	ASTM C 496/AASHTO T 198
Modulus of Elasticity of Concrete	ASTM C 496
Unsealed Free Shrinkage	ASTM C 157 AASHTO T 160
Sealed Free Shrinkage	ASTM C 1090
Restrained Shrinkage of Concrete	AASHTO T334-08

TEST RESULTS AND DISCUSSION

The mix designs of this project were evaluated based on results obtained from tests performed on the concrete in both fresh and hardened states.

FRESH PROPERTY TESTS

Slump and air content tests were performed on fresh concrete for each mix design to evaluate workability and durability properties.

Slump Test

The slump test (Figure 6) was performed following the procedures of ASTM C 143/AASHTO T 119 “Slump of Hydraulic Cement Concrete”. Based on ACI 211.1-91 “Standard Practice for Selecting Proportions for Normal Heavyweight, and Mass

Concrete" as well as WSDOT recommendations, a slump of at least 3 in. is desired. However, as stated in ACI 211.1-91, when chemical admixtures are used and the concrete mix does not exhibit segregation potential or excessive bleeding, the slump value may be increased. In this study, a High Range Water Reducing Admixture (HRWRA or superplasticizer) was used to increase the slump value. It is anticipated that when a low cement paste content (as compared to the WSDOT current mix design practice) is used, the workability of concrete mix will be reduced.

Figure 6 Slump Test

<u>Air Content Test</u>

Two methods of measuring air content were used in this study: the pressure method (Figure 7) and the volumetric method (Figure 8). The pressure method follows AASHTO T 152/ASTM C 231 "Air Content of Freshly-mixed Concrete by the Pressure Method", while the volumetric method follows AASHTO T 196/ASTM C 173 "Air

Content of Freshly-mixed Concrete by the Volumetric Method". As stated in the AASHTO standards, the pressure method applies to concretes and mortars made with relatively dense aggregates, and it does not apply to concrete with lightweight aggregates, air-cooled blast-furnace slag, or aggregates of high porosity. Most of the concrete mixes in this study were comprised of dense aggregates, and the pressure method was used for these mixes. For the mixes incorporating slag, the volumetric method was utilized. The ACI 211.1-91 recommended value for air content is 5.5 percent for severe exposure when the nominal maximum aggregate size is 1.5 in. However, in a recent WSDOT bridge deck project, the WSDOT required the air content to be a minimum of 6.5 percent and a maximum of 9.5 percent. Therefore, the target air content in this study was chosen as 8 percent.

Figure 7 Air Content Test by Pressure Method

Figure 8 Device for Air Content Test by Volumetric Method

Test Results of Fresh Concrete Properties

The slump test and air content test data for all the concrete mixes with either eastern Washington (EW) or western Washington (WW) aggregates are listed in Table 11. The slump values are in the range of 3 to 6 in., indicating good workability for all the concrete mixes. The air contents are also within the desired range for most of the concrete mixes. For several of the concrete mixes (e.g., EW-FA-SRA, WW-SRA, WW-FA-SL-SRA), the air contents are lower than the desired value. However, the use of several chemicals in the same mix made the desired concrete properties difficult to achieve, especially when three chemicals were used in one concrete mix.

Table 11 Slump and Air Content Test Data

EW Mixture	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WSDOT	EW 2”	EW 2.5”
Slump (in.)	4.8	6.5	3.7	3.3	4.6	6.0	5.8	3.5	4.0	5.0	5.5
Air Content (%)	7.2	n/a*	7.8	7.8	3.0	n/a	10.0	7.5	6.5	7.0	10.0
WW Mixture	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2”	WW 2.5”
Slump (in.)	4.2	3.8	3.6	5.0	3.25	6.5	3.8	5.3	4.0	3.3	5.8
Air Content (%)	4.8	5.5	8.8	6.2	5.0	4.5	8.0	7.1	4.8	9.8	10.0

MECHANICAL PROPERTY TESTS

Three basic mechanical properties were evaluated for the hardened concrete obtained from the mix designs: compressive strength, modulus of elasticity, and flexural strength. These tests were conducted to evaluate the ability of the concrete mix to meet the requirements for the intended applications in bridge decks.

Compressive Strength Test and Results

The compressive strength test (Figure 9) was conducted following the procedures of ASTM C 39/AASHTO T 22 “Compressive Strength of Cylindrical Concrete Specimens”. For bridge deck applications, the WSDOT requires a minimum compressive strength of 4,000 psi at 28 days. The compressive strength of all concrete mixes at the 7^{th} day was also obtained to provide information on the rate of strength gain with concrete age.

Figure 9 Compressive and Modulus of Elasticity Test

Concrete Mixes with EW Aggregates: The test data for the compressive strength of concrete mixes with eastern Washington (EW) aggregates are listed in Table 12 and graphically presented in Figure 10. The current WSDOT concrete mix design has the highest compressive strength at both 7 days and 28 days (see Figure 10).

As shown in Figure 11(a) for mixes WSDOT, EW, EW 2" and EW 2.5", an increase in nominal aggregate size as well as the associated reduction in paste content results in decreased compressive strength. However, the compressive strengths for these four mixes all exceed the minimum WSDOT compressive strength requirement of 4,000 psi at 28 days.

As shown in Figure 10, the replacement of cement by slag or silica fume increases the compressive strength of concrete. A 20% replacement of cement by slag increases the 28-day strength of concrete from 4,989 psi to 6,947 psi for concrete mixes with SRA. A 16% replacement of cement with 4% silica fume increases the 28-day compressive strength from 4,989 psi to 5,582 psi for concrete mixes with SRA.

For concrete using Portland cement only (no other cementitious materials), Figure 11(b) shows that the addition of SRA does not significantly affect compressive strength. However, when 20% of cement is replaced by FA, the concrete strength for mix without SRA decreases significantly, with the 28-day compressive strength decreasing from 4,556 psi to 3,466 psi, more than a 20% decrease. When SRA is added, the 28-day compressive strength of the concrete mix using 20% replacement of cement by FA reduces only slightly. SRA increases the 28-day compressive strength of FA concrete from 3,466 psi to 4,515 psi, resulting in a 28-day strength that exceeds the WSDOT minimum requirement of 4,000 psi. Mixes containing SL + FA and SF + FA exhibit the combined effects for the compressive strength when SL, SF, FA are applied separately. The effect of SRA on the combinations of FA, SL, and SF is shown in Figure 11(c).

Table 12 Compressive Strength of Mixes with EW Aggregate (psi)

Mixtures	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WS DOT	EW 2"	EW 2.5"
7-day Strength	4228	5691	4337	4792	3892	3369	2921	3739	6199	3887	3566
28-day Strength	4989	6947	4556	5582	4515	5461	3466	4234	7226	4400	4248

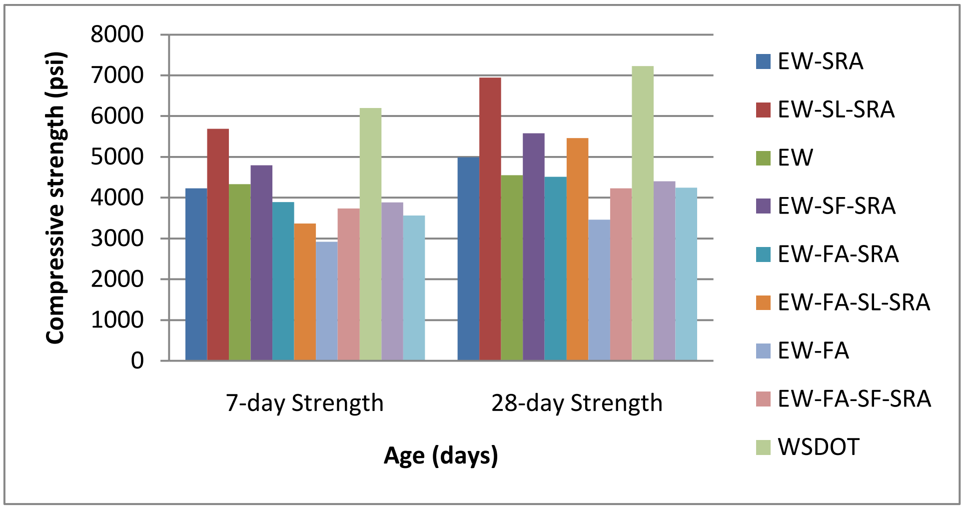
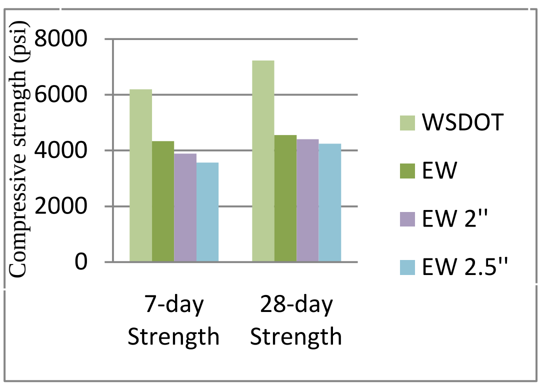
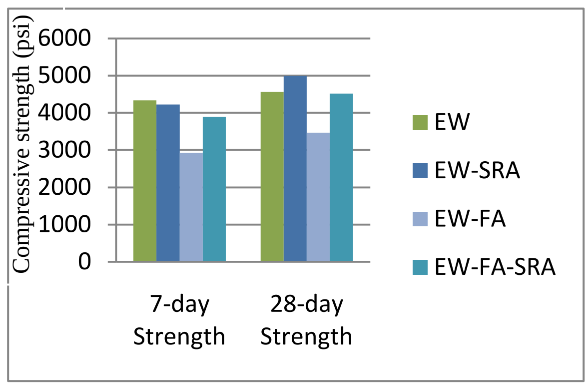


Figure 10 Compressive Strength of Concrete Mixes with EW Aggregate



(a)



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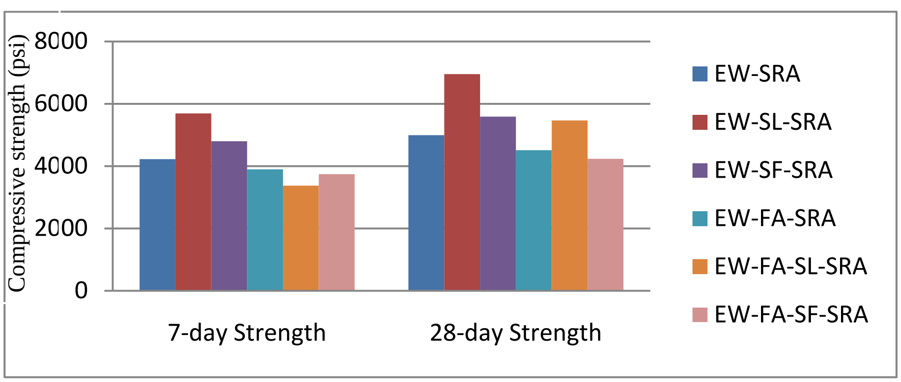


(c)

Figure 11 Trends of Compressive Strength of Concrete Mixes with EW Aggregate with Respect to (a) Size of Aggregate, (b) SCMs, and (c) SRA

Concrete Mixes with WW Aggregates: The compressive strength test results for the concrete mixes with western Washington (WW) aggregates are presented in Table 13 and graphically in Figure 12. Comparison of results for LD-WSDOT (LD refers to Low Degradation aggregate), WW, WW2'', and WW 2.5'' in Figure 12 show that LD-WSDOT has the lowest compressive strength at all ages. LD-WSDOT has a water-to-cementitious material (w/cm) ratio of 0.48, and its paste volume is 25.8%. The high w/cm ratio of LD-WSDOT leads to its low strength.

