# Louisiana Transportation Research Center

## Final Report 631

# Influence of Internal Curing on Measured Resistivity

by

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13. Abstract

The objective of this study was to evaluate the influence of internal curing and coarse aggregate type on concrete's 28-day strength, as well as surface resistivity over time (at days 7, 14, 28, 56, 90, and 180). A total of 96 concrete mixtures were prepared to identify the effects of three coarse aggregate types, two water-to-cementitious (w/cm) ratios, three fine lightweight aggregate (LWA) sources, and four variations of supplementary cementitious materials (SCMs). The compressive strength tests showed that in most cases, the presence of lightweight aggregate had a positive effect on strength (i.e., either had equal or better strength). Concerning surface resistivity, the statistical analyses determined that the use of SCMs, w/cm ratio, coarse aggregate type, and presence of LWAs had significant effects. The use of SCMs caused significant increases in surface resistivity for all groups due to their pozzolanic activity, and significantly outperformed the specimens prepared with only portland cement. The w/cm ratio had a high impact on resistivity as expected, where the lower w/cm ratio consistently produced higher resistivity values over time for all specimen groups. The presence of LWAs had an overall positive effect on resistivity, where each of the LWA sources had an equal or better performance than the control

specimens based on the findings from the statistical analyses. Lastly, the coarse aggregate type affected resistivity, albeit predominantly based on the porosity of the aggregate itself rather than the mineralogy.

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# Abstract

The objective of this study was to evaluate the influence of internal curing and coarse aggregate type on concrete's 28-day strength, as well as surface resistivity over time (at days 7, 14, 28, 56, 90, and 180). A total of 96 concrete mixtures were prepared to identify the effects of three coarse aggregate types, two water-to-cementitious (w/cm) ratios, three fine lightweight aggregate (LWA) sources, and four variations of supplementary cementitious materials (SCMs). The compressive strength tests showed that in most cases, the presence of lightweight aggregate had a positive effect on strength (i.e., either had equal or better strength). Concerning surface resistivity, the statistical analyses determined that the use of SCMs, w/cm ratio, coarse aggregate type, and presence of LWAs had significant effects. The use of SCMs caused significant increases in surface resistivity for all groups due to their pozzolanic activity, and significantly outperformed the specimens prepared with only portland cement. The w/cm ratio had a high impact on resistivity as expected, where the lower w/cm ratio consistently produced higher resistivity values over time for all specimen groups. The presence of LWAs had an overall positive effect on resistivity, where each of the LWA sources had an equal or better performance than the control specimens based on the findings from the statistical analyses. Lastly, the coarse aggregate type affected resistivity, albeit predominantly based on the porosity of the aggregate itself rather than the mineralogy.

# Acknowledgments

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# Implementation Statement

The results from this study provide guidance on how surface resistivity requirements are to be implemented for internally cured concrete. Based on the trends observed, the Department may also provide recommendations on the concrete mixture parameters that yield the lowest permeability for structural concrete applications.

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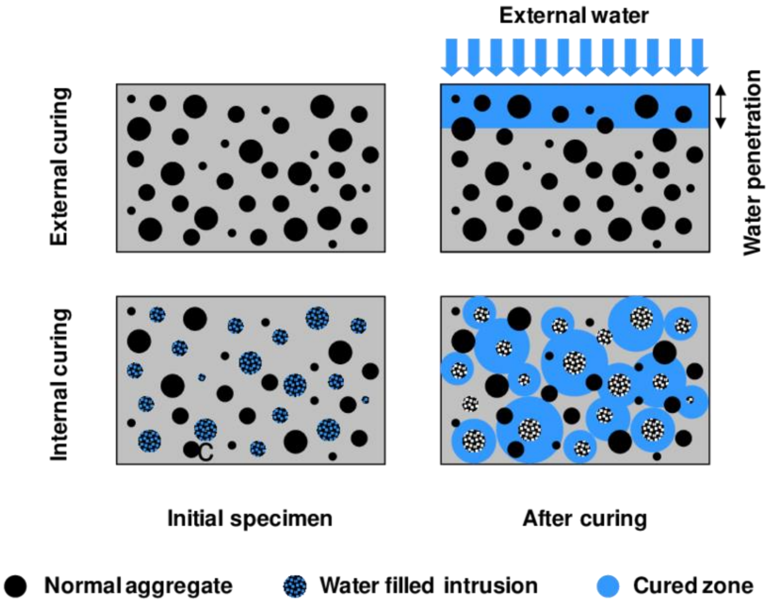
# Introduction

State highway agencies (SHAs) have begun to implement more internally cured concrete (ICC) mixtures in the design and construction of pavements and structures. Internal curing provides moisture throughout concrete after setting by utilizing agents such as pre-wetted lightweight aggregates (LWAs), pre-wetted crushed returned concrete fines, superabsorbent polymers, and pre-wetted wood fibers [1] [2]. LWAs are often used for ICC as they are the most economical and most widely available option [3]. In contrast, the conventional curing method involves externally wetting the concrete surface, which is limited by a shallow water penetration depth. The difference between the two methods is illustrated in Figure 1.

**Figure 1. Differences between external curing and internal curing provided by pre-wetted LWAs [3]**



Internal curing extends hydration, improves performance by increasing the reaction of supplemental cementitious materials (SCMs), and ensures that sufficient curing occurs in mixtures. By prolonging hydration, this process also mitigates the detrimental effects of autogenous and plastic shrinkage, as well as self-desiccation [4] [5] [6]. The addition of moisture internally can also benefit the mixture by reducing damage from alkali-silica reactions (ASR) due to dilution by providing space to accommodate ASR gel and by altering the pore solution composition [7]. Internal curing also provides additional strength during freeze-thaw performance [8]. The Lafayette Consolidated Government in Louisiana currently requires ICC for use in all cast-in-place structural concrete. Applications for internal curing in other states have been researched for use in bridge decks in Colorado, Illinois, Indiana, New York, Ohio, Oregon, and Utah [3].

In addition to ICC, SHAs are increasingly looking to adopt performance-based specifications instead of prescriptive ones to improve the durability and service life of the transportation infrastructure. In April 2016, the American Association of State Highway and Transportation Officials (AASHTO) released the PP 84-18 provisional standard on "Developing Performance Engineered Concrete Pavement Mixtures," which provides guidance for performance characteristics, including concrete's transport properties measured through surface resistivity [9]. The Louisiana Department of Transportation and Development (DOTD) has required surface resistivity measurements specifically for structural concrete applications since 2013. The most recent *Standard Specifications for Roads and Bridges* in 2016 included a surface resistivity requirement as a pay item [10].

Besides Louisiana, Florida and Kansas require surface resistivity results for certain classes of structural concrete mixture design approvals [11] [12]. At least 12 other DOTs are in the process of adopting similar requirements for the acceptance of mixture designs. However, there is limited information regarding the effect of saturated LWA on surface resistivity. As such, this study seeks to further analyze the effects of internally cured concrete on concrete's surface resistivity over time by identifying effects of coarse aggregate, water-to-cementitious (w/cm) ratios, LWA source, and variations of SCMs. The results of this study will provide recommendations on whether the inclusion of LWAs is beneficial to the measured resistivity of concrete and whether a correction factor is warranted.

# Literature Review

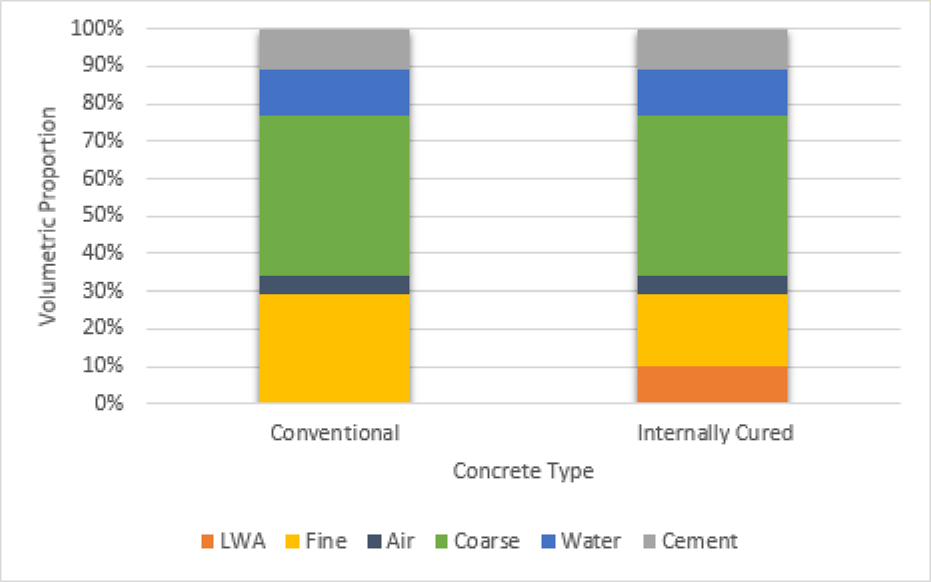
## Internally Cured Concrete

Lightweight Aggregates (LWA) are generally highly porous and highly absorbent materials compared to conventional, normal-weight aggregates. Pre-wetted LWAs made from expanded shale and clay have been increasingly used for internal curing applications. Unlike porous normal-weight aggregates, pre-wetted LWAs can reduce concrete’s transport properties through internal curing. Chia and Zhang observed that for a given strength of concrete, the water permeability of concrete with LWAs could be lower than that of concrete containing conventional aggregates, as LWAs improved the interfacial transition zone and promoted a more unified microstructure [13].

Mixture proportioning with internal curing provides the necessary additional water to prolong the time during which saturated conditions are maintained within the hydrating cement paste. This can be done by calculating the cementitious mixture's water demand by taking into account factors such as shrinkage and the expected maximum degree of reaction from the binder. The sorption capacity of the LWAs is also taken into account to determine the required dry mass of the LWA needed to provide the necessary internal curing water [14].

Once the quantity of required LWA mass is determined, the final replacement of normal weight aggregates (NWAs) by LWAs should be performed on a volume-to-volume basis, due to their significant differences in density [15]. Figure 2 provides an example of the volumetric proportions of a conventional concrete mixture design next to an ICC mixture design. In addition, LWAs must be pre-wetted or soaked in water for at least 24 hours to obtain the benefits of internal curing, and many specifications require a 72-hour pre-wetting period since the aggregates may continue to absorb water for three days or longer. If excessive slump losses (greater than 2 in.) occur with concrete mixtures using LWAs, it is likely that the LWAs were not adequately soaked [16].

**Figure 2. Example of volumetric mixture proportions of both conventional and ICC concrete**



Successful applications have been reported with LWA dosages ranging from 200 lbs/yd$^3$ to 300 lbs/yd$^3$ [14]. It is worth noting that pre-wetted LWAs requires a moisture correction before adding in a concrete mixture in order to maintain the desired water-to-cementitious ratio. There are currently two main methods used to quantify the absorbed moisture and surface moisture for LWAs. The "paper towel method" (ASTM C1761) has been used to calculate the moisture correction for pre-wetted LWAs. However, this method tends to be time-consuming, has a high variability between different operators, and may prove challenging to use in large-scale operations. An alternative method proposed by Miller et al. uses a centrifuge for moisture corrections of fine LWAs [17]. This procedure is reportedly simpler, faster, and more precise. Strong correlations were also observed between the centrifuge method and the ASTM C1761 method when the centrifuge was set to spin for 3 minutes at 2000 rpm.

## Factors Affecting Permeability

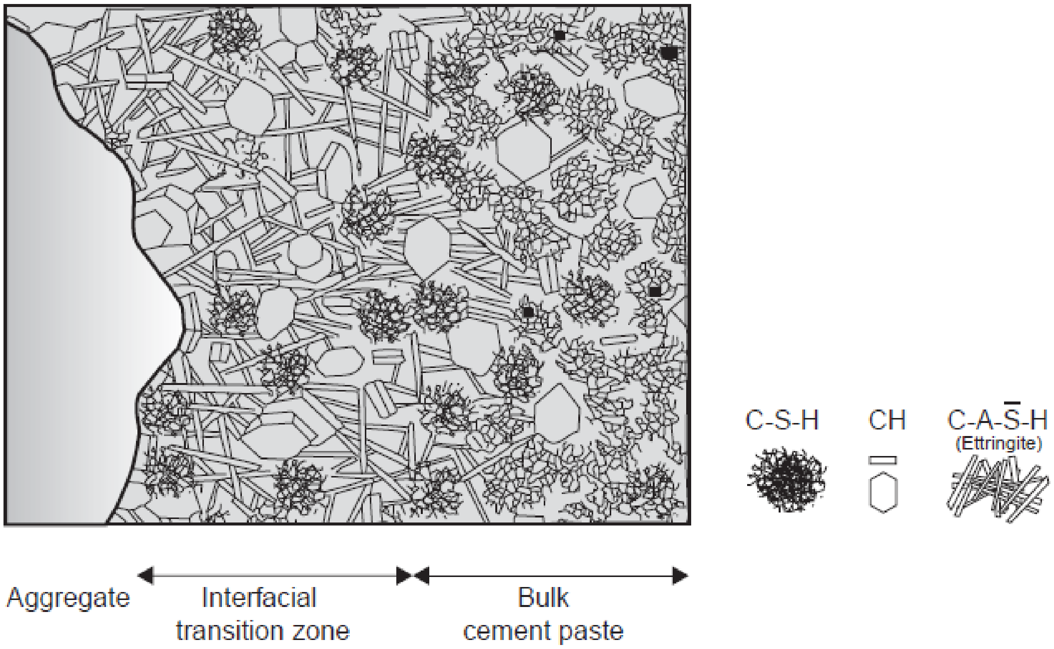
The most important factor affecting water permeability is the water-cementitious materials (w/cm) ratio.  Lower w/cm ratios are known to reduce permeability, as this provides less evaporable water within the mixture after drying. As a result, the capillary porosity and the pore size distribution decrease, yielding a denser microstructure [18].

The degree of hydration of the cement paste is another critical factor that affects permeability and is dependent on the curing regime and age of the cement paste. As the cement continues to hydrate, the hydration products begin to form and fill the voids within the cement paste. This effectively decreases the volume, size, and, most importantly, the interconnectivity of the capillary pores [18].

Supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume have been demonstrated to reduce permeability. SCMs are classified as pozzolans, as they chemically react with calcium hydroxide, the most soluble cement hydration product, to produce calcium silica hydrates (C-S-H) and thereby densify the concrete matrix [19].

The aggregate's morphology, in particular with coarse aggregates, affects the composition of the interfacial transition zone (ITZ). The ITZ is generally the weakest component within concrete with respect to its mechanical and transport properties. Compared to the bulk cement paste, the ITZ has a higher porosity, higher contents of calcium hydroxide and ettringite, and lower contents of C-S-H (Figure 3). The ITZ can be up to 10 times more susceptible to chloride diffusion than the bulk cement paste [20].

**Figure 3. Schematic of the interfacial transition zone (ITZ) in concrete [18]**



Studies have shown that large flat, elongated aggregates tend to have a weaker ITZ that is more susceptible to cracking [18]. A normal-weight aggregate's porosity is also known to influence concrete’s permeability, particularly if the aggregate’s pores are interconnected [21] [22] [23] [24]. It is worth noting that this observation does not apply to aggregates that enable internal curing in concrete. Aggregate mineralogy may also affect the interfacial transition zone considerably [18] [25]. However, the influence of the aggregate’s mineralogy on concrete’s permeability may not be readily apparent in most standardized testing procedures.

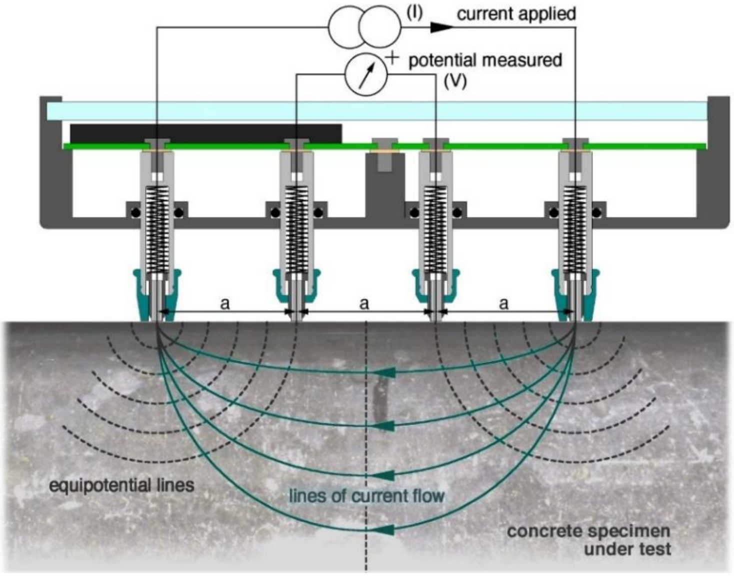
## Measuring Permeability

Evaluating concrete transport properties such as permeability and chloride ion penetration is of particular concern to owners, designers, and materials engineers, as these properties are related to concrete’s durability. The transport mechanisms that influence the movement of fluids and ions include water absorption through capillary suction, permeability, and diffusion [26]. Permeability defines the ease at which fluids move under pressure variations, and diffusion describes the movement of ions under variations in concentration. Chloride ion penetration into the pore solution can negatively affect concrete durability by corroding the steel reinforcement, by affecting the chemical/electrical balance, and by inducing premature deterioration in concrete [27]. As such, it is imperative to develop concrete which strongly resists chloride penetration to extend the service life of PCC pavements and structures.