The effect of aggregate size on compressive strength is shown in Figure 13(a). Compared to the EW 2" aggregates, the 2 in. nominal size aggregates of WW 2'' (#357) includes both the larger size aggregates of 1 in. and 2 in., and they are thus better graded (see Table 4). The aggregates for WW 2'' and WW 2.5'' are similar except that WW 2.5'' has around 8% more of larger size aggregates of 2.5 in. Well-graded aggregates require less paste to achieve good workability and thus have better bonding between aggregates and cement paste. Therefore, the compressive strength of WW 2'' and WW 2.5'' are similar, and both are larger than that of WW (see Figure 13(a)). They are higher than the respective compressive strength values of their counterparts (i.e., EW 2" and EW 2.5").

As shown in Figure 13(b), the addition of SRA increases the 28-day compressive strength of both WW and WW-FA, which is consistent with the observation for the eastern Washington aggregate data. Also, the replacement of cement using FA reduces the strength of concrete both with and without the addition of SRA. WW-FA has the lowest compressive strength of all the mixes, and its compressive strength is below the WSDOT minimum requirement of 4,000 psi at 28 days. As shown in Figure 13(c), the mix design of WW-SF-SRA (i.e., the replacement of cement by 4% of silica fume), has the highest compressive strength at all ages. Compressive strengths for mixes with a replacement of cement by other cementitious materials, such as fly ash, slag, and the combination of two cementitious materials, are all lower than that of WW.

Table 13 Compressive Strength of Mixes with WW Aggregate (psi)

Mixtures	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2	WW 2.5
7-day Strength	4971	4356	4766	6591	4175	3779	3221	3809	3461	6002	6003
28-day Strength	6322	5651	5652	7725	5310	5060	3966	5263	4432	6578	6485

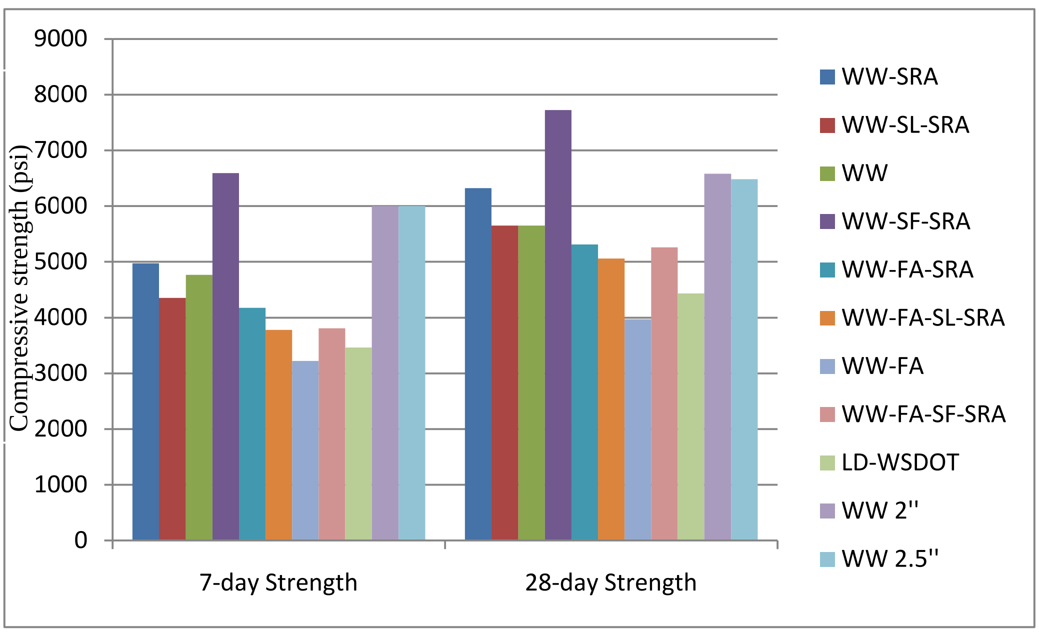
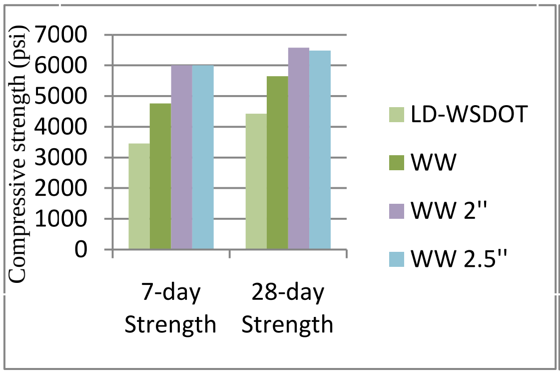
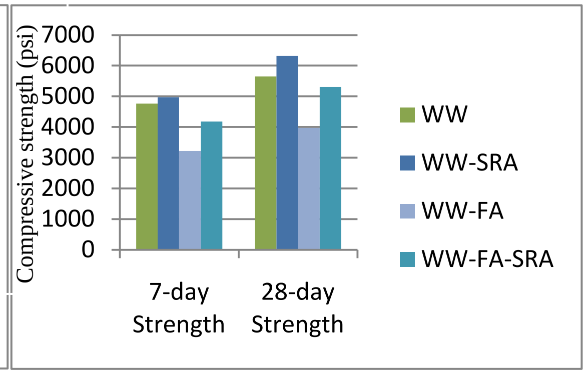


Figure 12 Compressive Strength of Concrete Mixes with WW Aggregate



(a)



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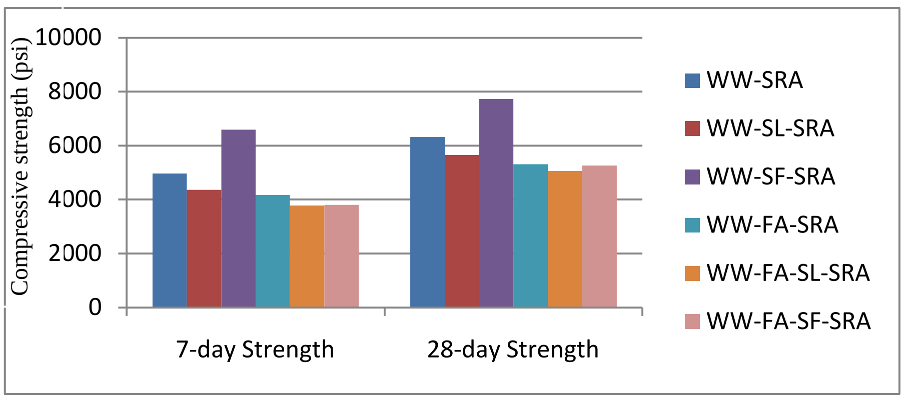


(c)

Figure 13 Trends of Compressive Strength of Concrete Mixes with WW Aggregate with Respect to (a) Size of Aggregate, (b) SCMs and (c) SRA

Modulus of Elasticity Test and Results

The modulus of elasticity test (see Figure 9) was conducted following the procedures of ASTM C469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression". The modulus of elasticity was determined at 7 and 28 days for the concrete mixes.

Concrete Mixes with EW Aggregates: Modulus of elasticity data of concrete mixes with eastern Washington (EW) aggregate are listed in Table 14 and graphically shown in Figure 14. As was the case for compressive strength, EW-SL-SRA has the highest modulus of elasticity. The replacement of cement by slag increases both compressive strength and modulus of elasticity. The inclusion of SRA increases the modulus of elasticity of both EW and EW-FA. EW-FA has the lowest modulus, just as it has the lowest compressive strength. EW has a lower modulus than that of the control WSDOT mix. However, EW 2” and EW 2.5” have slightly higher moduli than that of EW.

Table 14 Modulus of Elasticity of Mixes with EW Aggregate (x10^6 psi)

Mixtures	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WSDOT	EW 2"	EW 2.5"
7-day Modulus	4.15	5.00	3.75	3.75	4.20	3.70	3.20	4.15	4.55	3.70	4.00
28-day Modulus	4.75	5.15	3.85	3.85	4.50	4.40	3.60	4.90	4.75	4.10	4.10

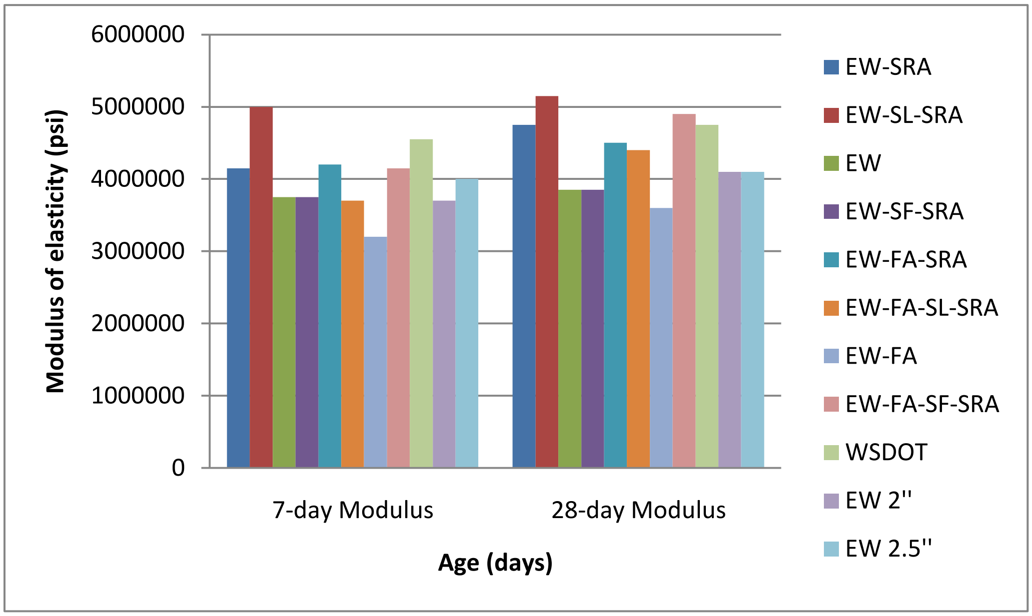


Figure 14 Modulus of Elasticity of Concrete Mixes with EW Aggregate

Concrete Mixes with WW Aggregates: Modulus of elasticity results for concrete mixes with western Washington (WW) aggregate are presented in Table 15 and shown graphically in Figure 15. The replacement of cement by silica fume results in the highest modulus among all these mixes with the WW aggregates; while the LD-WSDOT has the lowest. WW 2" and WW 2.5" have higher moduli than that of WW, which is consistent with the compressive strength comparison. Unlike with the eastern Washington concrete mixes, the replacement of cement by slag decreases the modulus of original concrete mix.

Table 15 Modulus of Elasticity of Mixes with WW Aggregate (x10^6 psi)

Mixtures	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2"	WW 2.5"
7-day Modulus	4.15	3.7	4.55	5.1	4	4	3.6	4	2.95	4.85	4.45
28-day Modulus	4.65	3.95	4.7	5.35	4.8	4.3	3.95	4.45	3.4	5.15	5.25

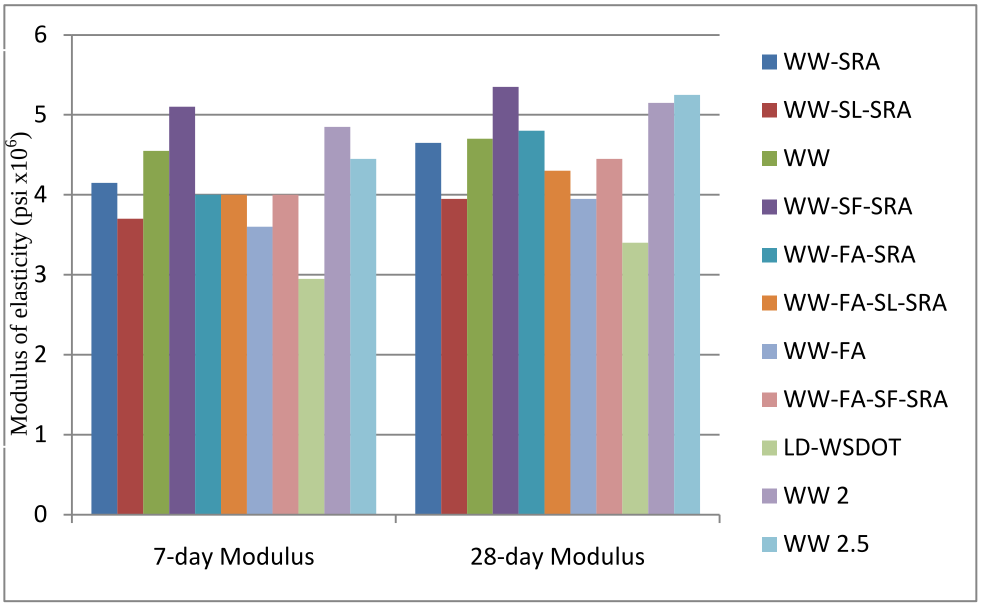


Figure 15 Modulus of Elasticity of Concrete Mixes with WW Aggregate

Flexural Strength Test and Results

The flexural strength test (Figure 16) was performed following AASHTO T 97/ASTM C 78 "Standard Method of Test for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)". In order to gain information on the rate of flexural strength gain with age, flexural strength tests were performed at 3, 7, 14, and 28 days for all concrete mixes.

Figure 16 Flexural Strength Test

<u>Concrete Mixes with EW Aggregates</u>: Flexural strength test data are listed in Table 16 and also graphically in Figure 17. For early-age shrinkage cracking, the early-age flexural strength plays an important role.

For the mix designs of WSDOT, EW, EW 2'' and EW 2.5'', the effect of aggregate size on of flexural strength as shown in Figure 18(a) are similar to the trend for compressive strength, except that the flexural strength of EW is higher than that of WSDOT at 3 days.

By comparing two pairs of the mixes with and without SRA (i.e., EW-SRA with EW and EW-FA-SRA with EW-FA) (Figure 18(b)), the data show that when SRA is used, the early-age flexural strength increases. SRA not only increases the early-age flexural strength, but also later strength. For the 28-day strength, the addition of SRA increases the flexural strength of EW by 16% and increases the flexural strength of EW-FA by 20%.

The replacement of cement by FA decreases the flexural strength of concrete at all ages, for both the EW-FA mix and the EW-FA-SRA mix. As shown in Figure 18(c), the replacement of cement by slag increases the flexural strength of concrete at all ages for EW-SL-SRA. However, when combined with fly ash, the flexural strength decreases at all ages for EW-FA-SL-SRA when compared with EW-SRA. The replacement of cement by silica fume also decreases the flexural strength of EW-SF-SRA when compared with EW-SRA. This is probably caused by the low paste content present in all the mix designs, resulting in a weaker bond between the paste and aggregates. On the other hand, the low paste content can reduce the shrinkage tendency.

Table 16 Flexural Strength of Mixes with EW Aggregate (psi)

Mixtures	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WSD OT	EW 2"	EW 2.5"
3-day	699	748	575	638	574	436	549	544	867	636	523
7-day	793	863	709	673	713	517	602	678	939	633	612
14-day	955	961	740	858	789	681	563	763	1032	687	696
28-day	823	944	709	820	760	762	634	844	1070	700	546

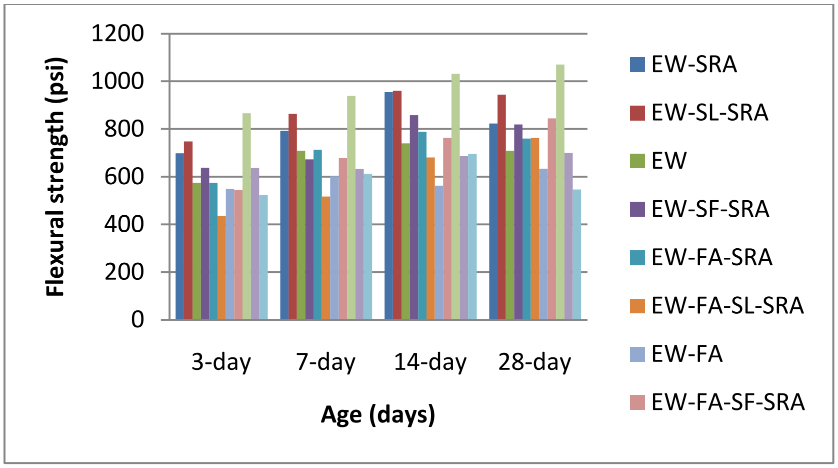
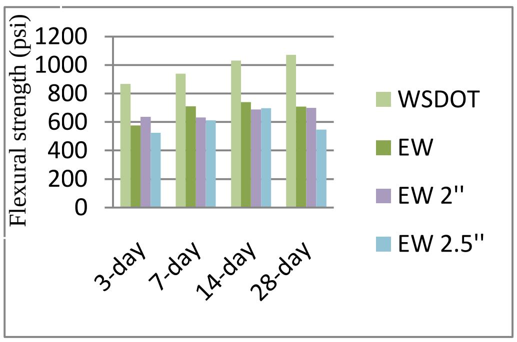


Figure 17 Flexural Strength of Concrete Mixes with EW Aggregate



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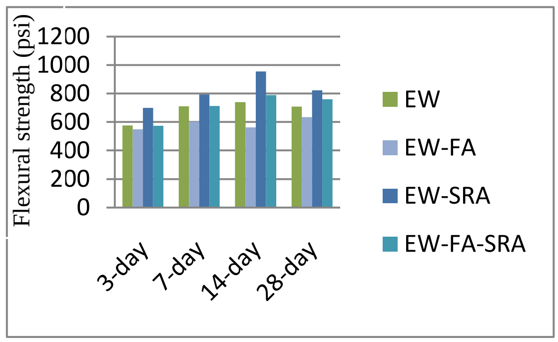

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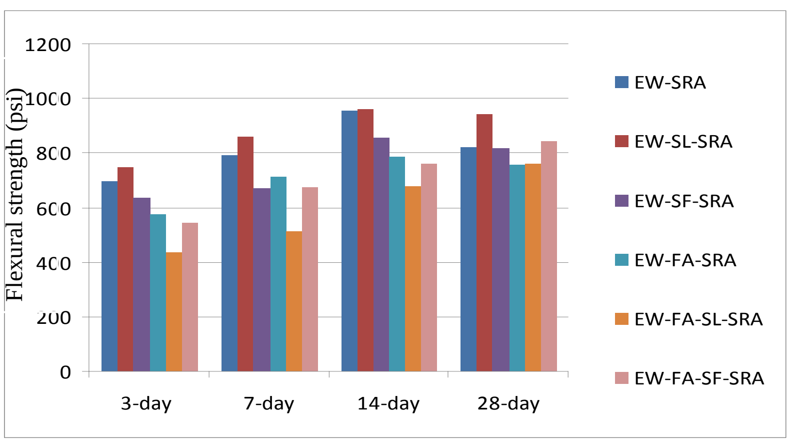


(c)

Figure 18 Trends of Flexural Strength of Concrete Mixes with EW Aggregate with Respect to (a) Size of Aggregate, (b) SCMs and (c) SRA

Concrete Mixes with WW Aggregates: Flexural strength results for concrete mixes with western Washington (WW) aggregates are shown in Table 17 and also graphically in Figure 19.