In order to effectively measure chloride permeability, electrical test methods have been developed to provide a rapid indication of concrete’s resistance to chloride penetration including the ASTM C1202/AASHTO T 277 rapid chloride permeability test (RCPT), the AASHTO T 358 surface resistivity test, and the ASTM C1760 bulk conductivity test. It is important to note that these procedures are applicable to types of concrete that were used to correlate the electrical conductance of concrete with long-term chloride ponding exposures such as those described in AASHTO T 259 or ASTM C1556.

Electrical resistivity measurements have the potential to provide a performance-based evaluation of hardened concrete. Past and recent efforts have correlated surface resistivity to chloride ion penetrability [28] [29] [30] [31] [32] [33]. AASHTO T 358 is the standard test method for determining surface resistivity (measured in kΩ-cm or kΩ-m) using a Wenner array probe. The test method requires a current to be applied across the outside two probes while measuring the resistance (potential) with the inside two probes, as shown in Figure 4 [34].

**Figure 4. Test setup to measure concrete's surface resistivity with the Wenner array probe**



Surface resistivity is a valuable tool in assessing concrete's transport properties, as it is able to capture the effects that influence concrete's permeability. Specifically, resistivity readings are known to be affected by the water-cement ratio, the presence of SCMs, polymeric admixtures, air-void system, aggregate type, and degree of consolidation.

It is important to note that this test method can produce misleading results when calcium nitrite has been admixed into concrete, as it may increase the conductivity of the pore solution and therefore decrease the measured resistivity. This test method is also not valid in concrete mixtures containing steel reinforcement or other conductive materials embedded within the concrete mixture.

The curing conditions which control concrete's degree of water saturation and temperature also have a substantial impact on the results, as it is an electrical test method. As such, AASHTO T 358 specifies a standardized conditioning procedure that maintains a 100% relative humidity condition at an air temperature range of 68°F to 77°F to minimize the variability of the resistivity results in concrete.

# Objective

This study's objective was to analyze the effects of internally cured concrete on concrete’s surface resistivity over time by identifying effects of coarse aggregate, water-to-cementitious (w/cm) ratios LWA source, and variations of SCMs.

# Scope

The scope of this study was to evaluate the influence of internally cured concrete on surface resistivity, measured periodically at 7, 14, 28, 56, 90, and 180 days of age. Pre-wetted lightweight aggregates made from expanded shale and clay were used to enable internal curing. The results of this study were limited to concrete mixtures made from ordinary portland cement, and mixtures containing supplementary cementitious materials such as Class C fly ash and grade 100 ground granulated blast-furnace slag cement.

# Methodology

## Concrete Testing

Surface resistivity was measured per AASHTO T 358 for all samples at days 7, 14, 28, 56, 90, and 180. Concrete cylinders of 4 in. x 8 in. in dimension were prepared per ASTM C192 for this study. Once the samples were cast, they remained in the cylinder molds for 48 hours before demolding to simulate the worst-case scenario allowed by specification for field cast cylinders. After demolding, the samples were placed in a 100% relative humidity room until testing. Fresh concrete properties such as slump were evaluated following ASTM C143 standards, and compressive strength tests were conducted per ASTM C39 once concrete reached 28 days of age.

## Concrete Mixture Design

The influence of internal curing on concrete's surface resistivity was evaluated by taking into account the following variables: lightweight aggregate (LWA) source, coarse aggregate type, water-to-cementitious (w/cm) ratio, and supplementary cementitious materials (SCMs). Three sources of LWAs were selected (from Texas, Alabama, and Louisiana) and featured different absorption values. The characteristics of the LWAs are described in Table 1. Pre-wetted LWA was added to the concrete mixture design by replacing a portion of fine aggregate with 250 lbs/yd$^3$ on a volume-to-volume basis. The LWAs were soaked in water for 72 hours prior to usage in concrete. Moisture corrections were done for LWAs by following the centrifuge procedure [17]. Control specimens with no LWAs were used for comparison.

**Table 1. Lightweight aggregate source characteristics**

| Property | LWA Source | | |
|---|---|---|---|
| | Alabama | Louisiana | Texas |
| Specific Gravity (SSD) | 1.24 | 1.75 | 1.90 |
| 72-Hour Absorption (%) | 37.3 | 23.6 | 18.2 |
| Desorption (%) | 92.2 | 90.6 | 85.3 |
| Quantity of Internal Curing Water per CY of Concrete | 65.9 | 70.7 | 41.0 |

Four different combinations of cementitious materials were evaluated using Type I portland cement, Class C fly ash, and grade-100 ground granulated blast furnace slag. Specifically, samples were prepared using (a) 100% Type I portland cement (100TI); (b) 70% Type I portland cement and 30% Class C fly ash (70TI-30C); (c) 50% Type I portland cement and 50% grade 100 ground granulated blast-furnace slag (50TI-50S); and (d) a ternary mix of 30% Type I portland cement, 30% Class C fly ash, and 40% grade 100 ground granulated blast-furnace slag (30TI-30C-40S). In addition, three different types of coarse aggregates were tested to analyze their influence on surface resistivity as well, all with a No. 67 gradation. The concrete used a 60/40 coarse to fine aggregate ratio. Lastly, a superplasticizer was used to ensure workability. Table 2 shows the experimental matrix for this study, using mixtures commonly used in Louisiana. A total of 96 mixtures were produced.

**Table 2. Proposed experimental factorial**

| Factor | Levels | Description |
|---|---|---|
| Water-to-cementitious (w/cm) ratio | 2 | 0.35, 0.45 |
| Total cementitious content | 1 | 500 lbs/yd$^3$ |
| Cementitious combinations & Mixture ID | 4 | -100% Type I cement (100TI)<br>-70% Type I cement and 30% Class C fly ash (70TI-30C)<br>-50% Type I cement and 50% slag (50TI-50S)<br>-30% Type I cement, 30% Class C fly ash, and 40% slag (30TI-30C-40S) |
| Coarse aggregate type | 3 | Siliceous Limestone (SL), Dolomitic Limestone (L), and Gravel (G) |
| LWA dosage rates | 2 | 0, 250 lbs/yd$^3$ |
| LWA sources | 3 | -Louisiana (LWA-LA)<br>-Alabama (LWA-LA)<br>-Texas (LWA-TX) |
| Super Plasticizer dosage* | 1 | -10 oz/cwt @ 0.35 w/cm<br>-1 oz/cwt @ 0.45 w/cm |
| Curing regimen | 1 | 100% RH |

*Super plasticizer dosage was modified to 13 oz/cwt @ 0.35 w/cm, and 3 oz/cwt @ 0.45 w/cm for the dolomitic limestone mixtures.

# Discussion of Results

## Fresh Concrete Properties

The slump test results were summarized in Table 3. It is worth noting that most zero-slump concretes were observed with samples containing LWAs, indicating that a lower workability can be expected when using ICC. To compensate for a lower workability, modest increases in super-plasticizers or water-reducing admixtures are recommended.

In general, the specimens prepared with gravel as the coarse aggregate were found to have higher slumps than equivalent mixtures prepared with siliceous limestone aggregates (albeit with one exception at 0.45 w/cm for the control 70TI-30C mixture). This was attributed to the angularity of the limestone aggregates, which increase the internal friction between concrete's components, resulting in a stiffer mixture. In contrast, gravel features rounder edges and smoother surface textures which result in more workable mixtures. It is worth noting that the non-siliceous limestone (L) samples had a significantly higher dust content, and thus increased the water demand of the mixture. To alleviate this problem, the super plasticizer dosage was increased from 10 oz/cwt to 13 oz/cwt at the 0.35 w/cm ratio, and from 1 oz/cwt to 3 oz/cwt at the 0.45 w/cm ratio. Such increases in super plasticizer dosage improved the workability, which yielded higher slumps than the other gravel and siliceous limestone mixtures.

**Table 3. Slump results**

| Mixture ID | CA Type | w/cm | C | AL | LA | TX |
|---|---|---|---|---|---|---|
| | | | **Slump (in.)** | **Slump (in.)** | **Slump (in.)** | **Slump (in.)** |
| 100TI | G | 0.35 | 0.00 | 0.25 | 0.00 | 0.00 |
| 70TI-30C | G | | 0.25 | 0.25 | 0.50 | 0.75 |
| 50TI-50S | G | | 0.25 | 0.50 | 0.00 | 0.50 |
| 30TI-30C-40S | G | | 1.00 | 1.25 | 0.25 | 1.00 |
| 100TI | L | | 3.75 | 0.00 | 0.00 | 0.00 |
| 70TI-30C | L | | 6.25 | 0.00 | 3.00 | 0.25 |
| 50TI-50S | L | | 0.25 | 0.00 | 0.00 | 0.25 |
| 30TI-30C-40S | L | | 6.25 | 0.00 | 0.50 | 5.00 |
| 100TI | SL | | 0.00 | 0.00 | 0.00 | 0.00 |
| 70TI-30C | SL | | 0.00 | 0.25 | 0.00 | 0.00 |
| 50TI-50S | SL | | 0.25 | 0.00 | 0.00 | 0.50 |
| 30TI-30C-40S | SL | | 0.50 | 0.00 | 0.00 | 0.50 |
| 100TI | G | 0.45 | 0.25 | 0.25 | 0.50 | 0.50 |
| 70TI-30C | G | | 0.50 | 6.00 | 2.00 | 1.00 |
| 50TI-50S | G | | 0.75 | 1.00 | 0.75 | 1.25 |
| 30TI-30C-40S | G | | 2.25 | 3.50 | 1.00 | 3.50 |
| 100TI | L | | 3.25 | 0.00 | 0.25 | 0.50 |
| 70TI-30C | L | | 3.50 | 0.25 | 0.00 | 1.50 |
| 50TI-50S | L | | 0.50 | 0.00 | 0.00 | 0.75 |
| 30TI-30C-40S | L | | 1.50 | 0.25 | 1.50 | 1.50 |
| 100TI | SL | | 0.00 | 0.00 | 0.00 | 0.00 |
| 70TI-30C | SL | | 1.25 | 0.00 | 1.50 | 1.00 |
| 50TI-50S | SL | | 0.25 | 0.00 | 0.25 | 0.50 |
| 30TI-30C-40S | SL | | 0.50 | 0.00 | 0.00 | 0.50 |

*G: Gravel; L: Limestone; SL: Siliceous Limestone: w/cm: water to cementitious material ratio; AL: Lightweight Aggregate from Alabama; LA: Lightweight Aggregate from Louisiana; TX: Lightweight Aggregate from Texas; C: Control.

## Compressive Strength

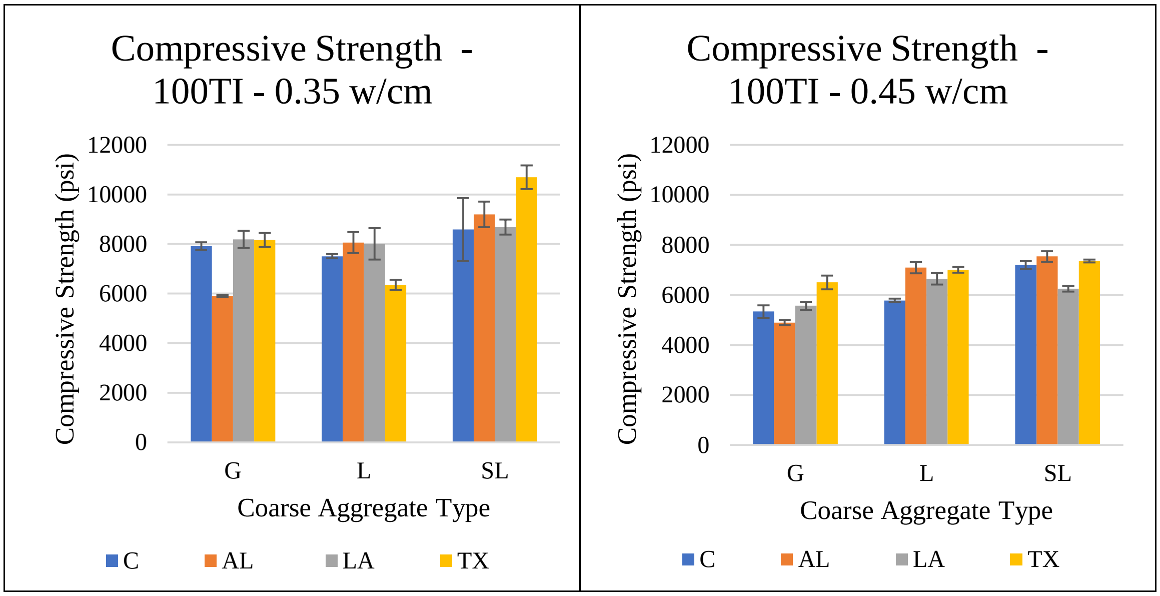
The compressive strength of all specimens was evaluated per ASTM C39 to determine whether the presence of lightweight aggregates had an effect (Figure 5). Overall, a general trend can be observed where the coarse aggregate type had an influence in strength, where the highest was observed with mixtures containing siliceous limestone, whereas the lowest strengths were observed for mixtures made with gravel. This can be attributed to the higher internal friction within the limestone mixtures (due to limestone's angular shape with rough surface texture) that ultimately contribute to higher strengths.

Within the gravel mixtures at the 0.35 w/cm ratio, the lightweight aggregate sourced from Alabama (LWA-AL) had a considerable decrease in strength compared to the control specimens in all cement combinations. The other lightweight aggregate sources mostly had a similar performance to the control specimens, with the exceptions of LWA-LA in the 50TI-50S mixture, and LWA-TX at the ternary mixture.  In contrast, at the 0.45 w/cm ratio, the specimens containing lightweight aggregates had a similar or improved strength than the control specimens (except for LWA-AL in the 100TI mixture).

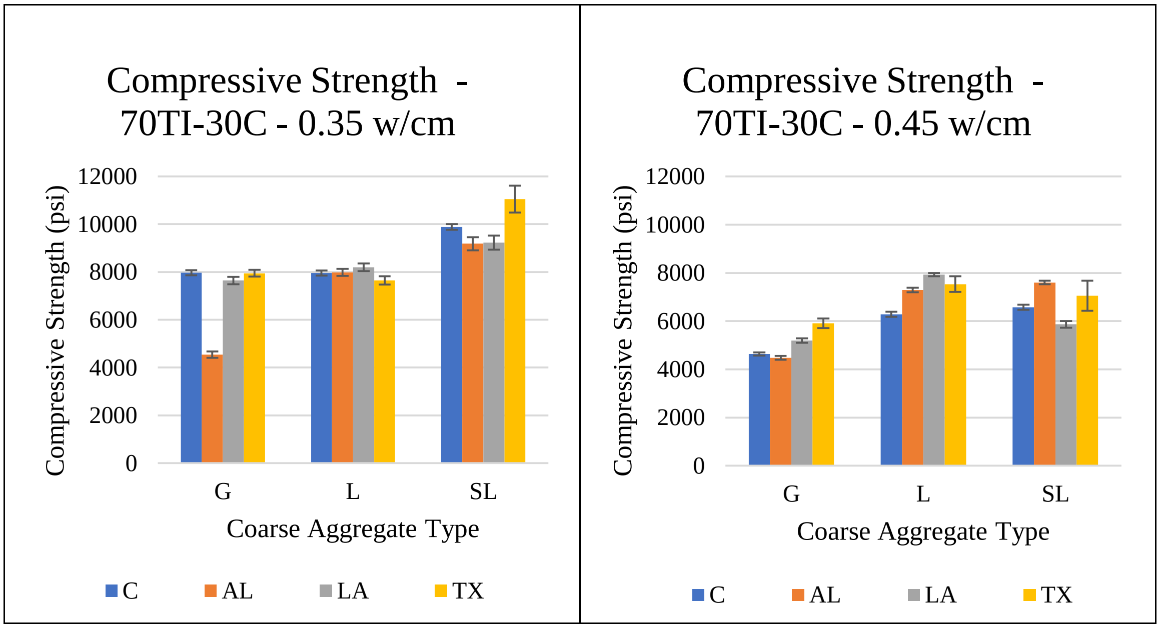
For the limestone mixtures at the 0.35 w/cm ratio, minimal differences were generally observed in strength between most specimens with lightweight aggregates and the controls in all cement combinations, with the exception of the ternary mixture where all samples with lightweight aggregates had substantial strength decreases. Other notable exceptions were found with LWA-TX in the 100TI mixture, and both LWA-AL and LWA-TX in the 50TI-50S mixture. At the 0.45 w/cm ratio, the samples with lightweight aggregates had an equal or better performance than the controls in all cement combinations, with the exception of LWA-LA in the ternary mixture.

For the siliceous limestone mixtures at the 0.35 w/cm ratio, the presence of lightweight aggregates in the specimens was generally beneficial, with equal or higher strengths than the control specimens within the OPC and binary mixtures (excluding LWA-AL in the 50TI-50S and 70TI-30C groups, and LWA-LA in the 70TI-30C mixture). For the ternary mixtures, however, all lightweight aggregate sources had lower strengths than the control specimens.  At the 0.45 w/cm ratio, positive results were also observed, where only LWA-LA decreased strength considerably within the 100TI and 70TI-30C mixtures. At the ternary mixture, only LWA-TX had a significantly lower strength than the control specimens.