Among the four concrete mix designs of LD-WSDOT, WW, WW 2'', and WW 2.5'', the flexural strength trend shown in Figure 20(a) is similar to that for compressive strength. LD-WSDOT has the lowest flexural strength, and WW 2'' and WW 2.5'' have the highest.

The addition of SRA increases the flexural strength of both WW and WW-FA (Figure 20(b)). Replacement of cement by fly ash reduces the flexural strength at all ages. Among those mix designs containing SRA (see Figure 20(c)), mixes with a replacement of cement by silica fume have the highest flexural strength at all ages. The replacements of cement by other cementitious materials, such as fly ash, slag, or the combination of different cementitious materials, all have smaller flexural strengths than that of WW-SRA.

Table 17 Flexural Strength of Mixes with WW Aggregate (psi)

Mixtures	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2"	WW 2.5"
3-day	646	579	630	784	508	445	449	451	412	833	900
7-day	851	754	725	887	625	576	562	589	499	749	869
14-day	903	788	814	919	713	688	607	688	594	825	954
28-day	915	753	762	1022	744	759	577	831	748	932	921

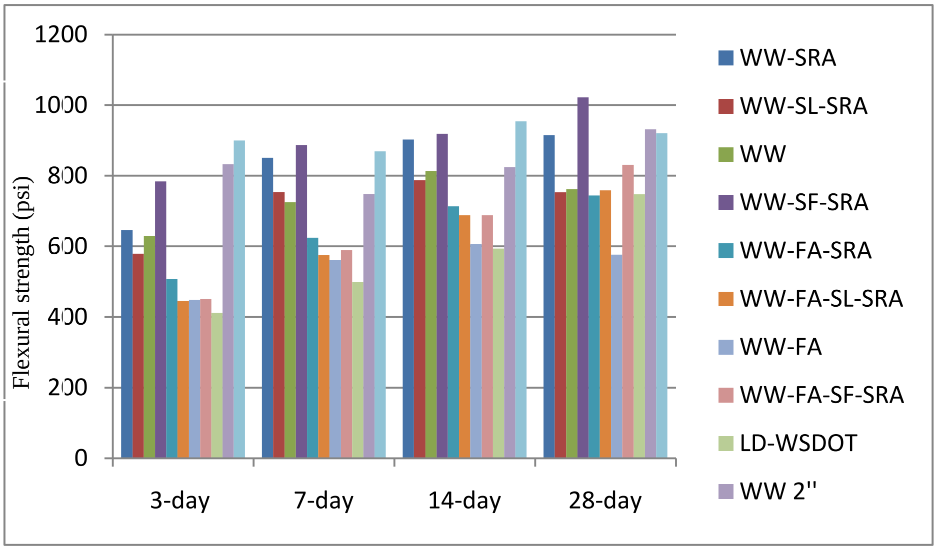
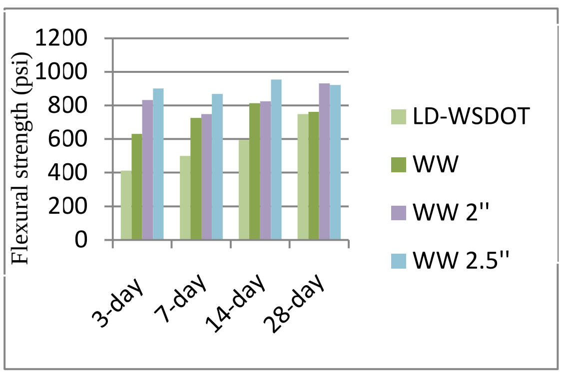
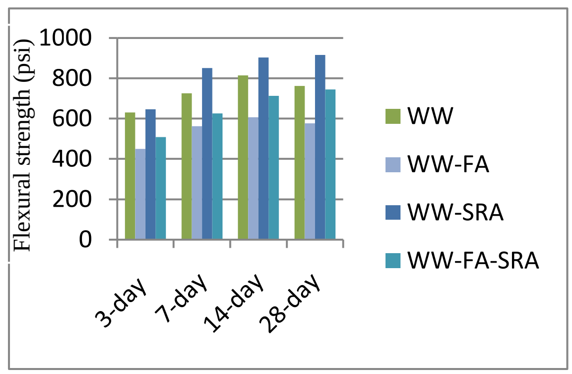


Figure 19 Flexural Strength of Concrete Mixes with WW Aggregate



(a)



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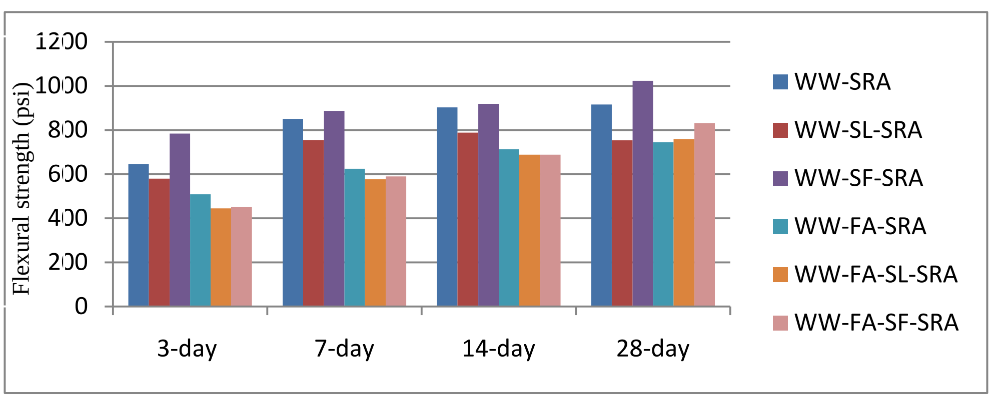

(c)

Figure 20 Trends of Flexural Strength of Concrete Mixes with WW Aggregate with Respect to (a) Size of Aggregate, (b) SCMs and (c) SRA

SHRINKAGE PROPERTY TESTS

Two tests on shrinkage properties were performed for all concrete mixes: free shrinkage and restrained shrinkage. The free shrinkage test (shown in Figure 21) provides the basic shrinkage characteristics of the concrete without any restraint, while the restrained shrinkage test (shown in Figures 22 and 23) provides a measure of the combination of concrete tensile strength and shrinkage properties and approximately mimics the condition of a concrete deck being restrained by girders.

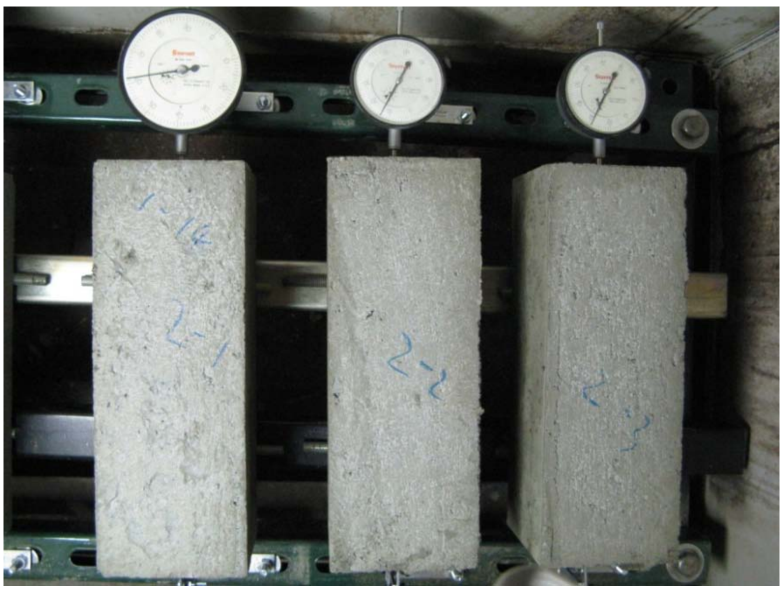

Figure 21 Free Shrinkage Test

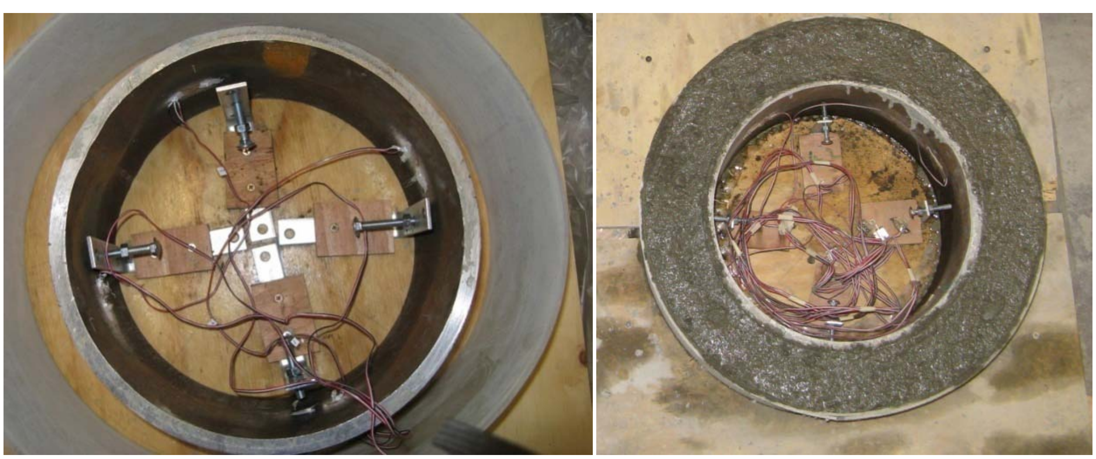

Figure 22 Restrained Shrinkage Ring Apparatus

Figure 23 Data Acquisition System for Restrained Shrinkage Measurement in the Conditioning Room

Free Shrinkage Test and Results

The free shrinkage test (Figure 21) followed the procedures given in AASHTO T 160 (ASTM C 157) "Length Change of Hardened Hydraulic Cement Mortar and Concrete". Free shrinkage data were collected on concrete samples at 1, 2, 3, 4, 5, 6, 7, 14, 21, and 28 days from which the free shrinkage tendency diagrams were created for all concrete mixes. Recently, the WSDOT established a bridge deck performance requirement that the free shrinkage at 28 days should be less than 320 $\mu\varepsilon$.