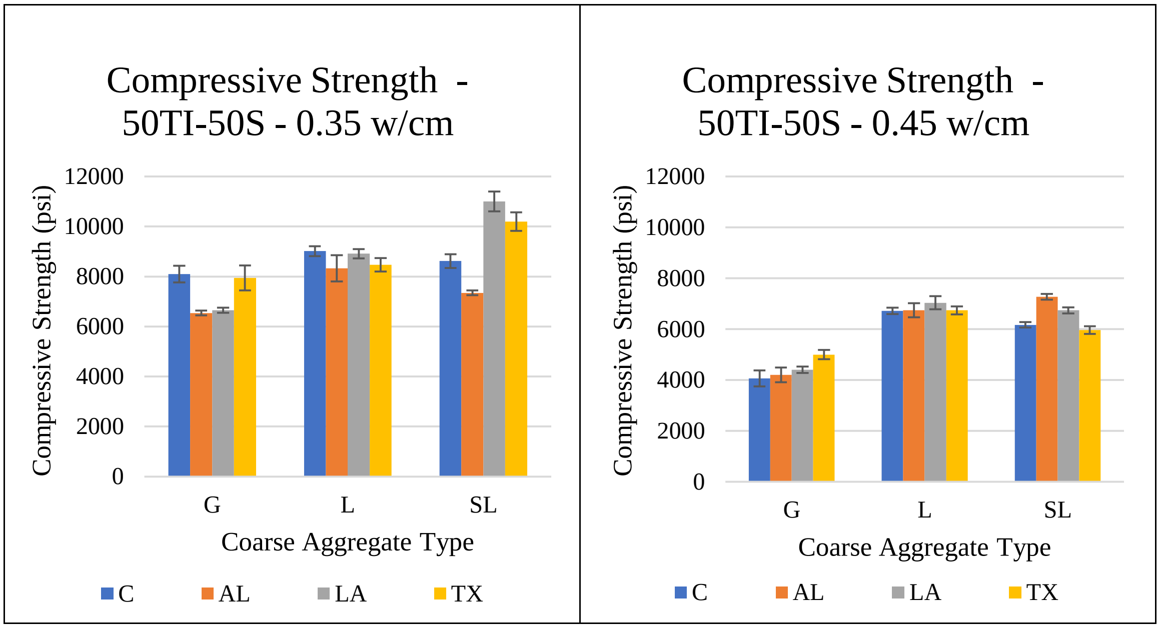
**Figure 5. Influence of lightweight aggregates and coarse aggregate type on compressive strength at 28 days**



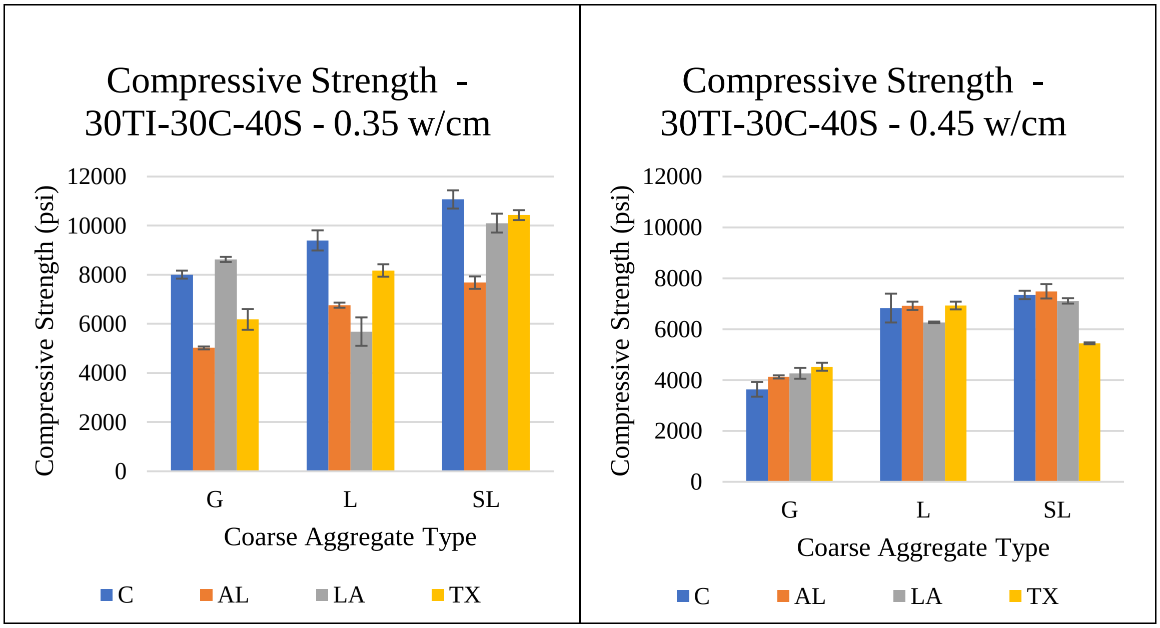
(a) 100TI at 0.35 w/cm (b) 100TI at 0.45 w/cm



(c) 70TI-30C at 0.35 w/cm (d) 70TI-30C at 0.45 w/cm



(e) 50TI-50S at 0.35 w/cm (f) 50TI-50S at 0.45 w/cm



(g) 30TI-30C-40S at 0.35 w/cm (h) 30TI-30C-40S at 0.45 w/cm

A statistical analysis was conducted using Duncan's multiple range test at a 5% significance level, comparing whether lightweight aggregates had an influence on strength for specimens made from the same cementitious content, water-to-cementitious ratio, and coarse aggregate type. The results showed that in most cases, lightweight aggregates had a positive effect on strength (i.e., either had equal or better strength). There were some exceptions, however, where lightweight aggregates had a significantly lower strength than the controls, as shown in Table 4.

**Table 4. Lightweight aggregate sources that had a significantly lower strength than the controls**

| CA Type | Mix ID | LWA Source | |
|---|---|---|---|
| | | 0.35 w/cm | 0.45 w/cm |
| Limestone (L) | 100TI | TX | - |
| | 70TI-30C | - | - |
| | 50TI-50S | AL & TX | - |
| | 30TI-30C-40S | AL & LA & TX | LA |
| Siliceous Limestone (SL) | 100TI | - | LA |
| | 70TI-30C | AL & LA | LA |
| | 50TI-50S | AL | - |
| | 30TI-30C-40S | AL & LA & TX | TX |
| Gravel (G) | 100TI | AL | AL |
| | 70TI-30C | AL | - |
| | 50TI-50S | AL & LA | - |
| | 30TI-30C-40S | AL & TX | - |

Overall, out of 72 mixtures containing lightweight aggregates, 23 of these mixtures had a negative impact on strength. Based on Table 4, it can be observed that the differences in strength are most noticeable at a lower water-cement ratio, where 18 cases were seen to have a negative effect on strength at a 0.35 w/cm ratio, whereas only 5 cases were observed to have a negative effect on strength at a 0.45 w/cm ratio. The compressive strength of the ternary mixtures (30TI-30C-40S) seemed to be the most affected by the presence of lightweight aggregates, and most notably with those mixtures containing limestone. In addition, the lightweight aggregate sourced from Alabama seemed to have a negative impact on strength in most cases, particularly at the 0.35 w/cm ratio, whereas the lightweight aggregate from Louisiana had a negative impact in most cases at the 0.45 w/cm ratio.

## Surface Resistivity

A total of 96 specimen groups were prepared to measure the effects of three coarse aggregate types, two w/cm ratios, four combinations of cementitious materials, and three sources of LWAs on concrete's surface resistivity. The results were used to classify concrete's chloride ion penetrability per AASHTO T 358 (Table 5). For reference, Louisiana's *Standard Specifications for Roads and Bridges* in 2016 requires a minimum surface resistivity of 22 kΩ-cm for structural concrete measured at 28 days of age [10].

**Table 5. Chloride ion penetration rating based on surface resistivity readings [35]**

| Chloride Ion Penetration | Surface Resistivity (kΩ-cm) (4 in. x 8 in. cylinders) |
|---|---|
| High | <12 |
| Moderate | 12-21 |
| Low | 21-37 |
| Very Low | 37-254 |
| Negligible | >254 |

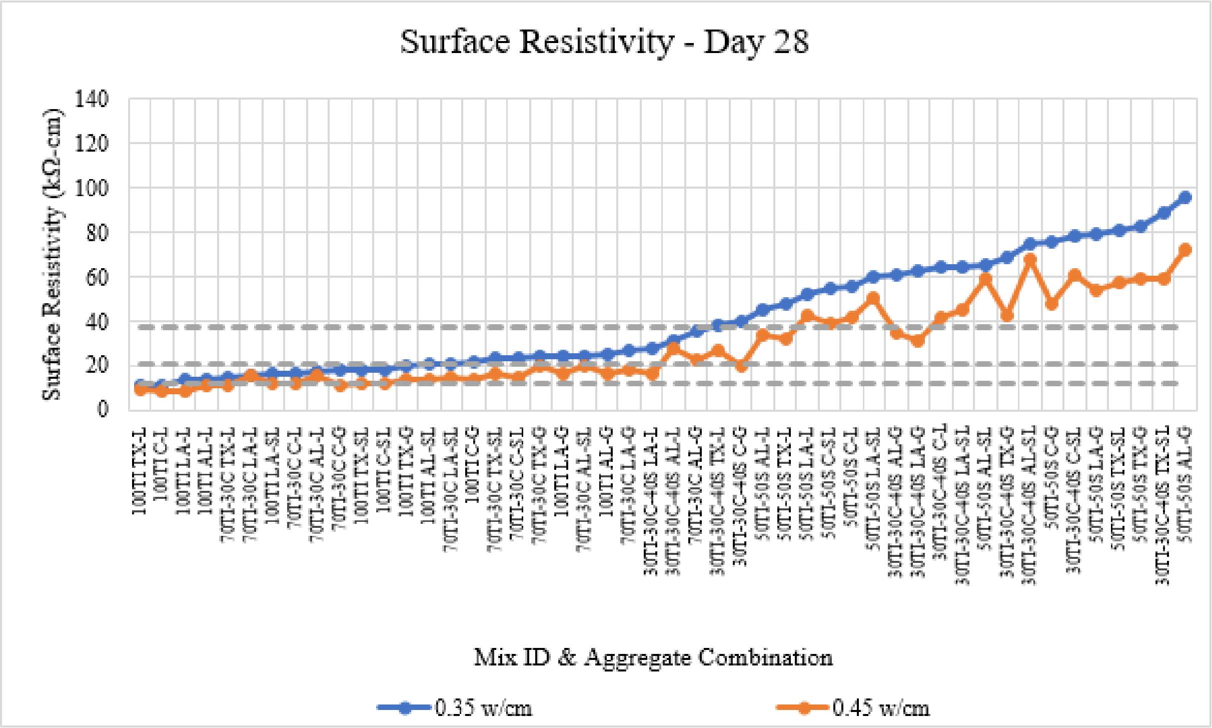
### Influence of Water-to-Cementitious Ratio

Figure 6 illustrates the surface resistivity measurements at 28 and 56 days of age for all specimens, as these are the test ages used for quality control and acceptance of structural concrete in DOTD's specifications [10]. The surface resistivity results were sorted in ascending order for the 0.35 w/cm ratio and grouped by their respective w/cm ratio. The dashed lines were used to illustrate the regions that define the chloride ion penetration ratings based on the surface resistivity readings.

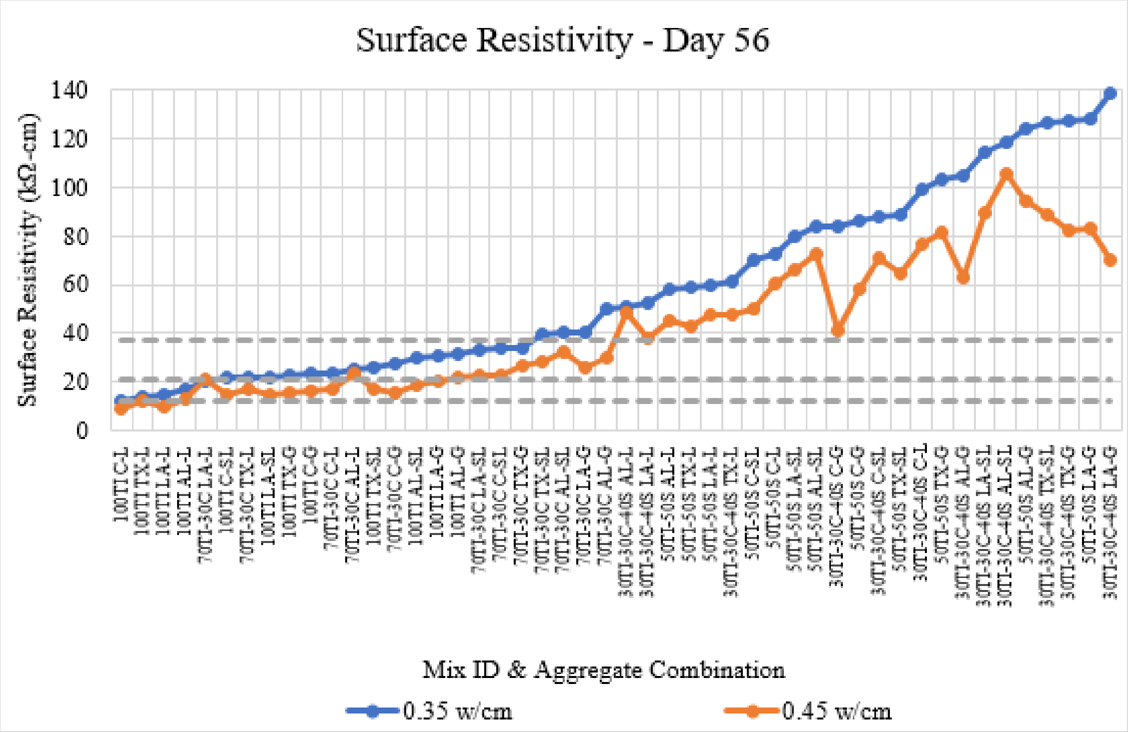
As expected, the results showed that the w/cm ratio is a controlling factor in surface resistivity, verifying results found in the literature [28] [36]. This was attributed to the fact that a lower w/cm ratio decreases the permeability of hardened concrete, since more mixing water leads to a higher capillary porosity [18]. The largest increases in surface resistivity were observed in specimens containing SCMs after reducing the w/cm ratio, most notably with the mixtures containing slag cement. In some cases, however, the increases in surface resistivity readings were not always enough to reduce the chloride ion penetrability rating for equivalent mixtures differing only in w/cm ratios. This observation was mostly applicable to the 100TI specimens at the 28-day resistivity readings, where 6 out of 12 specimens remained in the same chloride ion penetrability rating (per Table 5) even after the w/cm ratio was lowered.

The curing age also had a notable impact in surface resistivity readings, as expected, since concrete’s degree of hydration increases over time (provided adequate moisture and temperature ranges are maintained). At the 0.45 w/cm ratio, 25 out of 48 samples did not meet the 22 kΩ-cm threshold, whereas at the 0.35 w/cm ratio 16 of 48 samples did not meet the 22 kΩ-cm threshold after testing at 28 days. On the other hand, when the testing is conducted at 56 days, 16 out of 48 samples did not meet the 22 kΩ-cm threshold at the 0.45 w/cm ratio, whereas 8 out of 48 samples did not meet the 22 kΩ-cm threshold at the 0.35 w/cm ratio.

**Figure 6. Surface resistivity measurements for all specimens sorted in ascending order relative to the 0.35 w/cm ratio at (a) Day 28, and (b) Day 56**



(a) 28 days



(b) 56 days

### Influence of Supplementary Cementitious Materials

It was shown in Figure 6 that the specimens containing slag (50TI-50S and 30TI-30C-40S) produced concrete with high surface resistivity readings and, therefore, low chloride ion penetration ratings. Most specimens that had a "Very Low" chloride ion penetration ratings (i.e., surface resistivity readings exceeding 37 kΩ-cm) were from the slag mixtures at both w/cm ratios, while the vast majority of mixtures with "High" chloride ion penetration ratings were from those containing only portland cement (100TI). This result is consistent with the findings from the literature [28] [37] and was attributed to the fact that the pozzolanic reactions enabled by the SCMs can densify the cementitious matrix and reduce the chloride ion permeability [18]. In addition, SCMs can change the pore solution's chemistry in concrete, which also leads to increases in surface resistivity [38].

### Influence of LWA Source

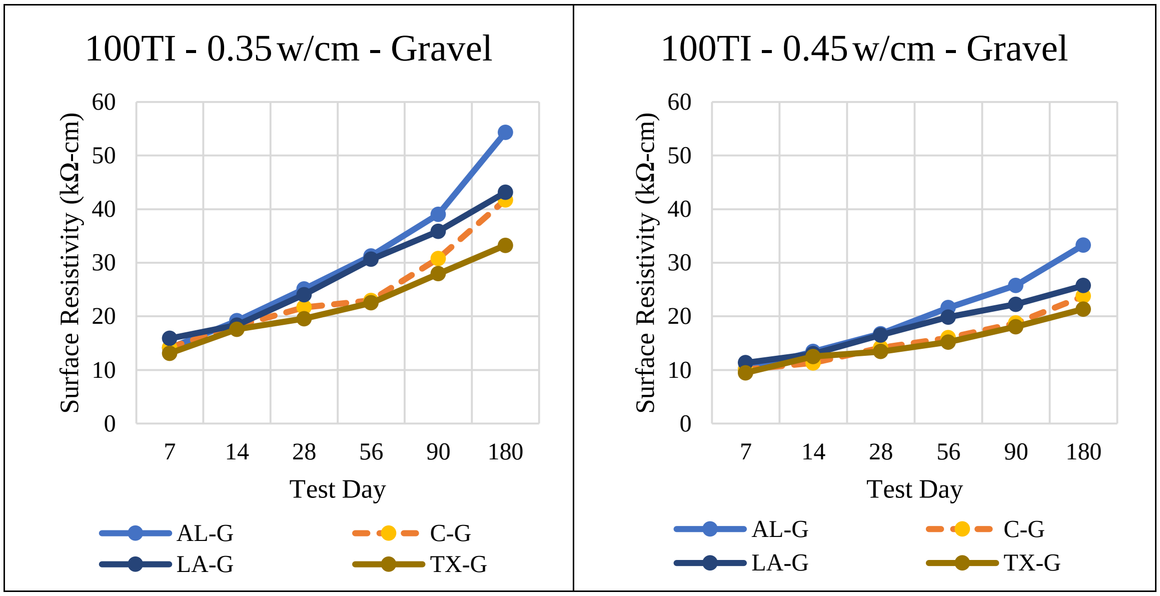
To analyze the influence of LWA source on surface resistivity over time, the effects of the three sources were compared with respect to each other and to the control specimens containing no LWAs.

Mixtures prepared with a specific coarse aggregate type and w/cm ratio are shown in Figure 7 for samples prepared with ordinary portland cement (100TI). The results showed that the addition of LWAs was generally beneficial for all specimens, with similar or improved performance in surface resistivity than the control specimens over time. The samples prepared at a 0.35 w/cm ratio seemed to have more considerable differences in surface resistivity (relative to the controls) than the samples prepared at a 0.45 w/cm ratio.

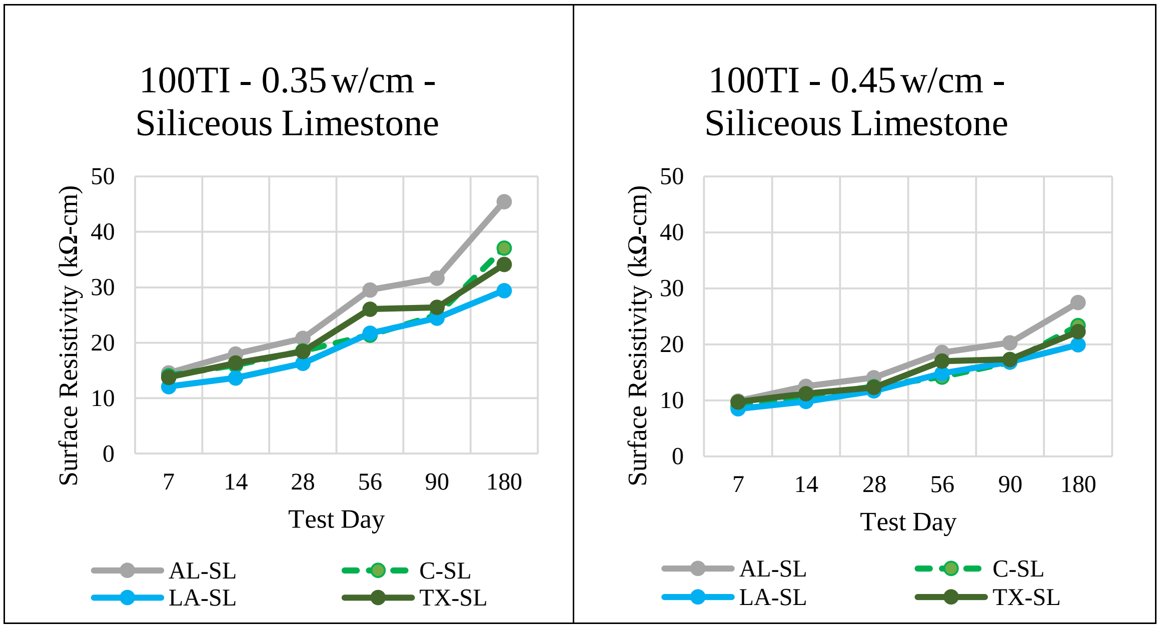
Moreover, the specimens with gravel (Figure 7a and Figure 7b) and siliceous limestone (Figure 7c and Figure 7d) had a higher resistivity than the specimens made with limestone from the Yucatan region (Figure 7e and Figure 7f). This can be attributed to the fact that the dolomitic limestone used was sourced from the Yucatan Peninsula of Mexico and was characterized as a very porous limestone [39]. Porous aggregates are known to increase the bulk pore connectivity within the cementitious matrix significantly and therefore yield a more permeable concrete mixture [21] [22] [24].

The highest performing LWA was sourced from Alabama, yielding the highest surface resistivity values in all cases for the 100TI mixtures. At the 0.35 w/cm ratio, the lowest performing LWA was from Texas, while at the 0.45 w/cm ratio the lowest performing LWA was from Louisiana. However, it is important to note that such specimen groups still had a similar or better surface resistivity than the control specimens, in particular within the first 90 days.

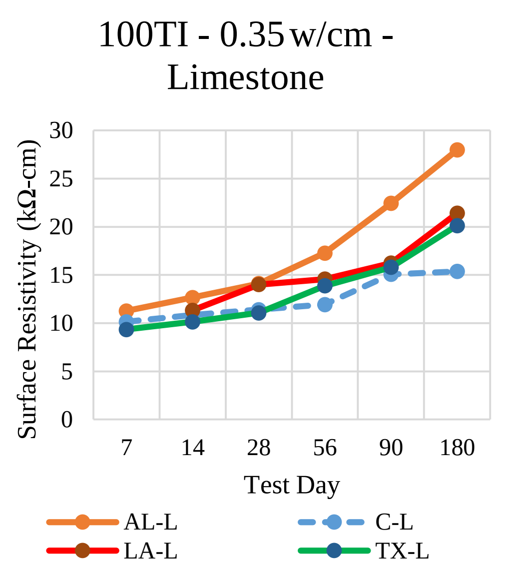
**Figure 7. Influence of lightweight aggregates on surface resistivity over time for mixtures made from 100% portland cement (100TI)**



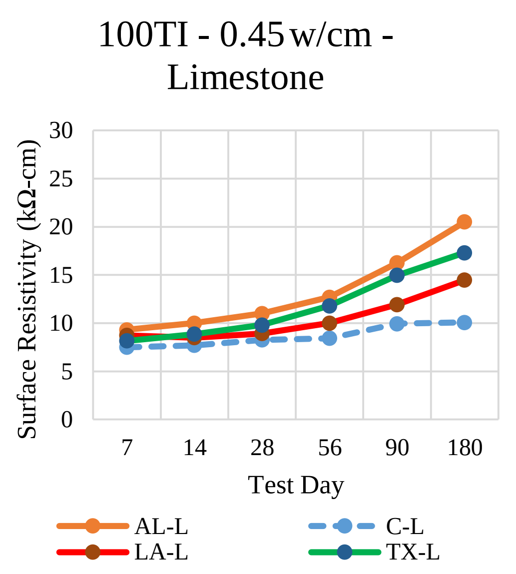
(a) Gravel at 0.35 w/cm (b) Gravel at 0.45 w/cm



(c) Siliceous Limestone at 0.35 w/cm (d) Siliceous Limestone at 0.45 w/cm



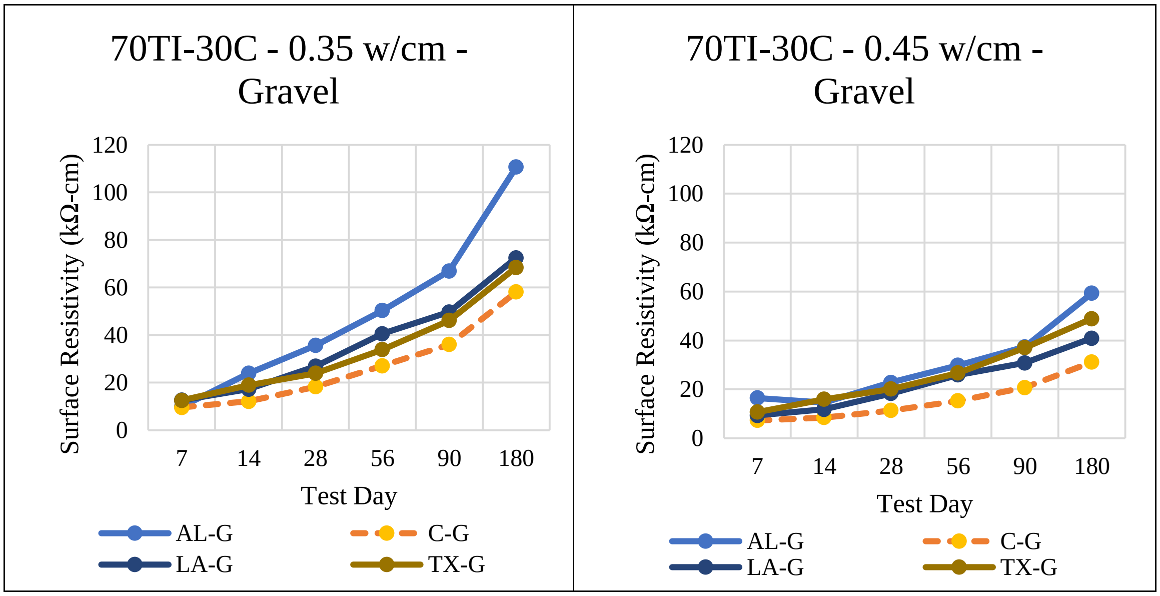
(e) Limestone at 0.35 w/cm



(f) Limestone at 0.45 w/cm specimens

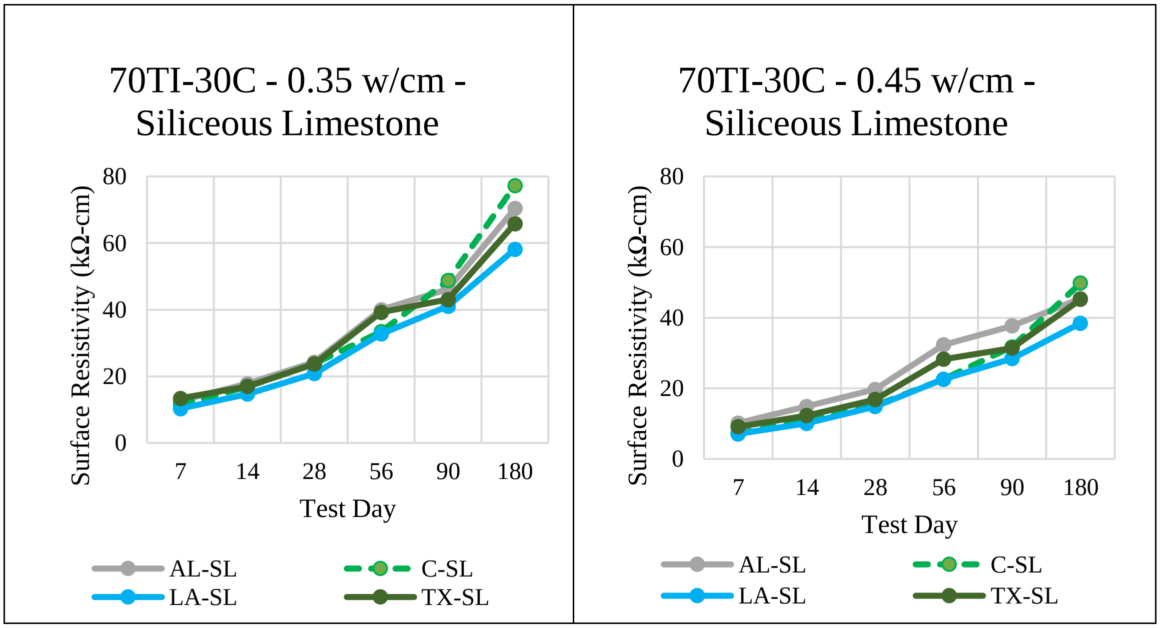
Figure 8 shows the surface resistivity progression over time for samples prepared with 70% portland cement and 30% Class C fly ash (70TI-30C). The results showed that the addition of LWAs was also beneficial for all specimens, with equal or better performance in surface resistivity than the control specimens over time. LWAs significantly increased concrete’s surface resistivity more noticeably for the gravel (Figure 8a and Figure 8b) and limestone mixtures (Figure 8e and Figure 8f). For the siliceous limestone mixtures (Figure 8c and Figure 8d), the control specimens seemed to have slightly higher resistivity values at the later ages (days 90 and 180, respectively). Overall, the LWA from Alabama seemed to have the highest surface resistivity values in virtually all 70T-30C mixtures, following the same trend observed with the 100TI mixtures.

**Figure 8. Influence of lightweight aggregates on surface resistivity over time for mixtures made from 70% portland cement and 30% Class C fly ash (70TI-30C)**



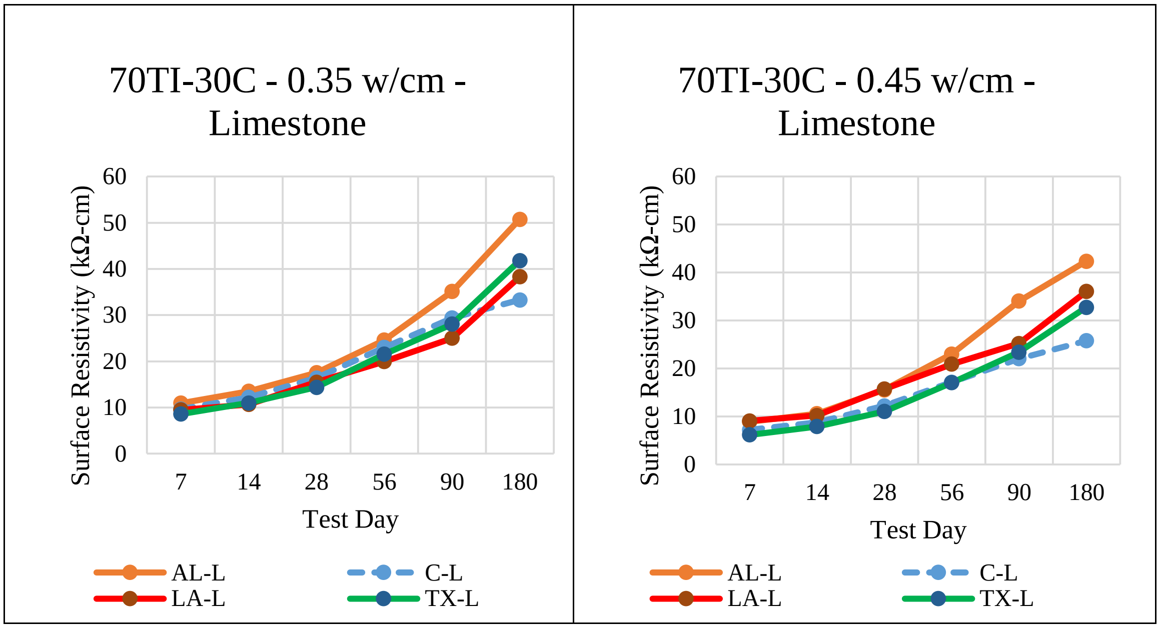
(a) Gravel at 0.35 w/cm

(b) Gravel at 0.45 w/cm



(c) Siliceous Limestone at 0.35 w/cm

(d) Siliceous Limestone at 0.45 w/cm

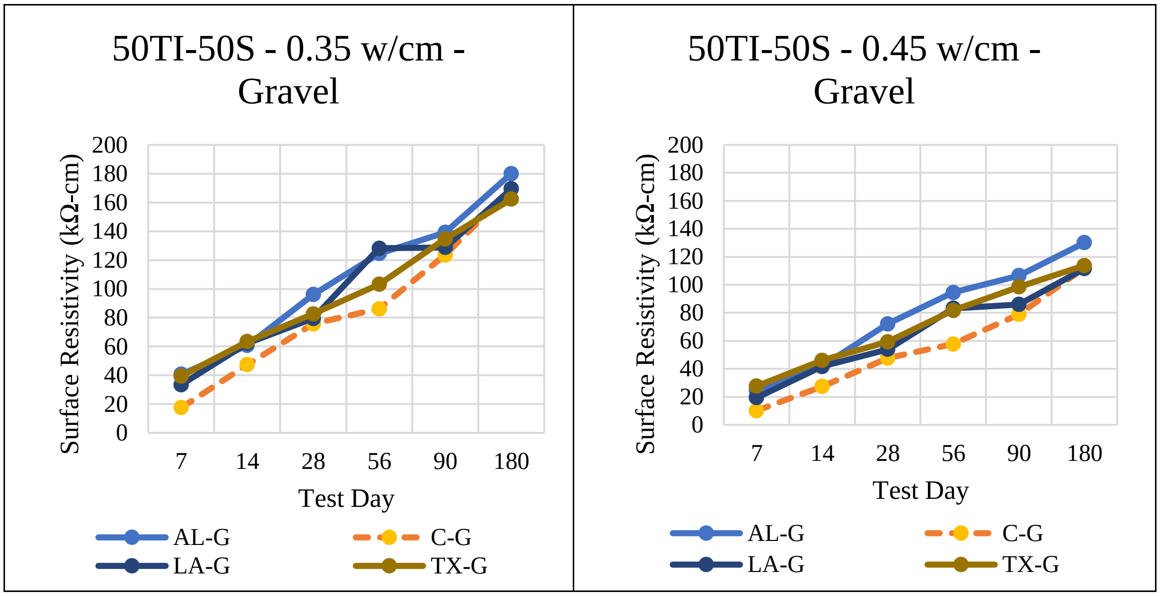


(e) Limestone at 0.35 w/cm

(f) Limestone at 0.45 w/cm specimens

Figure 9 shows the surface resistivity progression over time for samples prepared with 50% portland cement and 50% slag cement (50TI-50S). Similar to previous results, the addition of LWAs was generally beneficial, with comparable or better performance in surface resistivity than the control specimens over time. Within the gravel mixtures (Figure 9a and Figure 9b), the LWA sourced from Alabama had slightly higher resistivity values than the rest of the specimen groups over time. For the siliceous limestone mixtures (Figure 9c and Figure 9d), similar trends were observed where the LWA specimens outperformed the controls, albeit with the LWA from Texas outperforming all specimen groups at days 28 and 56 at the 0.35 w/cm ratio, respectively. However, for the limestone mixtures (Figure 9e and Figure 9f), the previous trends were not applicable since the control specimens exhibited slightly higher resistivity values than the LWA specimen groups.