Concrete Mixes with EW Aggregates: The free shrinkage data for the concrete mixes with eastern Washington (EW) aggregates are listed in Table 18, and their tendency diagrams are plotted in Figure 24. The influence of aggregates size on the free shrinkage is shown in Figure 25. It can be seen that the WSDOT mix shrinks the most, followed by EW. Both EW 2" and EW 2.5" have similar free shrinkage rates, which are smaller than that for the EW mix.

The combined effect of FA and/or SRA replacement of cement on free shrinkage is shown in Figure 26. For EW and EW-FA, no SRA is added, and their free shrinkages at 28 days are all more than 320 $\mu\varepsilon$. For EW and EW-FA, the replacement of cement by fly ash reduces the early-age free shrinkage, especially in the first 14 days. However, it increases later, making the 28-day free shrinkage larger than that for the mix without fly ash. When SRA is used, the free shrinkages of both EW-SRA and EW-FA-SRA are reduced considerably, especially for EW-FA-SRA. For EW and EW-FA, the addition of SRA reduces their 28-day free shrinkage by 38% and 71%, respectively. The combination of FA and SRA has the greatest effect, reducing the free shrinkage value of that mix to 122 $\mu\varepsilon$, which is well below the WSDOT limit of 320 $\mu\varepsilon$.

The effect of SRA on the free shrinkage is given in Figure 27. When SRA is used, the mix EW-SRA without using any cementitious materials except Portland cement has the largest 28-day free shrinkage. For EW-SF-SRA, the free shrinkage values are negative for the first 4 days, which means that the concrete beam sample may have expanded during the first 4 days. The samples of EW-SRA later do experience shrinkage, but they have the smallest 28-day free shrinkage of all the eight concrete mixes. The replacement of cement by slag increases early-age free shrinkage, but eventually reduces the 28-day free shrinkage. Both the combination of fly ash with slag and fly ash with silica fume decrease the free shrinkage when compared with the concrete mix containing only Portland cement.

Table 18 Free Shrinkage Test Data of Concrete Mixes with EW Aggregate (με)

Mixtures Days	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WSD OT	EW 2"	EW 2.5"
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	17.4	40.0	125.9	-20.7	18.7	17.5	32.0	2.6	56.0	18.7	17.8
2	31.1	57.2	149.6	-16.0	31.4	31.1	81.8	16.2	97.8	33.8	24.0
3	55.1	68.7	162.7	-5.9	37.6	47.4	107.3	31.2	127.4	73.8	49.2
4	79.3	88.3	183.4	-4.1	49.2	57.2	116.4	46.7	153.2	90.1	78.8
5	81.9	n/a	192.9	3.9	52.7	67.3	136.9	54.5	n/a	91.6	82.7
6	88.3	129.2	204.1	13.9	59.3	84.4	168.0	55.7	233.8	108.1	93.6
7	103.8	134.8	225.2	21.0	64.0	93.3	187.6	65.5	242.4	133.9	109.6
14	147.9	175.4	287.0	69.0	96.9	132.1	253.6	102.4	337.5	217.2	217.5
21	187.0	189.6	316.1	97.2	117.9	157.0	350.5	137.6	389.6	221.6	217.2
28	225.5	210.2	363.9	119.4	122.1	185.8	421.6	156.8	410.7	259.6	255.1

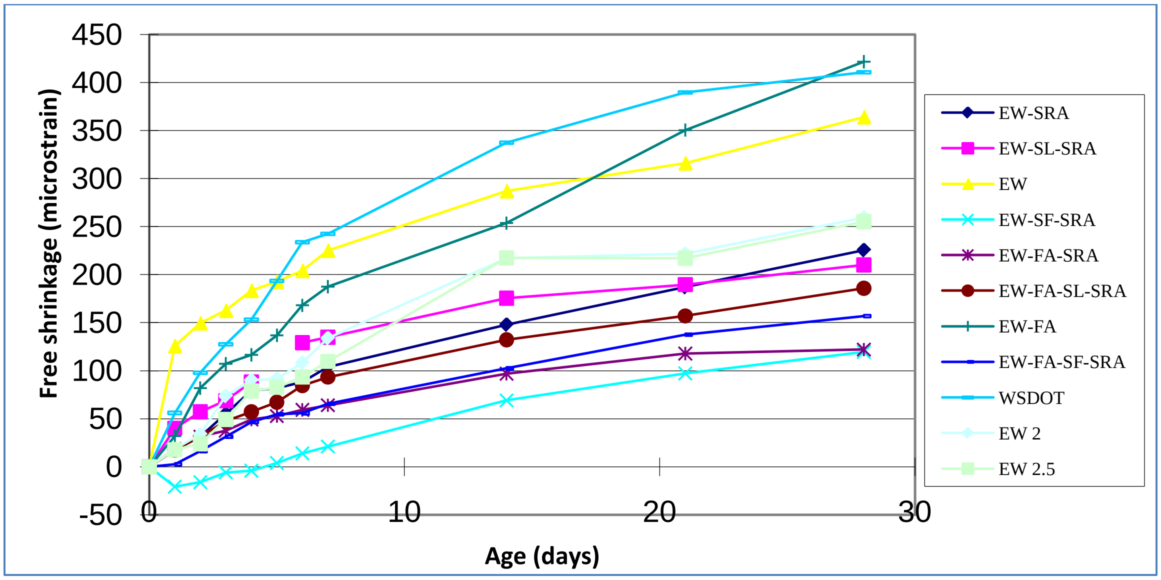

Figure 24 Free Shrinkage of Concrete Mixes with EW Aggregate

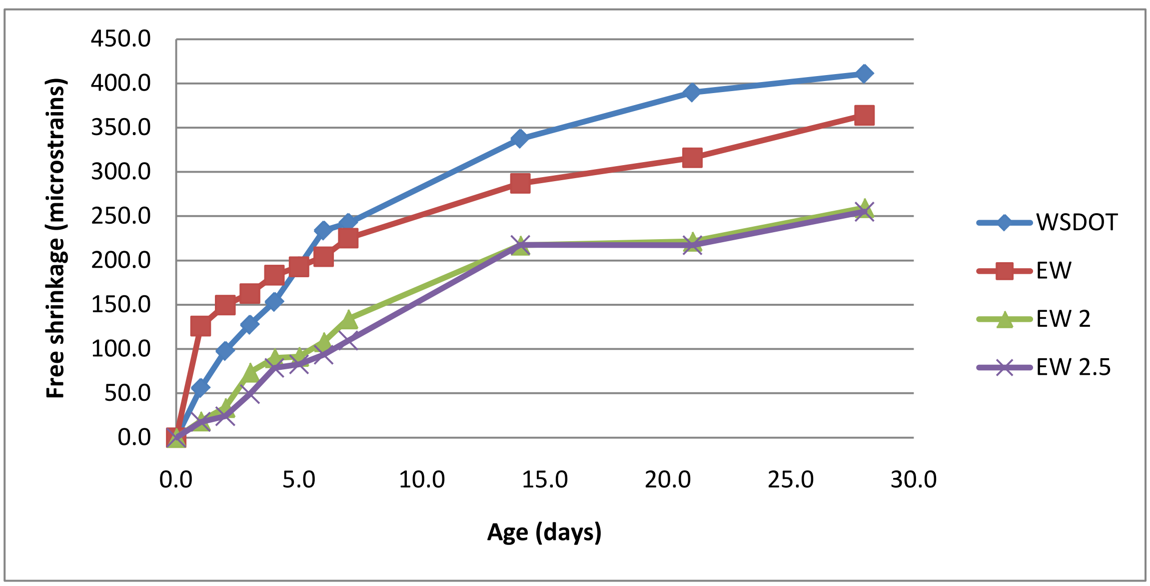

Figure 25 Free Shrinkage of WSDOT, EW, EW 2", EW 2.5"