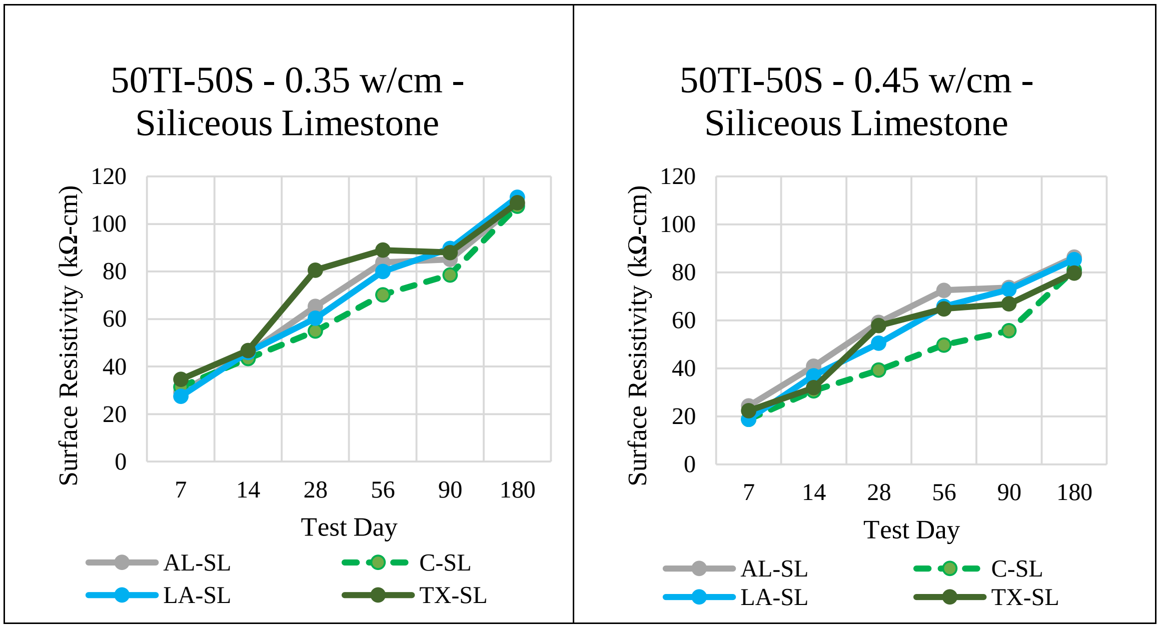
**Figure 9. Influence of lightweight aggregates on surface resistivity over time for mixtures made from 50% portland cement and 50% slag (50TI-50S)**


50TI-50S - 0.35 w/cm - Gravel

50TI-50S - 0.45 w/cm - Gravel

(a) Gravel at 0.35 w/cm

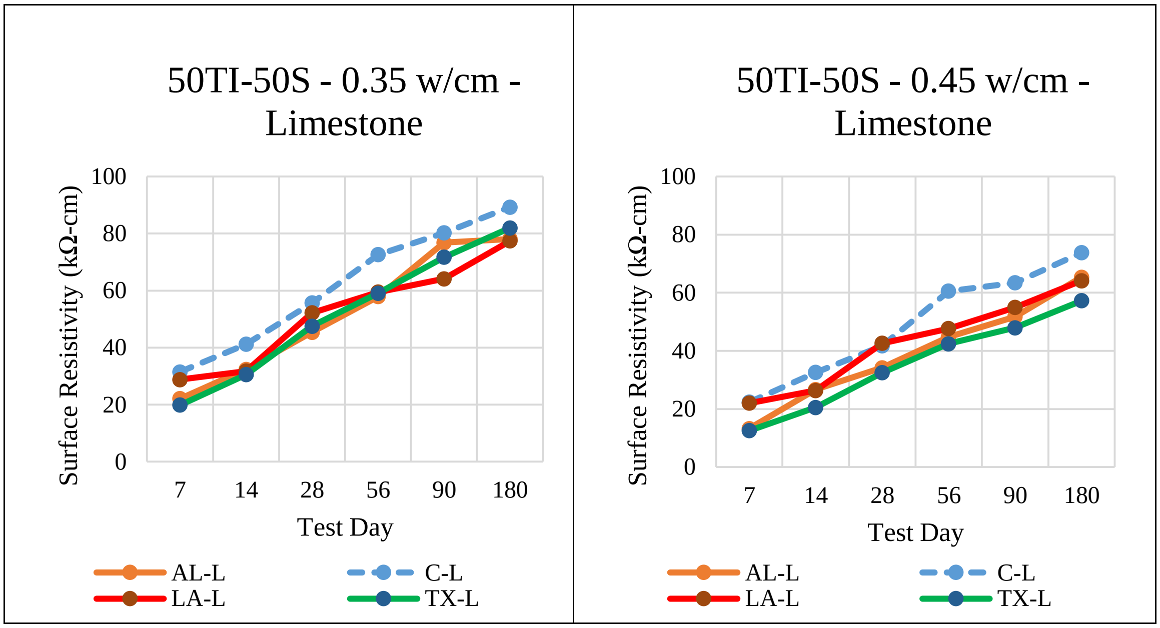
(b) Gravel at 0.45 w/cm


50TI-50S - 0.35 w/cm - Siliceous Limestone

50TI-50S - 0.45 w/cm - Siliceous Limestone

(c) Siliceous Limestone at 0.35 w/cm

(d) Siliceous Limestone at 0.45 w/cm

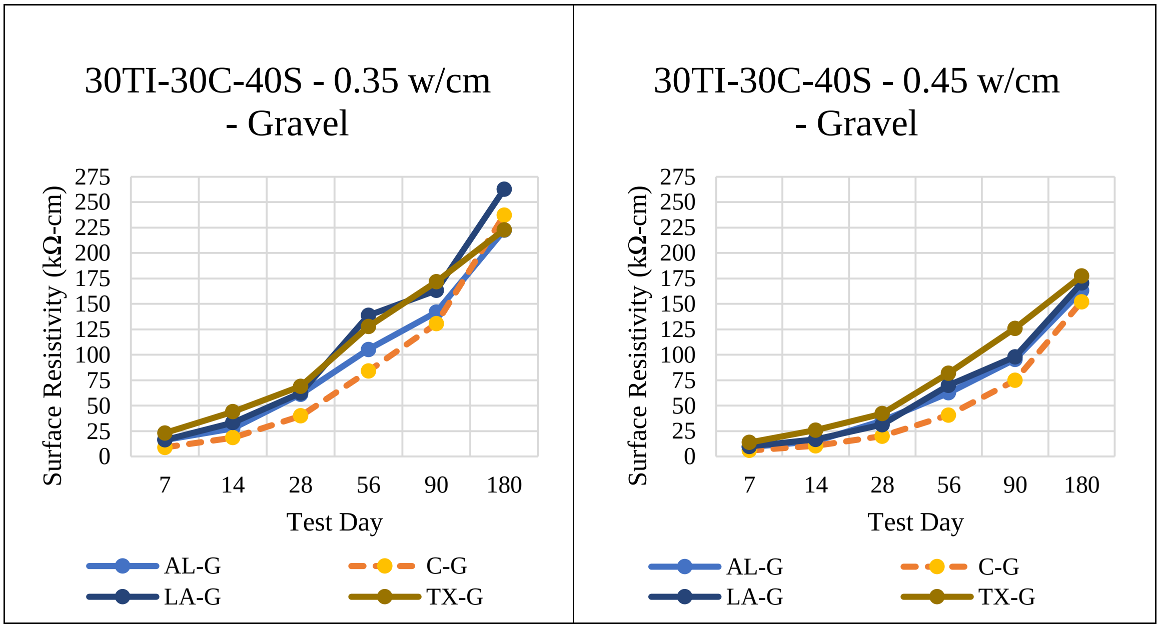


(e) Limestone at 0.35 w/cm

(f) Limestone at 0.45 w/cm specimens

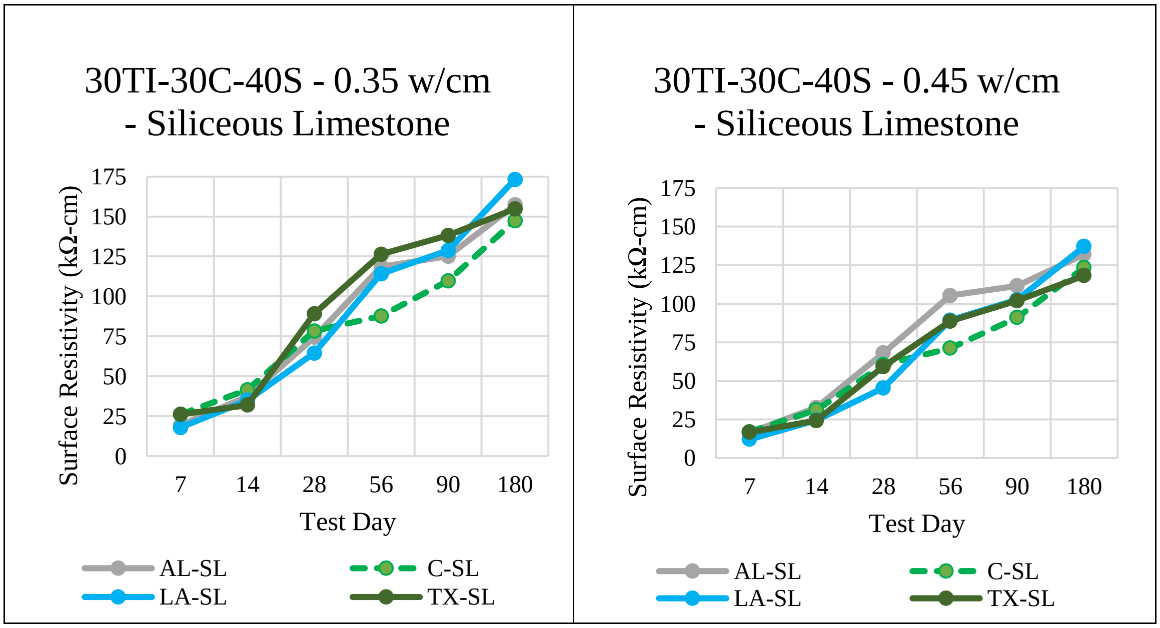
Figure 10 shows the surface resistivity progression over time for samples prepared with 30% portland cement, 30% Class C fly ash, and 40% slag cement (30TI-30C-40S). Overall, the results showed similar trends observed in the 50TI-50S mixtures, where the LWAs had a positive effect on surface resistivity for the gravel and siliceous limestone mixtures. Specifically, within the gravel mixtures (Figure 10a and Figure 10b), the LWAs sourced from Louisiana and Texas had slightly higher resistivity values, followed by the Alabama LWA and the control specimens, respectively. For the siliceous limestone mixtures (Figure 10c and Figure 10d), the differences in resistivity were minimal between the control and the LWA specimens at the early ages. After 28 days, the LWA specimens outperformed the controls. For the limestone mixtures (Figure 10e and Figure 10f), however, the control specimens exhibited higher resistivity values than the LWA specimen groups over time.

**Figure 10. Influence of lightweight aggregates on surface resistivity over time for mixtures made from 30% portland cement, 30% Class C fly ash, and 40% slag (30TI-30C-40S)**



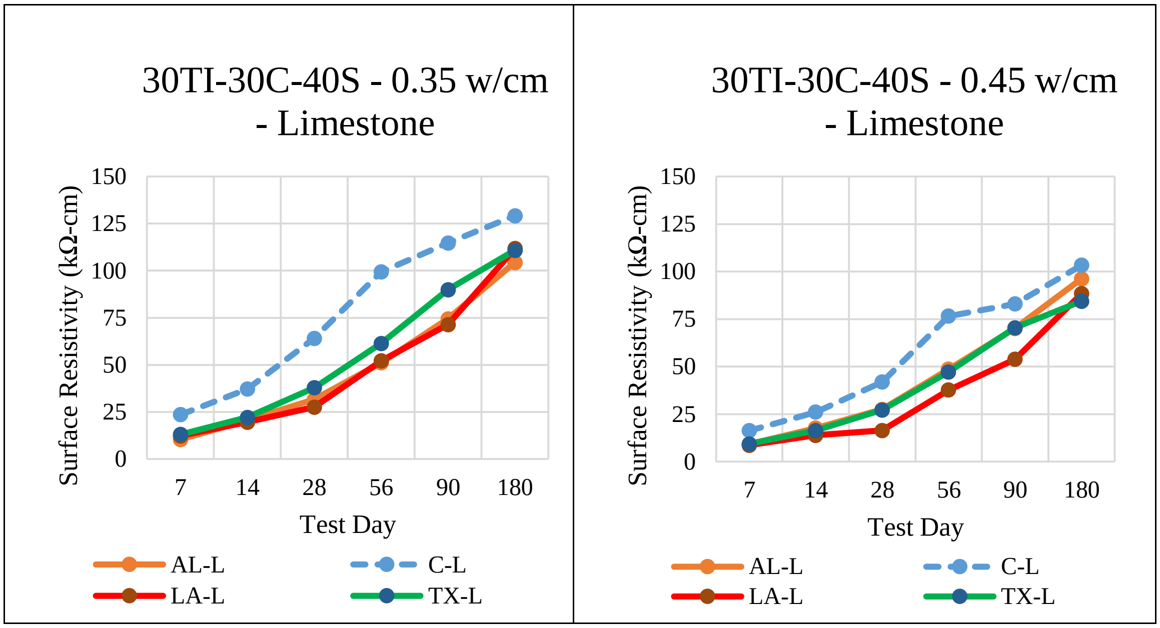
(a) Gravel at 0.35 w/cm

(b) Gravel at 0.45 w/cm



(c) Siliceous Limestone at 0.35 w/cm

(d) Siliceous Limestone at 0.45 w/cm



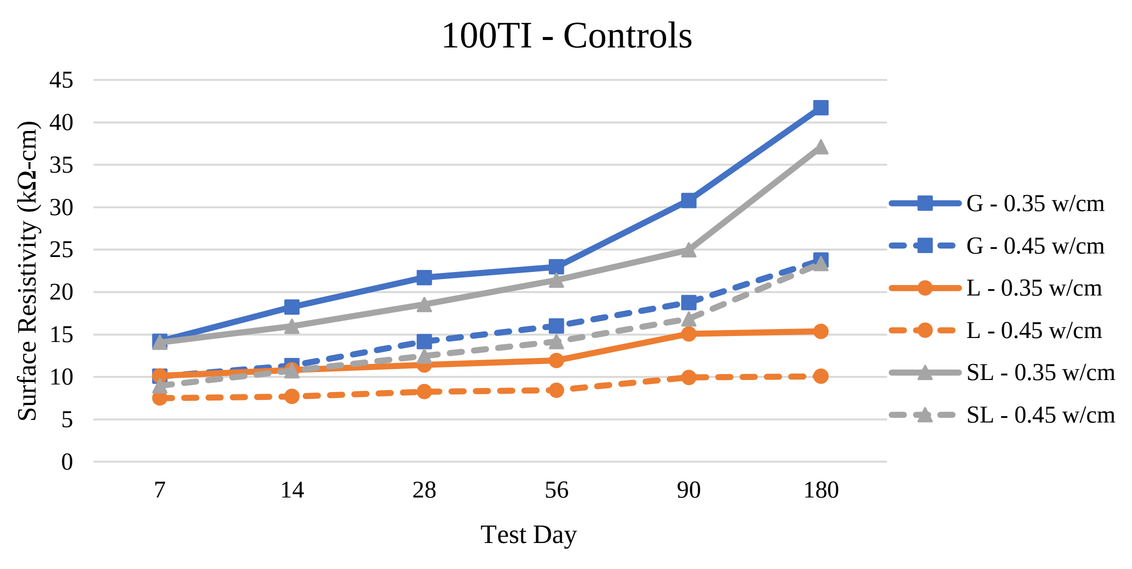
(e) Limestone at 0.35 w/cm

(f) Limestone at 0.45 w/cm specimens

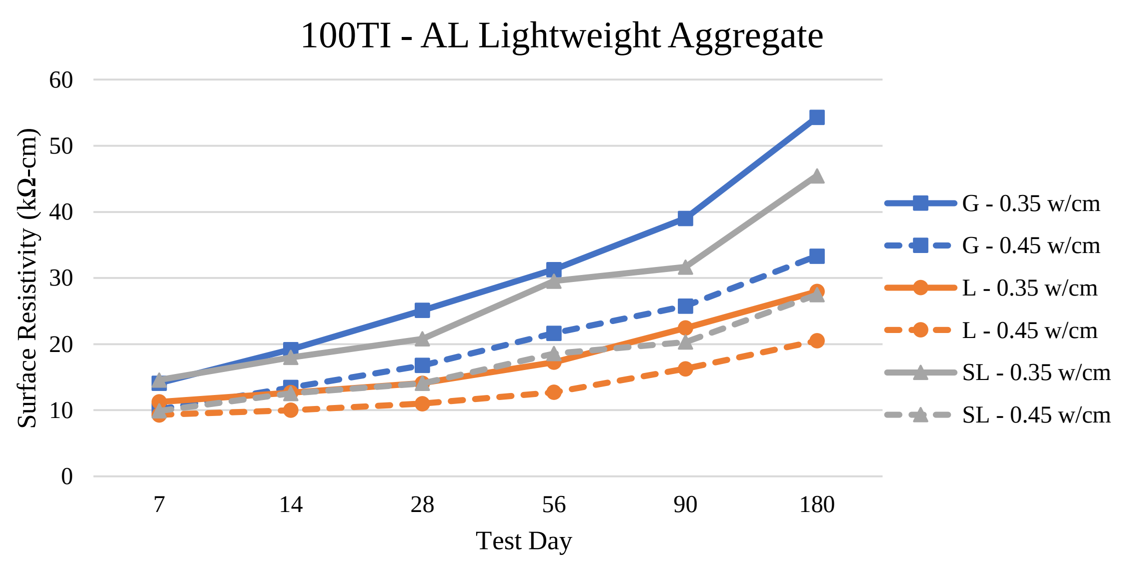
## Influence of Coarse Aggregate Type

In order to study the effect of the coarse aggregate type and LWA source on concrete's surface resistivity over time, a comparison was made between the specimen groups that shared the same cementitious materials and w/cm ratios. Figure 11 shows the effect of coarse aggregate type on surface resistivity for concretes made of ordinary portland cement for each LWA source. In general, the mixtures prepared with gravel had the highest surface resistivity values for both the control and the LWA specimens, at both w/cm ratios. For the LWA-TX specimens (Figure 11d), however, the differences between the gravel and siliceous limestone mixtures were minimal over time. In addition, the lowest resistivity values were consistently observed for the dolomitic limestone groups, regardless of whether LWAs were present.

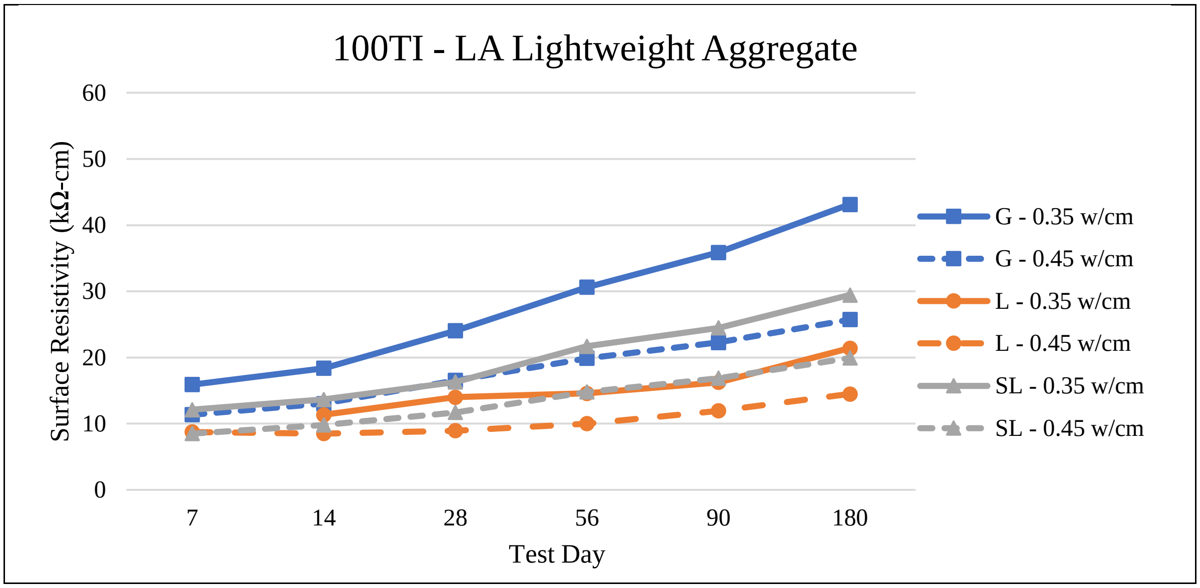
**Figure 11. Influence of coarse aggregate type on surface resistivity over time for mixtures made from 100% portland cement (100TI)**



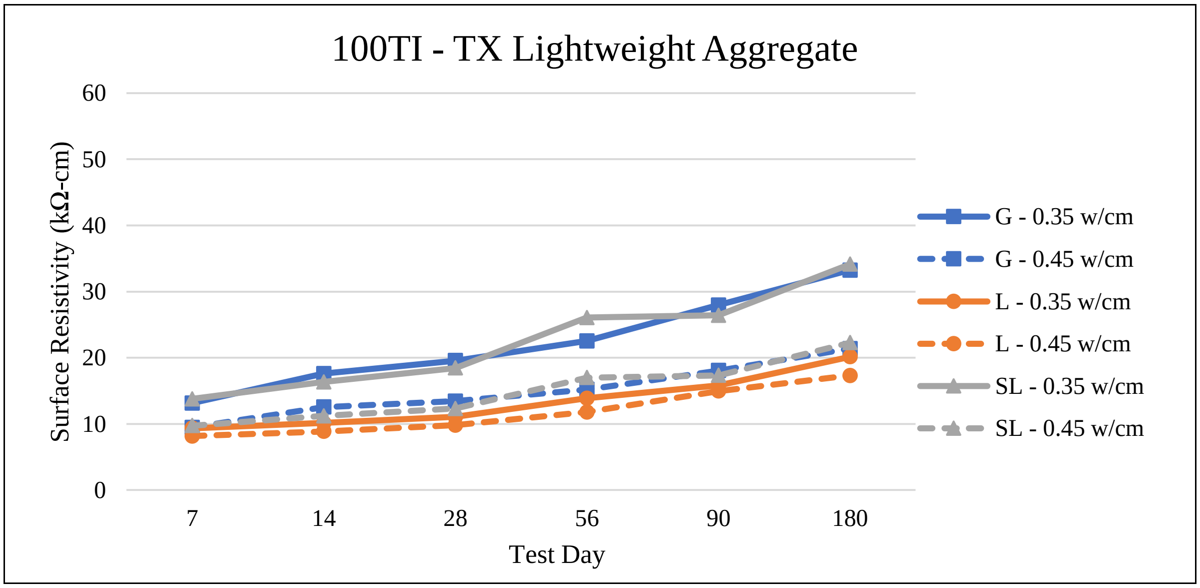
(a) Control



(b) LWA-AL



(c) LWA-LA

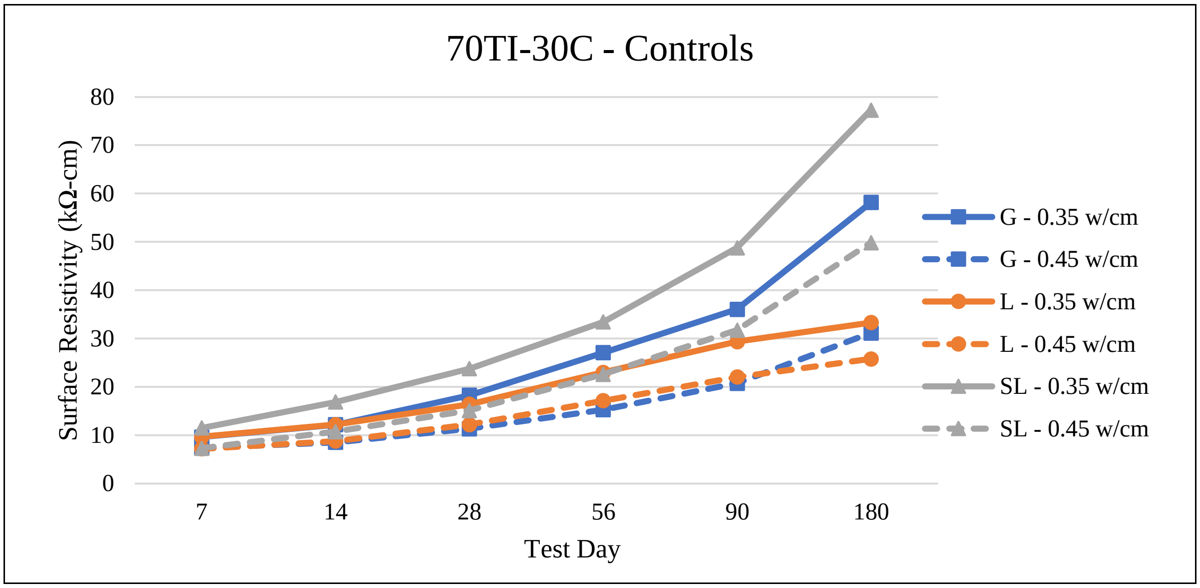


(d) LWA-TX

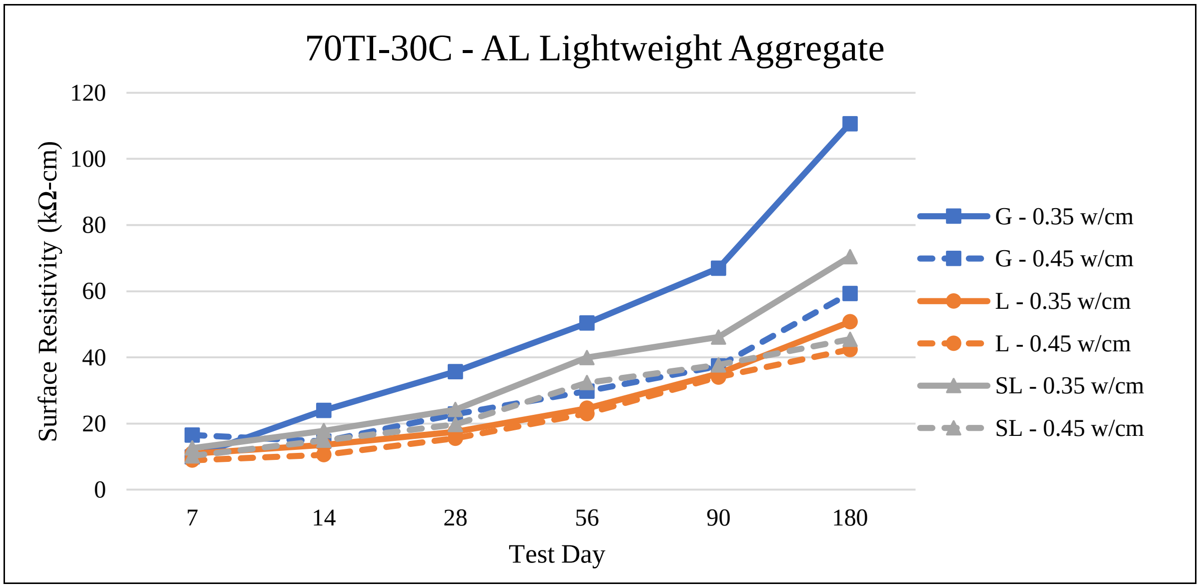
Figure 12 shows the effect of coarse aggregate type on surface resistivity for concretes made of 70% portland cement and 30% Class C fly ash for each LWA source. The results show that the mixtures prepared with gravel had the highest surface resistivity values for the LWA specimens, while the mixtures prepared with siliceous limestone produced the highest resistivity values for the control specimens, at both w/cm ratios. Similar to the 100TI mixtures, the porous limestone specimen groups yielded the lowest surface resistivity measurements. While clear differences are normally observed when the w/cm ratio is adjusted, specimen groups LWA-AL (Figure 12b) and LWA-LA (Figure 12c) showed minimal differences within the porous limestone specimens at the 0.35 w/cm and

0.45 w/cm ratios. For the LWA-TX specimens (Figure 12d), minimal differences between the gravel and siliceous limestone mixtures were observed over time as well.

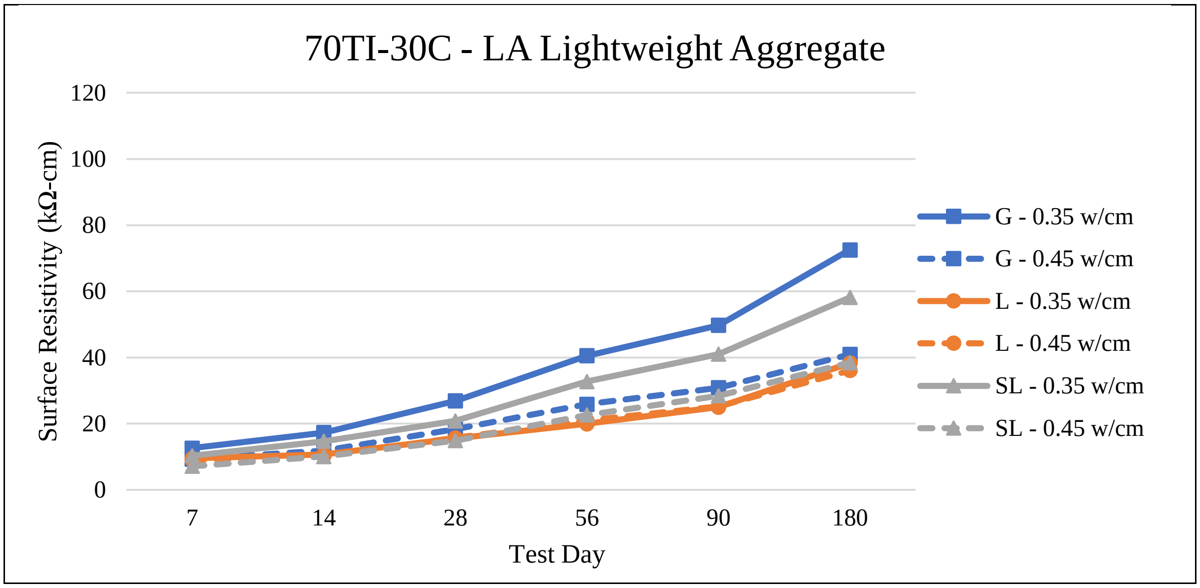
**Figure 12. Influence of coarse aggregate type on surface resistivity over time for mixtures made from 70% portland cement and 30% Class C fly ash (70TI-30C)**