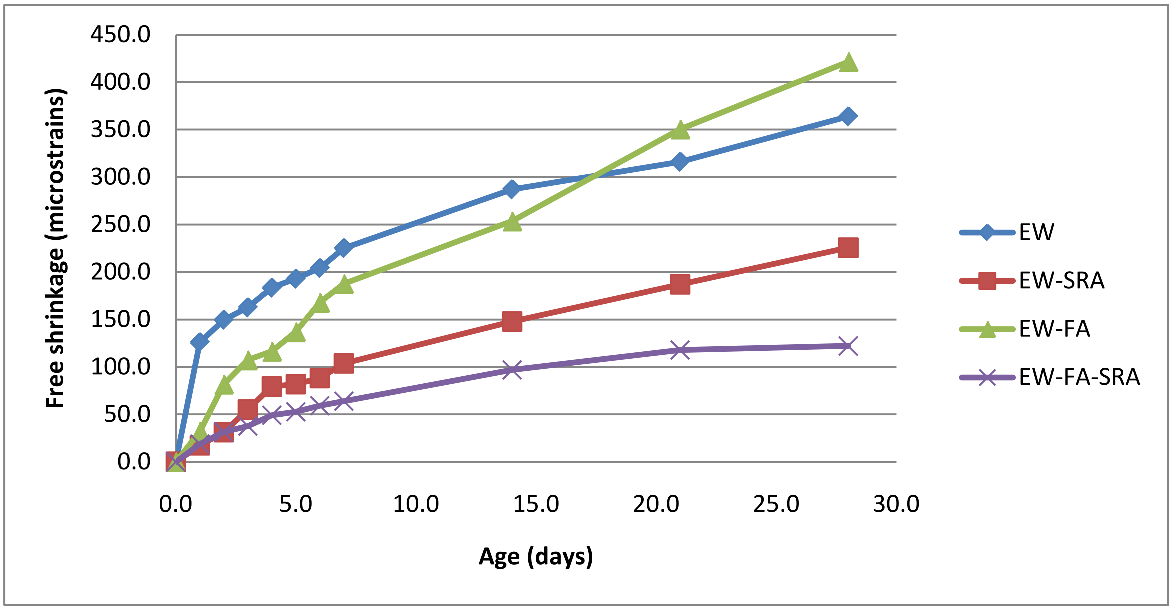

Figure 26 Free Shrinkage of EW, EW-SRA, EW-FA and EW-FA-SRA

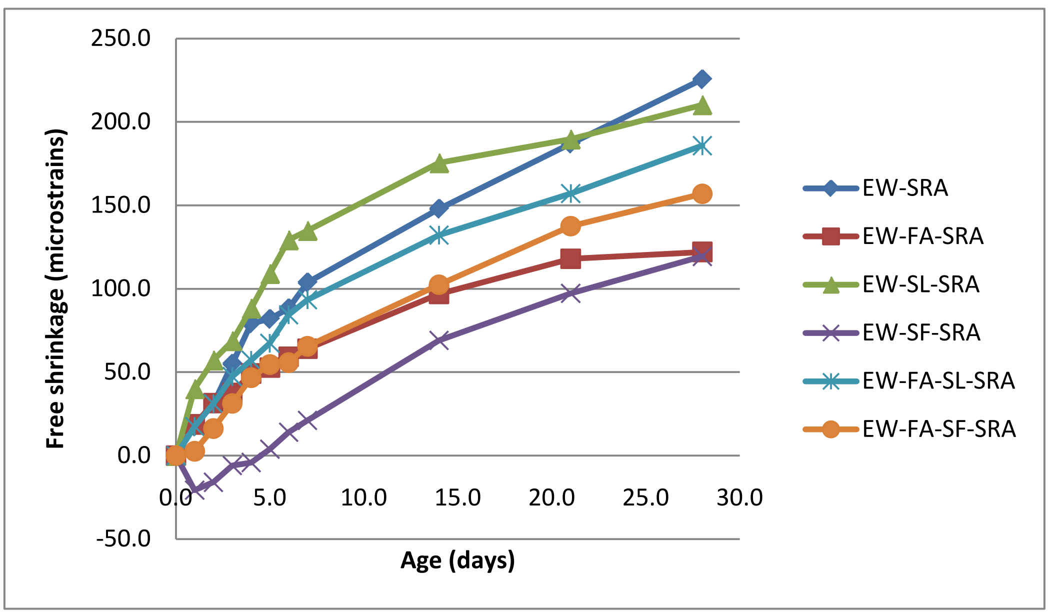

Figure 27 Effect of SRA on Free Shrinkage of Concrete Mixes with EW Aggregate

Concrete Mixes with WW Aggregates: The free shrinkage test results for the concrete mixes with western Washington (WW) aggregates are presented in Table 19 and graphically shown in Figure 28. The effect of aggregate size on free shrinkage is shown

Figure 29. The LD-WSDOT mix shows the largest free shrinkage tendency, followed by WW, WW 2” and WW 2.5”, though WW 2” and WW 2.5” have a similar free shrinkage rate. The LD-WSDOT mix has a w/cm ratio of 0.48, and it has the largest paste content of the four concrete mixes in Figure 29, thus leading to the highest free shrinkage. WW has the second largest value of free shrinkage. Both of these mixes have free shrinkage larger than 320 $\mu\varepsilon$ at 28 days. Therefore, LD-WSDOT and WW do not satisfy the WSDOT requirement of 320 $\mu\varepsilon$; in contrast, the free shrinkage values for WW 2” and WW 2.5” both meet the WSDOT requirements. As observed in Figure 29, the larger the aggregate sizes, the lower the free shrinkage.

Figure 30 shows that when fly ash is used to replace cement, the free shrinkage decreases, both for WW-FA and WW-FA-SRA. When no SRA is added, fly ash replacement of cement reduces the 28-day free shrinkage of WW by 37%. When SRA is added, the free shrinkage of WW decreases by 53%, from 416 $\mu\varepsilon$ to 197 $\mu\varepsilon$ at 28 days. The free shrinkage of WW-FA decreases by 39%, from 264 $\mu\varepsilon$ to 160 $\mu\varepsilon$ at 28 days.

Figure 31 shows the free shrinkage of concrete mixes when SRA is included in the mix. All the free shrinkage values are less than 200 $\mu\varepsilon$ at 28 days. The replacement of Portland cement by other cementitious materials further reduces the free shrinkage of concrete mixes with SRA.

Table 19 Free Shrinkage Test Data of Concrete Mixes with WW Aggregate (με)

Mixtures Days	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2"	WW 2.5"
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	17.2	5.0	53.9	-0.9	2.7	27.3	24.3	1.8	70.8	71.1	37.0
2	46.2	31.4	145.5	9.2	5.9	38.2	44.0	2.4	126.2	92.1	57.5
3	56.6	52.4	179.6	13.6	9.2	53.0	75.7	5.0	161.8	114.7	77.6
4	65.5	61.9	194.7	87.4	87.7	62.5	87.9	7.4	214.2	127.7	94.5
5	74.4	63.7	215.4	94.8	96.0	65.8	98.8	9.2	240.3	143.4	115.6
6	98.1	69.9	234.7	101.9	100.1	74.1	120.1	14.5	275.3	157.9	128.0
7	105.8	88.9	246.8	102.2	104.6	83.3	129.0	19.6	296.6	172.1	143.1
14	154.4	107.9	329.5	118.8	117.3	122.7	196.0	30.2	461.6	227.6	196.7
21	182.8	163.0	386.7	160.0	156.4	146.7	240.1	111.7	551.8	258.2	234.5
28	196.8	188.1	416.6	155.6	160.3	176.9	264.4	129.8	616.9	271.1	259.9

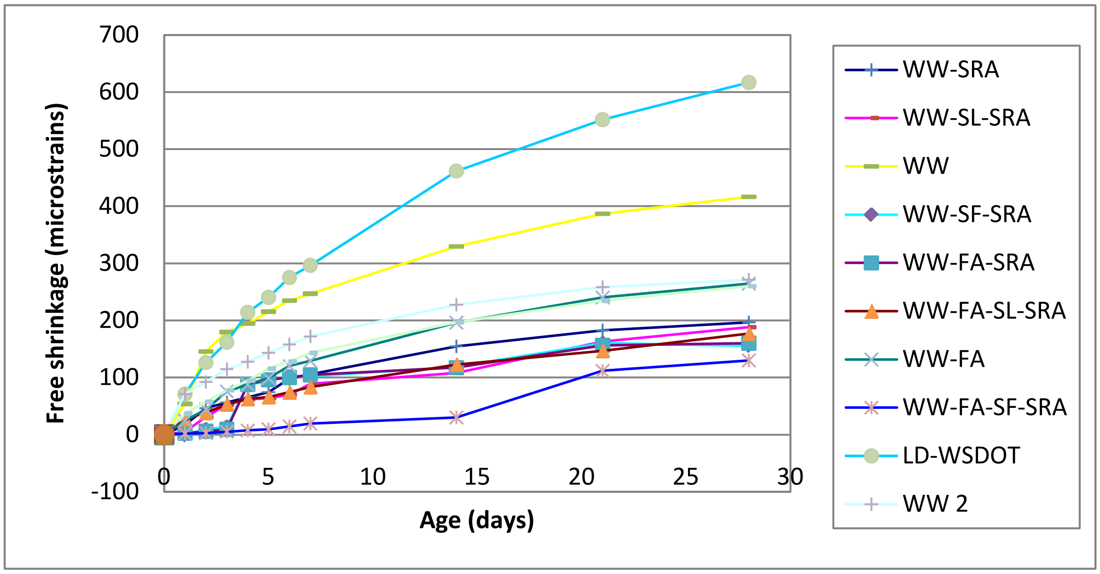

Figure 28 Free Shrinkage of Concrete Mixes with WW Aggregate

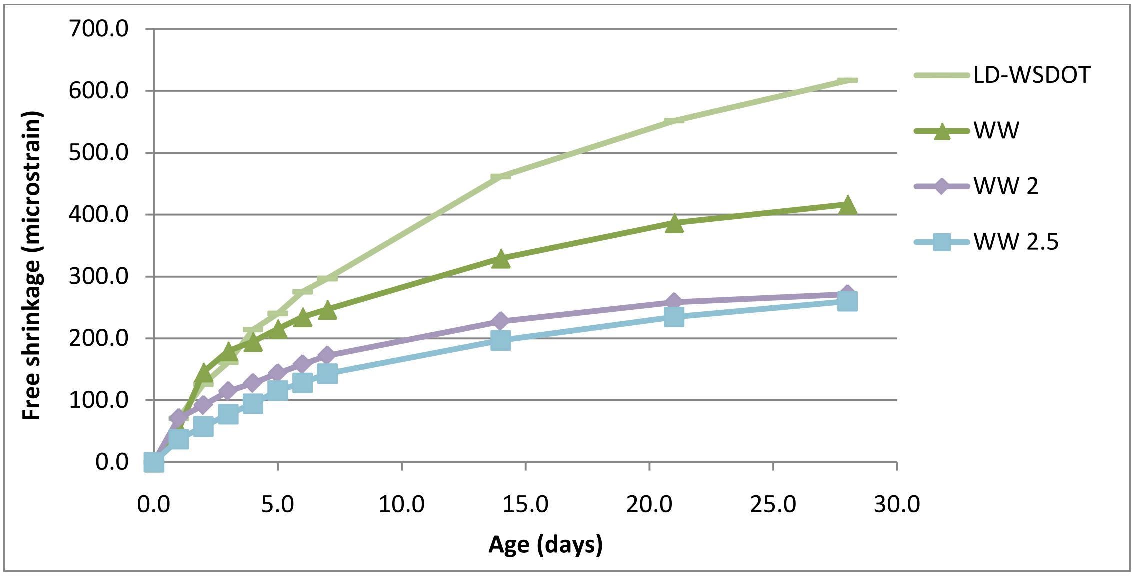

Figure 29 Free Shrinkage of LD-WSDOT, WW, WW 2”, WW 2.5”