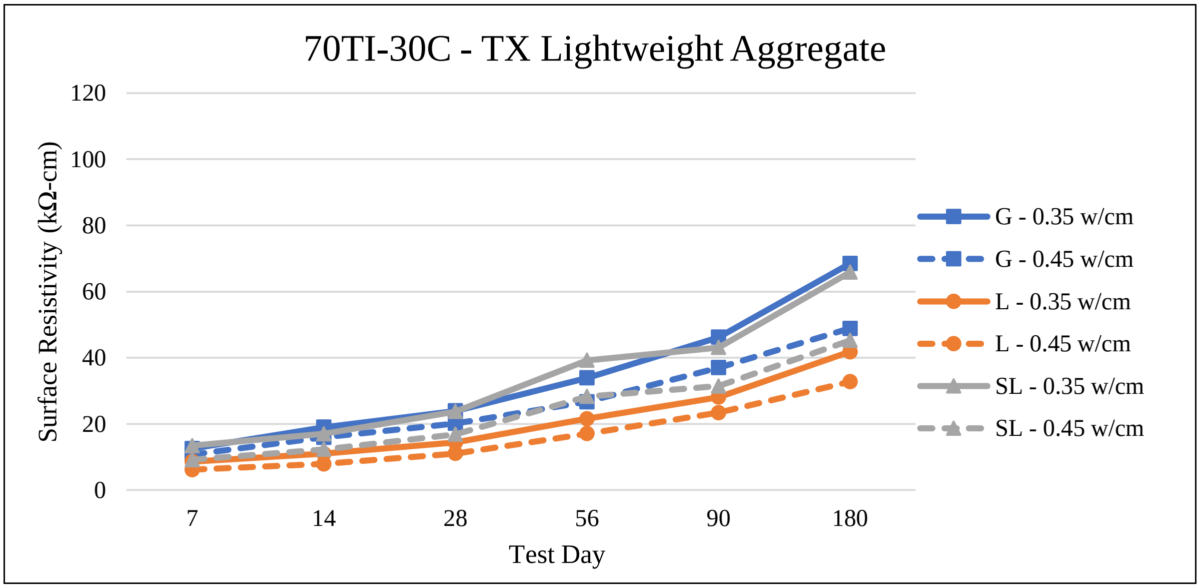
(a) Control



(b) LWA-AL



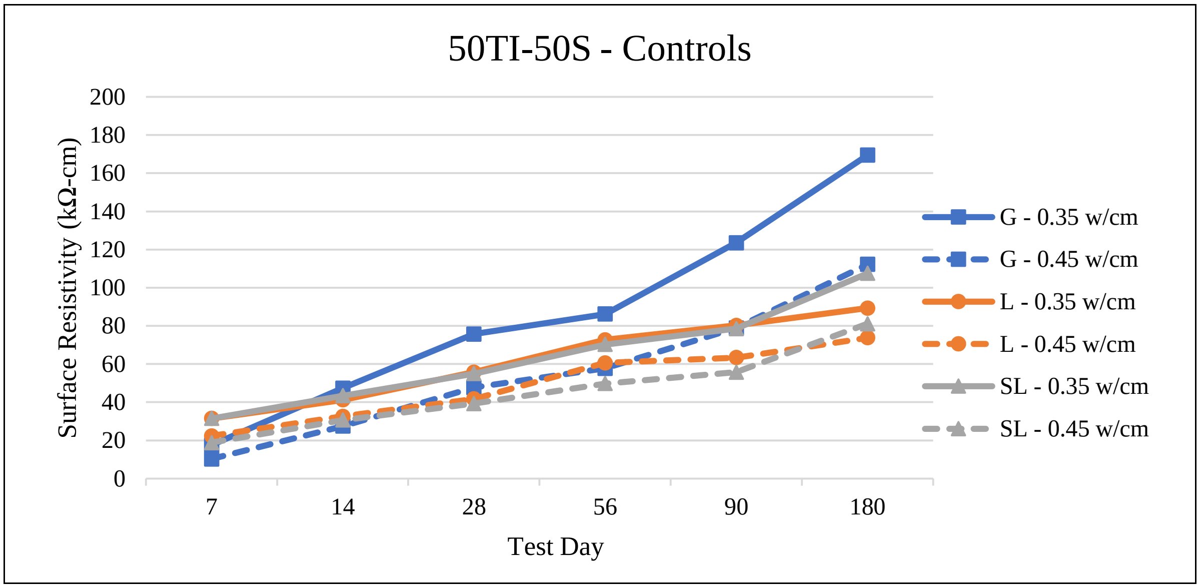
(c) LWA-LA



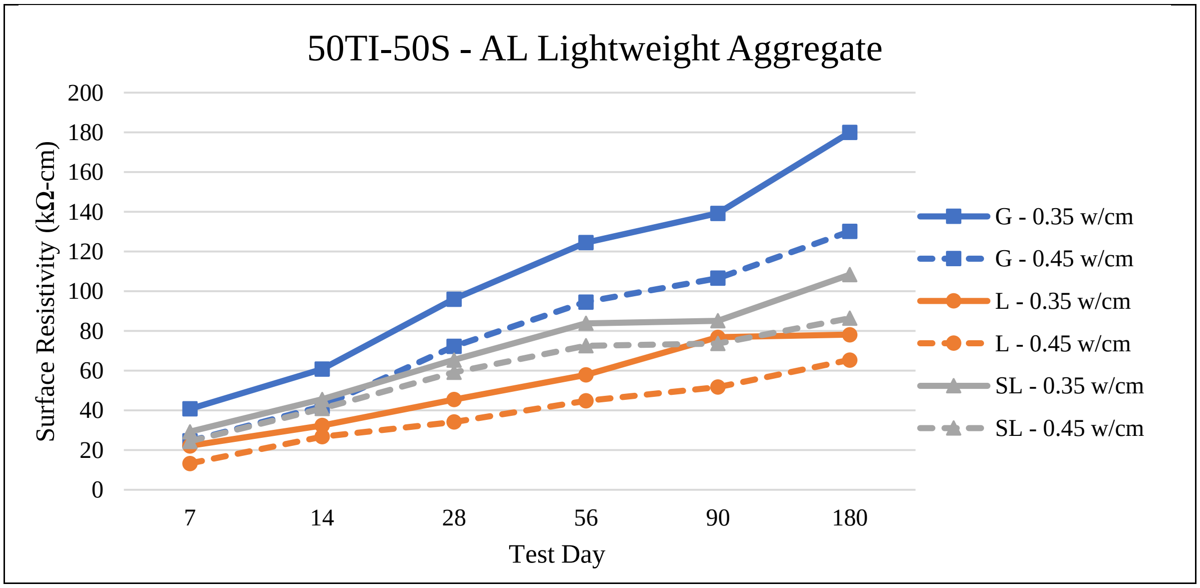
(d) LWA-TX

Figure 13 shows the effect of coarse aggregate type on surface resistivity for concretes made of 50% portland cement and 50% slag for each LWA source. The results showed that the mixtures prepared with gravel had the highest surface resistivity values for both the control and the LWA specimens. The mixtures prepared with the porous limestone yielded the lowest surface resistivity measurements across all LWA specimen groups. However, minimal differences in resistivity were observed between the siliceous limestone and porous limestone mixtures within the control groups (Figure 13a).

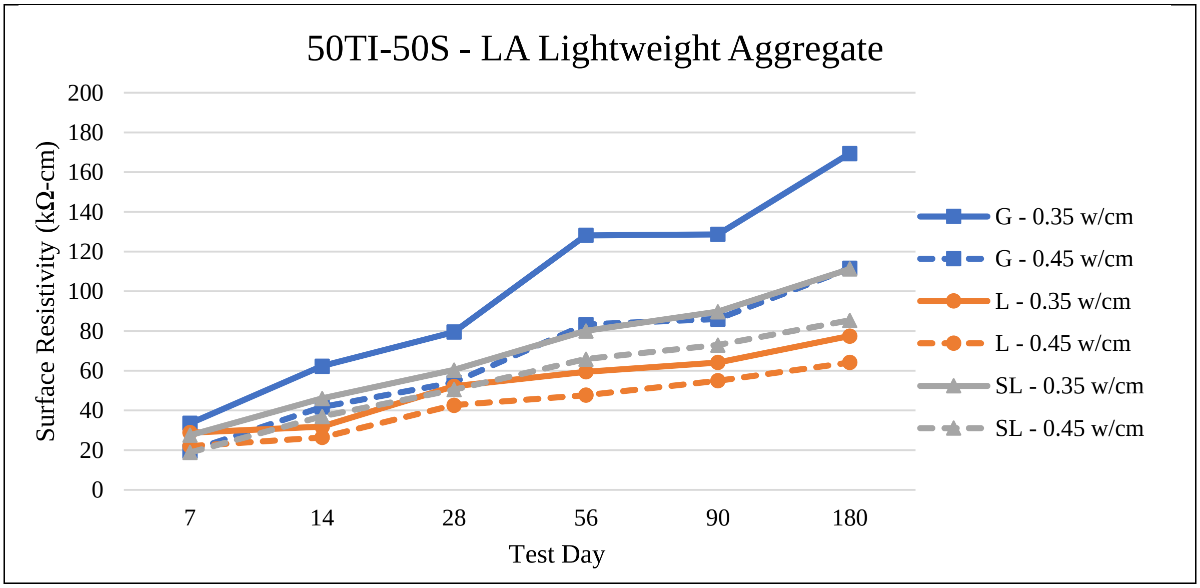
**Figure 13. Influence of coarse aggregate type on surface resistivity over time for mixtures made from 50% portland cement and 50% slag (50TI-50S)**



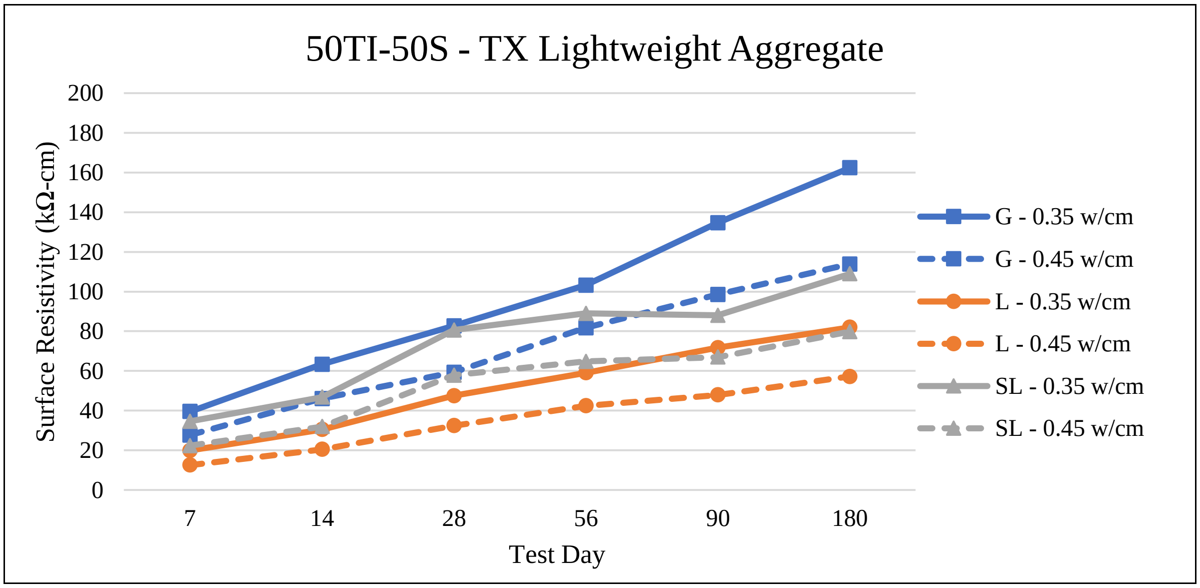
(a) Control



(b) LWA-AL



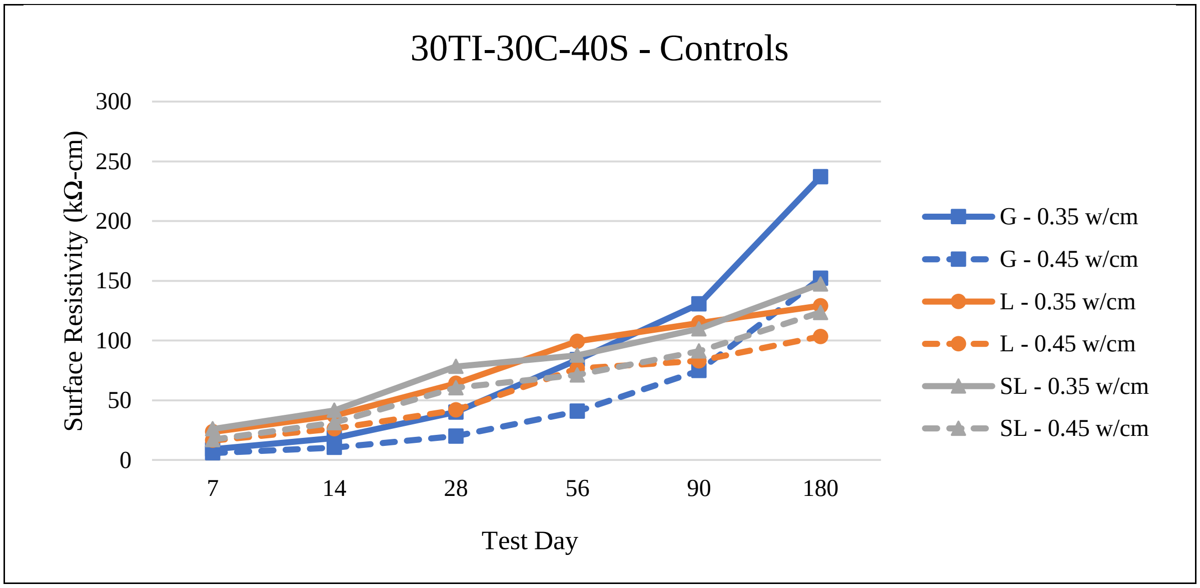
(c) LWA-LA



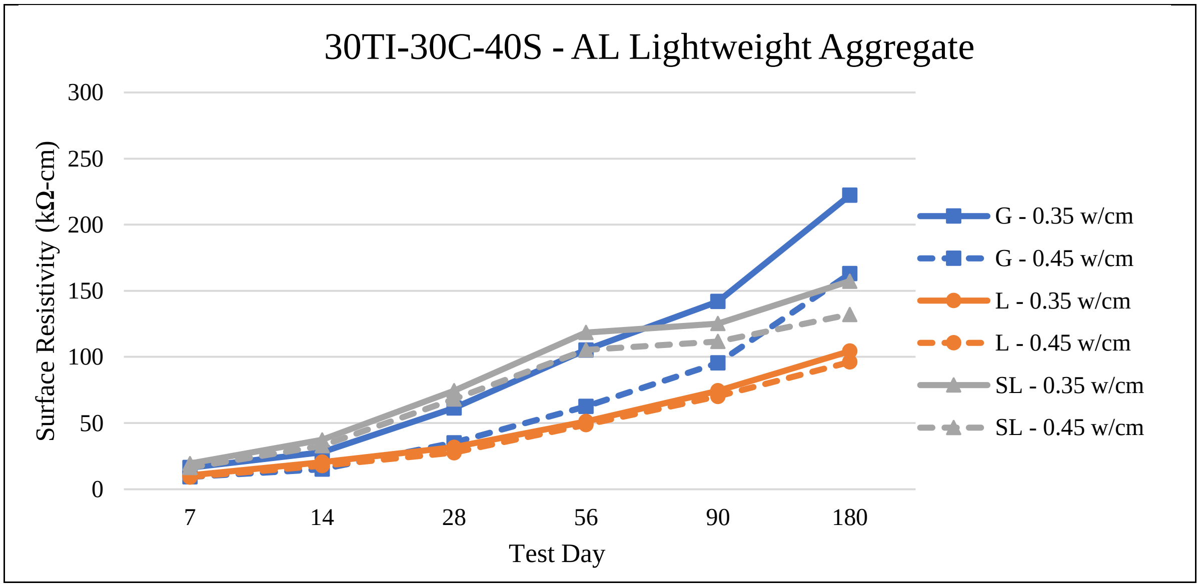
(d) LWA-TX

Figure 14 shows the effect of coarse aggregate type on surface resistivity for concretes made of 30% portland cement, 30% Class C fly ash, and 40% slag for each LWA source. In general, the differences in resistivity between the siliceous limestone and gravel mixtures were seemingly not as significant until after 56 days of testing. The mixtures prepared with the porous limestone yielded the lowest surface resistivity measurements across all LWA specimen groups. However, within the control specimens (Figure 14a), the porous limestone and the siliceous limestone mixtures had minimal differences in resistivity over time.

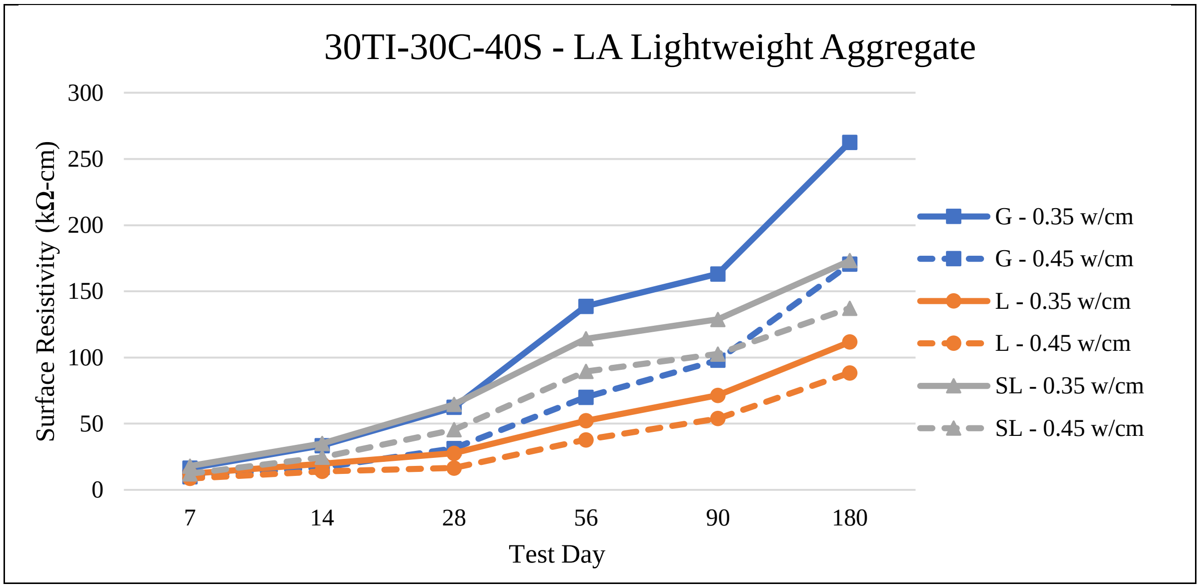
**Figure 14. Influence of coarse aggregate type on surface resistivity over time for (a) Control, (b) LWA-AL, (c) LWA-LA, and (d) LWA-TX specimens, made from 30% portland cement, 30% Class C fly ash, and 40% slag (30TI-30C-40S)**



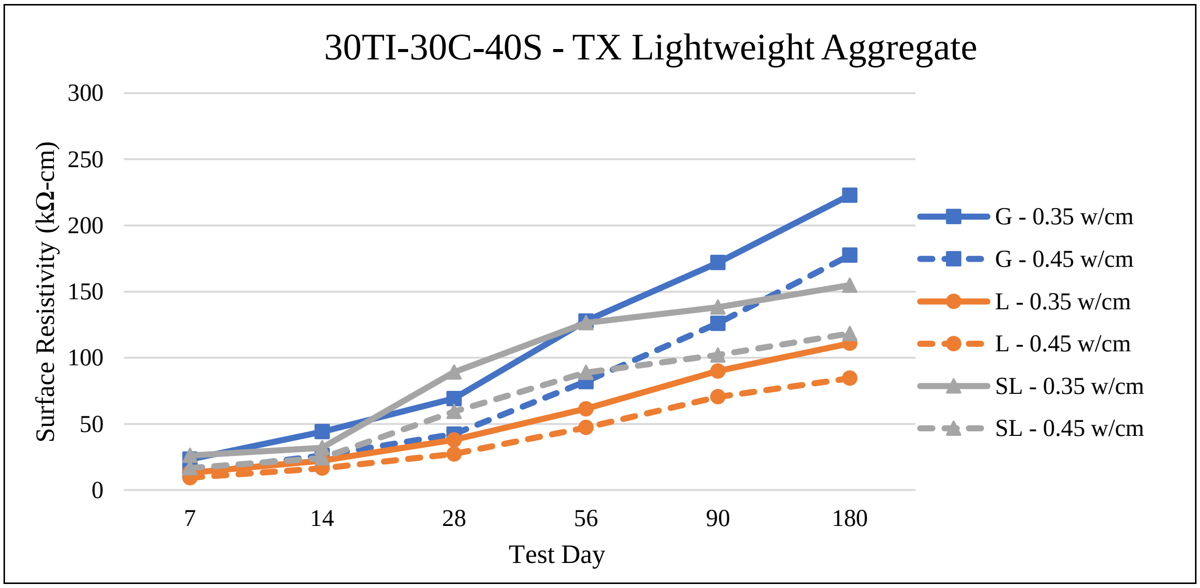
(a) Control



(b) LWA-AL



(c) LWA-LA



(d) LWA-TX

### Statistical Analysis

A statistical evaluation of the observed trends was performed using the statistical analysis software SAS 9.4. An analysis of covariance (ANCOVA) was conducted in order to evaluate whether there was a statistical effect due to the variables on the surface resistivity values of the 96 concrete mixtures at day 28 and day 56. Three cylinders or replicates of each of the 96 mixtures were evaluated, resulting in a total of 288 individual observations. Table 6 presents the results of the ANCOVA analysis for the complete data set. A 95% confidence value was used to determine statistical significance.