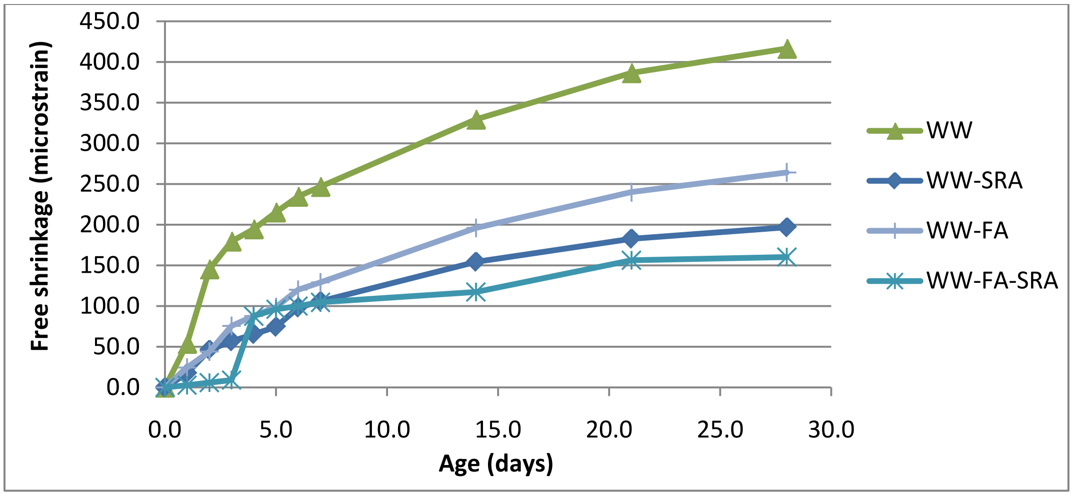

Figure 30 Free Shrinkage of WW, WW-SRA, WW-FA and WW-FA-SRA

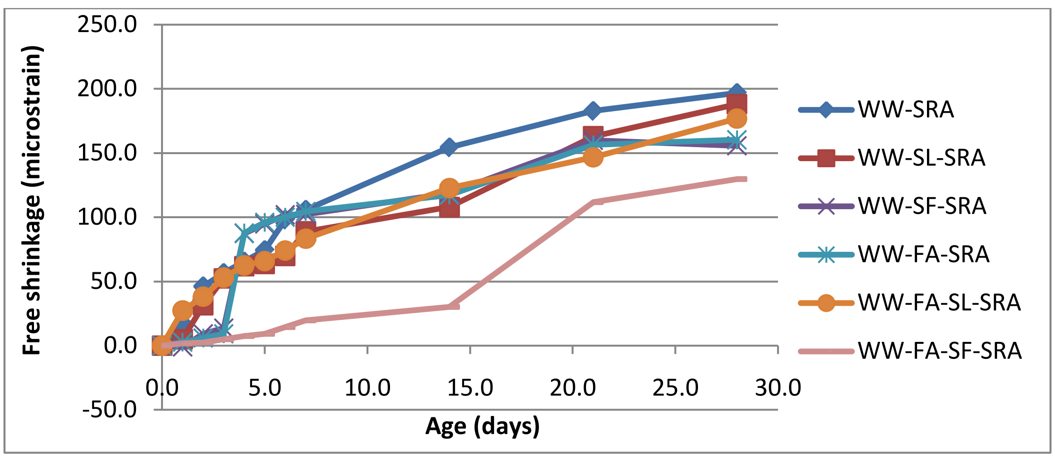

Figure 31 Effect of SRA on Free Shrinkage of Concrete Mixes with WW Aggregate

Restrained Shrinkage Test and Results

The restrained shrinkage test (Figures 22 and 23) followed the procedures of AASHTO T334-08 “Cracking Tendency Using a Ring Specimen”. Three ring specimens were cast for most of the mix designs: two standard 6 in. tall rings and one 3 in. tall ring. The 3 in. tall ring specimens were not cast for the concrete mix with the maximum nominal sizes of 2 in. and 2.5 in. aggregates due to the comparative height of the ring with the size of aggregates. The outer forms in Figure 22 were removed at an age of 8 hours, and then the specimens were moved to the conditioning room (Figure 23) with a constant air temperature of 75 ± 3.5^oF and 50 ± 4 % relative humidity. The data from the strain gages were recorded every second, and review of the strain data and visual inspection of cracking were conducted every 2 or 3 days. A sudden decrease of more than 30 με in compressive strain in one or both strain gages indicates cracking (see Figures 32 and 33). The time at which the concrete ring cracks and the cracking length and width on the exterior radial face were recorded. Due to the large number of mix designs considered in this research and limitations on the number of channels available with the existing data acquisition system, all the rings are monitored only up to 28 days. If no 30 με compressive strain drop and visual crack were observed in the 28-day period (for example, for the ring strain monitoring data shown in Figures 34 and 35), the ring was considered as "no crack" for the studied concrete mix. As an illustration, a concrete ring specimen with a visible crack due to restrained shrinkage is shown in Figure 36.

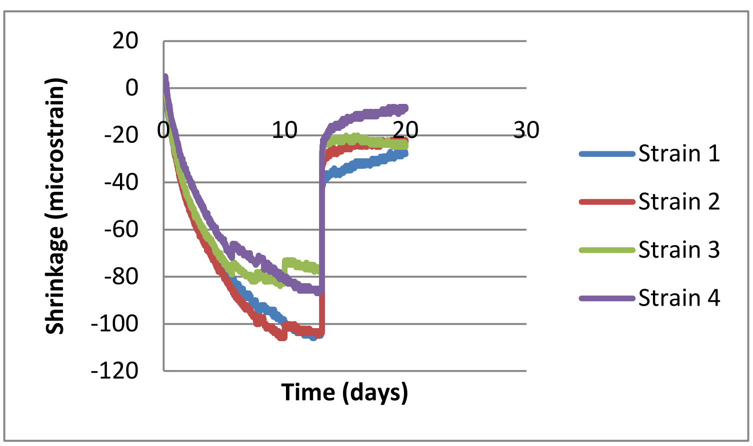

Figure 32 Strain Monitoring in Ring Test for EW (6 in., Ring A, from Day 1) Indicating a Crack at 13.1 Days

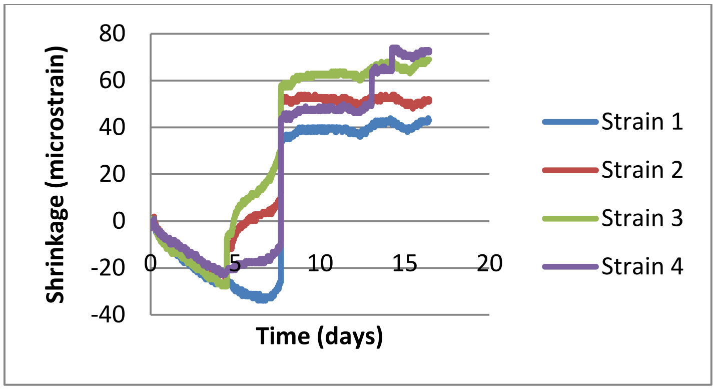

Figure 33 Strain Monitoring in Ring Test for WW (6 in., Ring A, from Day 4) Indicating a Crack at 9.4 Days

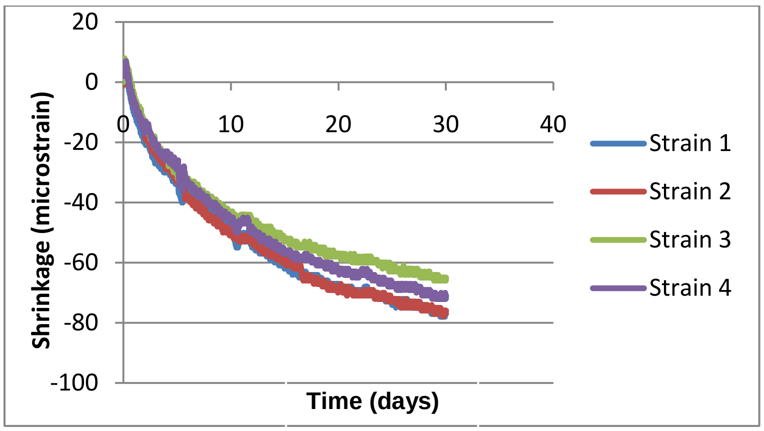

Figure 34 Strain Monitoring in Ring Test for EW-SRA (6 in., Ring A, from Day 1) Indicating "No Crack" during the 28-day Period

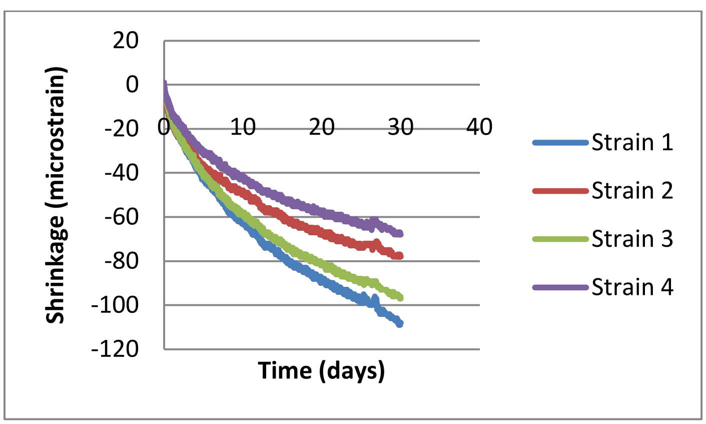

Figure 35 Strain Monitoring in Ring Test for WW-SRA (6 in., Ring A, from Day 1) Indicating "No Crack" during the 28-day Period

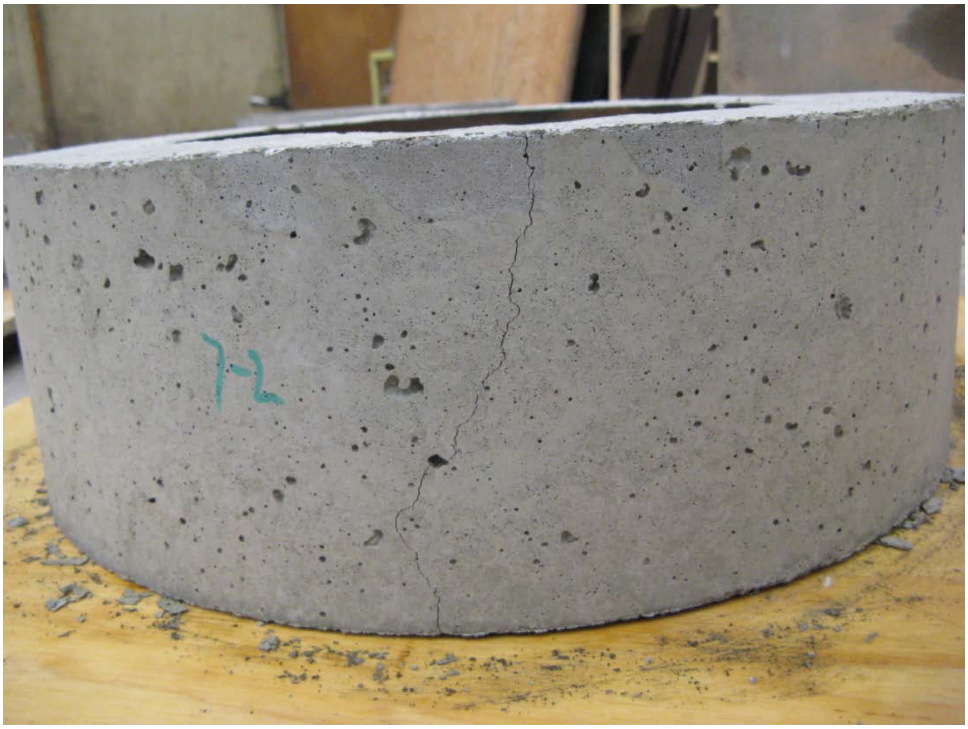

Figure 36 Restrained Shrinkage Cracking in a Ring Specimen

Concrete Mixes with EW Aggregates: The restrained ring test data for the concrete mixes with eastern Washington (EW) aggregate are listed in Table 20. Of the four concrete mixes WSDOT, EW, EW 2'', EW 2.5'', the ring specimens of the WSDOT concrete mix crack the earliest, even though it has the highest flexural (tensile) strength of all the four. The WSDOT concrete mix design has the largest paste content and also very large free shrinkage. Based on results for this mix, it can be seen that tensile strength is not the most critical factor in preventing early-age restrained shrinkage cracking. None of the 6-in. ring specimens containing SRA cracked within 28 days, even for the concrete mixes that have low flexural and compressive strengths. The reason that no shrinkage cracking of concrete rings occurred at 28 days is closely related to the low free shrinkage and improved flexural (tensile) strength of concrete mixes using SRA. The cracking of a ring specimen is the mutual effects of both concrete free shrinkage and concrete flexural (tensile) strength. When the free shrinkage values are low, the induced tensile stresses on specimens in the ring are low. For EW and EW-FA, the free shrinkages are large, and the flexural strengths are low, leading to the cracking of the rings early or within 28 days. Although the early-age free shrinkage of EW-FA is smaller than EW, its flexural strength is smaller than EW, and consequently, EW-FA cracks earlier than EW does.

Table 20 Restrained Ring Test Data for Concrete Mixes with EW Aggregate (Days of Cracking)

Mixtures	EW-SRA	EW-SL-SRA	EW	EW-SF-SRA	EW-FA-SRA	EW-FA-SL-SRA	EW-FA	EW-FA-SF-SRA	WSDOT	EW 2"	EW 2.5"
6" Ring No. 1	no crack	no crack	13.1	no crack	no crack	no crack	4.8	no crack	8.0	12.1	14.5
6" Ring No. 2	no crack	no crack	17.6	no crack	no crack	no crack	7.8	no crack	11.6	8.9	28.0
3" Ring	no crack	25.9	10.9	no crack	n/a*	no crack	3.3	no crack	n/a*	n/a*	n/a*

Note (*): n/a means that valid data could not be obtained from the given specimen.

Concrete Mixes with WW Aggregates: The ring test results for the concrete mixes with western Washington (WW) Aggregate are presented in Table 21. Of the four mixes LD-WSDOT, WW, WW 2”, and WW 2.5”, the LD-WSDOT mix cracks the earliest. LD-WSDOT has the smallest flexural strength at all ages, and its free shrinkage values are also always the highest. WW 2” cracked later than did WW, while WW 2.5” has the best cracking resistance of four mix designs. Note that the nominal size of aggregates used in WW 2” and WW 2.5” are already close to the concrete ring thickness in the ring test. Although WW-FA has smaller free shrinkage than that of WW at all ages, both of the 6-in. tall ring specimens of WW-FA crack earlier than those of the WW concrete mix. This is caused by the low flexural strength of WW-FA. None of the 6-in. rings for all the concrete mixes with SRA addition cracked within 28 days.

Table 21 Restrained Ring Test Data for Concrete Mixes with WW Aggregate (Days of Cracking)

Mixtures Days	WW-SRA	WW-SL-SRA	WW	WW-SF-SRA	WW-FA-SRA	WW-FA-SL-SRA	WW-FA	WW-FA-SF-SRA	LD-WSDOT	WW 2"	WW 2.5"
6" Ring No.1	no crack	no crack	9.4	no crack	no crack	no crack	7.8	no crack	6.7	9.7	10.9
6" Ring No.2	no crack	no crack	13.0	no crack	no crack	no crack	6.3	no crack	8.5	15.4	no crack
3" Ring	20.6	no crack	3.7	no crack	no crack	no crack	5.3	no crack	5.9	n/a*	n/a*

Note (*): n/a means that valid data could not be obtained from the given specimen.

SUMMARY AND DISCUSSION

The use of SRA significantly reduces the free shrinkage of all concrete mixes. At the same time, the flexural and compressive strength values of concrete mixes with SRA are larger than those without SRA. The combined effects of the improved flexural (tensile) strength properties and free shrinkage allow the concrete mixes with SRA to have greater shrinkage cracking resistance as evidenced by the restrained shrinkage tests. Fly ash replacement of cement significantly decreases the strength of concrete, making the concrete with fly ash more vulnerable to shrinkage cracking. Concrete mixes with larger sizes of aggregates (e.g., 2 in. or 2.5 in.) show a better shrinkage resistance, through with reduced strength properties. However, due to the limitation of ring test apparatus in this research, more research on larger size aggregates is recommended. SRA is recommended to be used to mitigate early-age cracking problems in bridge deck applications. Inclusion of large sizes of aggregate in concrete mix is also suggested to reduce shrinkage.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The goal of this study is to develop mitigation strategies for early-age shrinkage cracking in concrete bridge decks. A comprehensive literature search was first conducted. Based on the literature, the main causes of shrinkage cracking and mitigation strategies were identified. With input from the WSDOT and based on results from previous studies, the focus of this research was on evaluation of concrete mix designs to study early-age shrinkage cracking in concrete bridge deck. Considering different sources (eastern and western Washington) and sizes of aggregates, paste content, cementitious materials (cement, fly ash, silica fume, and slag), and shrinkage-reducing admixture (SRA), 20 concrete mixes were designed. Two current WSDOT concrete mixes were included as benchmarks for comparisons with other newly developed concrete mix designs. Fresh properties, hardened properties, and shrinkage properties were evaluated for all the 22 groups of concrete mixes.

CONCLUSIONS

Based on the experimental evaluation of different mix designs conducted in this study, the following conclusions are obtained.

1. The use of SRA significantly reduces the free shrinkage of all concrete mixes using aggregates from Washington State. It also decreases the restrained shrinkage cracking tendency of all concrete mixes. The laboratory test data show that none of the 6-in. tall concrete ring specimens in the restrained ring test with inclusion of SRA crack within 28 days.
2. The replacement of cement by fly ash decreases the strength of concrete. In the concrete mixes with both the eastern Washington and western Washington

aggregates, concrete containing fly ash cracks earlier than the corresponding concrete without fly ash.

3. Paste volume plays an important role in the free shrinkage of concrete. Concrete mixes with a small paste volume have lesser tendency of shrinkage cracking. The use of larger size aggregates reduces the paste volume in concrete mix. From the control concrete mixes to concrete using the nominal size of 2.5 in. aggregates, less paste volume was used. Free shrinkage became smaller, and cracking in the ring specimens is delayed.
4. When SRA is added, the replacement of Portland cement by fly ash, silica fume, and slag further reduces the free shrinkage of concrete. However, these replacements play a less significant role than the addition of SRA.
5. Concrete cracking resistance is the combined effects of both its flexural (tensile) strength and its free shrinkage property. The concrete mix that has an acceptable tensile strength and low free shrinkage strain is anticipated to have relatively good restrained shrinkage cracking resistance.
6. High-range water-reducing admixtures have a significant effect on adjusting the workability of concrete. The HRWRA is able to change the slump test value from almost zero to a high value to achieve the desired workability, especially for the newly-developed mixed designs with low paste content.
7. When several chemicals are used in one concrete mix, it is difficult to achieve the desired fresh concrete properties, such as air content.
8. Both the size of coarse aggregates and the source of coarse aggregates play a very important role in the property of concrete. As the size of coarse aggregates

increases, both the free shrinkage and restrained shrinkage properties are improved. The source of coarse aggregates also has some influence on the concrete properties, e.g., the strength properties of concrete mixes with western Washington aggregates are higher than those with eastern Washington aggregates. However, due to different gradation of coarse aggregates between the eastern and western Washington aggregates, it is difficult to reach definite conclusions on which source of aggregates is better than the other in their performance.

RECOMMENDATIONS

Based on the experimental program conducted in this study, the following recommendations are suggested for improved concrete design to reduce shrinkage cracking in concrete bridge decks.

1. SRA is recommended to be used in all concrete mixes to mitigate early-age shrinkage cracking in concrete bridge decks. However, trial batches are recommended to be conducted first before any field applications.
2. Adding fly ash or including more fly ash in the partial replacement of cement is not recommended due to its low early-age strength.
3. Concrete designs with less paste volume are recommended to be used to increase the cracking resistance.
4. As large a size of coarse aggregates as is practical is recommended in construction.
5. When several cementitious materials and chemical admixtures are used in the same concrete mix, trial batches are recommended to be evaluated before field applications.

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