**Table 6. Overall ANCOVA results**

| Variable | P-value (28 days) | P-value (56 days) | Statistically Significant Difference |
|---|---|---|---|
| Lightweight Aggregate Source | 0.0067 | 0.0018 | Yes |
| Coarse Aggregate Type | <0.0001 | <0.0001 | Yes |
| Water-to-Cementitious Ratio | <0.0001 | <0.0001 | Yes |
| Combination of Cementitious Materials | <0.0001 | <0.0001 | Yes |

The significance value or p-value is compared to a critical value (0.05 in this study) to determine whether the variable is statistically significant. The results show that all variables (i.e. lightweight aggregate source, coarse aggregate type, w/cm ratio, and combination of cementitious materials) had significant effects on surface resistivity. The variables were further analyzed categorically with respect to their effect on resistivity at day 28 and day 56 using Duncan’s Multiple Range Test (Table 7). The means with the same letter notation are not significantly different per Duncan’s grouping.

Overall, the results confirmed the trends which were observed in the data. The presence of LWAs had a positive effect on surface resistivity. At Day 28, the LWA from Alabama had a significantly higher resistivity, while the LWAs from Texas and Louisiana were not significantly different from the control specimens. At day 56, however, all LWA groups outperformed the control group with significantly higher measured resistivity values.

The means between the Gravel and Siliceous Limestone were not significantly different from each other; but when compared to the porous dolomitic limestone, they were statistically different, which reflects the adverse effect that this limestone had on surface resistivity. This was reflected in both the 28-day and 56-day surface resistivity results. Lastly, the means for the two w/cm ratios were significantly different, where a lower w/cm ratio produced higher resistivity values at both test ages as well.

**Table 7. Duncan multiple range tests for categorical variables**

| Variable | Category | Duncan Grouping (28 Days) | Mean Surface Resistivity, kΩ-cm (28 Days) | Duncan Grouping (56 Days) | Mean Surface Resistivity, kΩ-cm (56 Days) | Number of Observations |
|---|---|---|---|---|---|---|
| Lightweight Aggregate Source | LWA-AL | **A** | 37.8 | **A** | 54.2 | 72 |
| | LWA-TX | **B/A** | 36.7 | **A** | 52.0 | 72 |
| | Control | **B/C** | 33.5 | **B** | 45.4 | 72 |
| | LWA-LA | **C** | 33.0 | **A** | 51.7 | 72 |
| Coarse Aggregate Type | Gravel | **A** | 39.3 | **A** | 59.4 | 96 |
| | Siliceous Limestone | **A** | 40.4 | **A** | 56.0 | 96 |
| | Limestone | **B** | 26.0 | **B** | 37.1 | 96 |
| Water-to-Cementitious Ratio | 0.35 | **A** | 41.1 | **A** | 59.0 | 144 |
| | 0.45 | **B** | 29.4 | **B** | 42.7 | 144 |
| Combination of Cementitious Materials | 50TI-50S | **A** | 57.8 | **B** | 74.2 | 72 |
| | 30TI-30C-40S | **B** | 49.0 | **A** | 82.8 | 72 |
| | 70TI-30C | **C** | 18.9 | **C** | 27.8 | 72 |
| | 100TI | **D** | 15.2 | **D** | 18.5 | 72 |

# Conclusions

This study evaluated the influence of internal curing and coarse aggregate type on concrete's surface resistivity over time (at days 7, 14, 28, 56, 90, and 180), per AASHTO T 358. A total of 96 concrete mixtures were prepared to identify the effects of three coarse aggregate types, two water-to-cementitious (w/cm) ratios, three fine lightweight aggregate (LWA) sources, and four variations of supplementary cementitious materials (SCMs).

The slump test results showed that a majority of zero-slump concretes were observed with samples containing LWAs. While a lower workability can be expected when using LWAs for internal curing, modest increases in super plasticizer dosage are recommended to improve the workability without altering the w/cm ratio.

The compressive strength tests showed that in most cases, the presence of lightweight aggregate had a positive effect on strength (i.e., similar or better strength). Few exceptions were observed where LWAs had lower strengths than the control specimens, most notably within the ternary mixtures.

With respect to surface resistivity, the statistical analyses determined that the use of SCMs, w/cm ratio, coarse aggregate type, and presence of LWAs had significant effects. The use of SCMs caused significant increases in surface resistivity for all groups due to their pozzolanic activity. The presence of slag cement caused the highest increases in surface resistivity, which were also attributed to slag's influence on concrete's pore solution chemistry. Class C fly ash also produced higher resistivity values over time than the samples prepared with only portland cement.

The w/cm ratio was highly influential in resistivity as expected, where the lower w/cm ratio consistently produced higher resistivity values over time for all specimen groups. The presence of LWAs had an overall positive effect on resistivity, where each of the LWA sources overall had an equal or better performance than the control specimens based on the findings from the statistical analyses. Lastly, the coarse aggregate type had an effect on resistivity, albeit predominantly based on the porosity of the aggregate itself. While siliceous limestone and gravel have a different morphology and mineralogy, the statistical analysis did not find significant differences between the measured resistivity overall. Significant differences were only observed with the mixtures prepared with the porous limestone aggregates, as these specimens consistently had the lowest surface resistivity values.

# Recommendations

Based on the results of this study, internally cured concrete (through lightweight aggregates made from expanded shale or clay) did not have detrimental effects on concrete's surface resistivity over time. As such, no correction factors are warranted.

# Acronyms, Abbreviations, and Symbols

| Term | Description |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ANCOVA | Analysis of covariance |
| ASR | Alkali-silica reaction |
| ASTM | American Society for Testing and Materials |
| cm | centimeter(s) |
| C-S-H | Calcium silica hydrate |
| cwt | Hundredweight |
| CY | Cubic yard |
| DOTD | Department of Transportation and Development |
| FHWA | Federal Highway Administration |
| ft. | foot (feet) |
| ICC | Internally cured concrete |
| in. | inch(es) |
| ITZ | Interfacial transition zone |
| lb. | pound(s) |
| LTRC | Louisiana Transportation Research Center |
| LWA | Lightweight aggregate |
| LWA-AL | Lightweight aggregate from Alabama |
| LWA-LA | Lightweight aggregate from Louisiana |
| LWA-TX | Lightweight aggregate from Texas |
| NWA | Normal-weight aggregate |
| OPC | Ordinary portland cement |
| oz | Ounce(s) |
| PCC | Portland cement concrete |
| rpm | Revolutions per minute |
| SCM | Supplementary cementitious material |
| SHA | State highway agency |
| SSD | Saturated surface dry |

| **Term** | **Description** |
|---|---|
| w/cm | Water-to-cementitious ratio |
| yd | Yard(s) |
| Ω | Ohms |

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# Appendix

**Table A1. Surface resistivity results for 100TI specimens over time**

*Cells color-coded to represent different chloride ion penetrability ratings*

*(Red: high; Yellow: moderate; Green: low; Blue: very low)*

| Specimen ID* | w/cm | Surface Resistivity (kΩ-cm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Day 7 | Day 14 | Day 28 | Day 56 | Day 90 | Day 180 |
| 100TI C-G 0.35 | 0.35 | 14.20 | 18.23 | 21.70 | 22.97 | 30.80 | 41.73 |
| 100TI C-L 0.35 | | 10.13 | 10.83 | 11.40 | 11.93 | 15.07 | 15.37 |
| 100TI C-SL 0.35 | | 14.07 | 15.97 | 18.53 | 21.40 | 24.97 | 37.10 |
| 100TI AL-G 0.35 | | 14.10 | 19.17 | 25.10 | 31.27 | 39.03 | 54.30 |
| 100TI AL-L 0.35 | | 11.27 | 12.67 | 14.10 | 17.27 | 22.43 | 27.97 |
| 100TI AL-SL 0.35 | | 14.57 | 18.00 | 20.80 | 29.53 | 31.67 | 45.47 |
| 100TI LA-G 0.35 | | 15.90 | 18.37 | 24.03 | 30.63 | 35.87 | 43.13 |
| 100TI LA-L 0.35 | | NA** | 11.33 | 14.00 | 14.57 | 16.23 | 21.40 |
| 100TI LA-SL 0.35 | | 12.10 | 13.67 | 16.30 | 21.70 | 24.47 | 29.43 |
| 100TI TX-G 0.35 | | 13.13 | 17.60 | 19.57 | 22.53 | 27.97 | 33.23 |
| 100TI TX-L 0.35 | | 9.33 | 10.13 | 11.07 | 13.87 | 15.80 | 20.13 |
| 100TI TX-SL 0.35 | | 13.77 | 16.33 | 18.43 | 26.07 | 26.40 | 34.13 |
| 100TI C-G 0.45 | 0.45 | 10.07 | 11.33 | 14.17 | 16.00 | 18.77 | 23.77 |
| 100TI C-L 0.45 | | 7.50 | 7.70 | 8.27 | 8.43 | 9.93 | 10.07 |
| 100TI C-SL 0.45 | | 8.97 | 10.73 | 12.47 | 14.17 | 16.83 | 23.37 |
| 100TI AL-G 0.45 | | 10.13 | 13.43 | 16.77 | 21.63 | 25.77 | 33.30 |
| 100TI AL-L 0.45 | | 9.30 | 10.00 | 11.00 | 12.70 | 16.27 | 20.50 |
| 100TI AL-SL 0.45 | | 9.90 | 12.53 | 14.07 | 18.57 | 20.30 | 27.47 |
| 100TI LA-G 0.45 | | 11.37 | 13.03 | 16.53 | 19.87 | 22.27 | 25.73 |
| 100TI LA-L 0.45 | | 8.73 | 8.50 | 8.93 | 10.00 | 11.93 | 14.47 |
| 100TI LA-SL 0.45 | | 8.50 | 9.80 | 11.70 | 14.80 | 16.87 | 19.93 |
| 100TI TX-G 0.45 | | 9.47 | 12.53 | 13.43 | 15.20 | 18.07 | 21.37 |
| 100TI TX-L 0.45 | | 8.17 | 8.87 | 9.80 | 11.80 | 14.97 | 17.30 |
| 100TI TX-SL 0.45 | | 9.73 | 11.20 | 12.33 | 17.00 | 17.33 | 22.27 |

*Specimen ID uses the following convention: Mix ID, LWA type, CA type, and w/cm ratio.

G: Gravel; L: Limestone; SL: Siliceous Limestone: w/cm: water-to-cementitious ratio; AL: Lightweight Aggregate from Alabama; LA: Lightweight Aggregate from Louisiana; TX: Lightweight Aggregate from Texas; C: Control (no lightweight aggregates).

**No data points to report for Day-7 resistivity readings for specimen 100TI LA-L 0.35.

**Table A2. Surface resistivity results for 70TI-30C specimens over time**

*Cells color-coded to represent different chloride ion penetrability ratings*

*(Red: high; Yellow: moderate; Green: low; Blue: very low)*

| Specimen ID* | w/cm | Surface Resistivity (kΩ-cm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Day 7 | Day 14 | Day 28 | Day 56 | Day 90 | Day 180 |
| 70TI-30C C-G 0.35 | 0.35 | 9.60 | 12.17 | 18.27 | 27.07 | 36.03 | 58.13 |
| 70TI-30C C-L 0.35 | | 9.67 | 12.20 | 16.40 | 23.00 | 29.37 | 33.30 |
| 70TI-30C C-SL 0.35 | | 11.50 | 16.87 | 23.77 | 33.43 | 48.77 | 77.27 |
| 70TI-30C AL-G 0.35 | | 9.93 | 23.97 | 35.67 | 50.33 | 66.97 | 110.63 |
| 70TI-30C AL-L 0.35 | | 10.97 | 13.53 | 17.53 | 24.60 | 35.13 | 50.73 |
| 70TI-30C AL-SL 0.35 | | 12.60 | 17.80 | 24.23 | 39.97 | 46.13 | 70.40 |
| 70TI-30C LA-G 0.35 | | 12.60 | 17.30 | 26.87 | 40.53 | 49.70 | 72.50 |
| 70TI-30C LA-L 0.35 | | 9.50 | 10.67 | 15.50 | 19.97 | 25.00 | 38.30 |
| 70TI-30C LA-SL 0.35 | | 10.33 | 14.67 | 20.83 | 32.73 | 41.03 | 58.13 |
| 70TI-30C TX-G 0.35 | | 12.53 | 18.97 | 23.93 | 33.90 | 46.17 | 68.43 |
| 70TI-30C TX-L 0.35 | | 8.60 | 11.00 | 14.40 | 21.57 | 28.07 | 41.80 |
| 70TI-30C TX-SL 0.35 | | 13.40 | 17.00 | 23.70 | 39.23 | 43.07 | 65.83 |
| 70TI-30C C-G 0.45 | 0.45 | 7.33 | 8.50 | 11.33 | 15.27 | 20.73 | 31.13 |
| 70TI-30C C-L 0.45 | | 7.20 | 8.77 | 12.20 | 17.13 | 22.03 | 25.77 |
| 70TI-30C C-SL 0.45 | | 7.30 | 10.73 | 15.10 | 22.60 | 31.73 | 49.83 |
| 70TI-30C AL-G 0.45 | | 16.50 | 14.63 | 22.83 | 29.80 | 37.37 | 59.30 |
| 70TI-30C AL-L 0.45 | | 8.90 | 10.57 | 15.53 | 23.00 | 34.03 | 42.37 |
| 70TI-30C AL-SL 0.45 | | 10.20 | 14.90 | 19.70 | 32.33 | 37.70 | 45.47 |
| 70TI-30C LA-G 0.45 | | 9.30 | 11.83 | 18.30 | 25.87 | 30.83 | 40.90 |
| 70TI-30C LA-L 0.45 | | 9.07 | 10.20 | 15.70 | 20.90 | 25.20 | 36.07 |
| 70TI-30C LA-SL 0.45 | | 7.10 | 10.10 | 14.87 | 22.60 | 28.43 | 38.43 |
| 70TI-30C TX-G 0.45 | | 10.73 | 15.93 | 20.13 | 26.70 | 37.00 | 48.87 |
| 70TI-30C TX-L 0.45 | | 6.17 | 7.90 | 11.03 | 17.03 | 23.40 | 32.73 |
| 70TI-30C TX-SL 0.45 | | 9.13 | 12.30 | 16.83 | 28.27 | 31.43 | 45.20 |

*Specimen ID uses the following convention: Mix ID, LWA type, CA type, and w/cm ratio.

G: Gravel; L: Limestone; SL: Siliceous Limestone: w/cm: water-to-cementitious ratio; AL: Lightweight Aggregate from Alabama; LA: Lightweight Aggregate from Louisiana; TX: Lightweight Aggregate from Texas; C: Control (no lightweight aggregates).

### Table A3. Surface resistivity results for 50TI-50S specimens over time

*Cells color-coded to represent different chloride ion penetrability ratings*

*(Red: high; Yellow: moderate; Green: low; Blue: very low)*

| Specimen ID* | w/cm | Surface Resistivity (kΩ-cm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Day 7 | Day 14 | Day 28 | Day 56 | Day 90 | Day 180 |
| 50TI-50S C-G 0.35 | 0.35 | 17.53 | 47.33 | 75.73 | 86.17 | 123.50 | 169.43 |
| 50TI-50S C-L 0.35 | | 31.47 | 41.20 | 55.70 | 72.63 | 80.27 | 89.30 |
| 50TI-50S C-SL 0.35 | | 31.43 | 43.37 | 54.97 | 70.27 | 78.57 | 107.47 |
| 50TI-50S AL-G 0.35 | | 40.73 | 60.77 | 96.03 | 124.53 | 139.23 | 180.00 |
| 50TI-50S AL-L 0.35 | | 22.10 | 32.37 | 45.40 | 57.90 | 76.83 | 78.10 |
| 50TI-50S AL-SL 0.35 | | 29.23 | 45.50 | 65.33 | 83.87 | 85.10 | 108.40 |
| 50TI-50S LA-G 0.35 | | 33.47 | 62.30 | 79.50 | 128.20 | 128.73 | 169.47 |
| 50TI-50S LA-L 0.35 | | 28.80 | 31.77 | 52.17 | 59.47 | 64.17 | 77.43 |
| 50TI-50S LA-SL 0.35 | | 27.50 | 46.00 | 60.33 | 80.03 | 89.70 | 111.30 |
| 50TI-50S TX-G 0.35 | | 39.53 | 63.33 | 82.67 | 103.17 | 134.67 | 162.30 |
| 50TI-50S TX-L 0.35 | | 19.90 | 30.53 | 47.53 | 59.10 | 71.70 | 81.97 |
| 50TI-50S TX-SL 0.35 | | 34.63 | 46.80 | 80.63 | 89.00 | 88.03 | 108.93 |
| 50TI-50S C-G 0.45 | 0.45 | 10.23 | 27.47 | 47.70 | 57.77 | 78.87 | 112.23 |
| 50TI-50S C-L 0.45 | | 22.33 | 32.60 | 41.70 | 60.57 | 63.40 | 73.77 |
| 50TI-50S C-SL 0.45 | | 18.77 | 30.67 | 39.30 | 49.77 | 55.70 | 81.07 |
| 50TI-50S AL-G 0.45 | | 24.63 | 42.00 | 72.20 | 94.60 | 106.63 | 130.13 |
| 50TI-50S AL-L 0.45 | | 13.27 | 26.70 | 34.17 | 44.77 | 51.77 | 65.33 |
| 50TI-50S AL-SL 0.45 | | 24.37 | 40.90 | 59.17 | 72.57 | 73.70 | 86.40 |
| 50TI-50S LA-G 0.45 | | 19.50 | 41.70 | 54.03 | 83.30 | 86.00 | 111.60 |
| 50TI-50S LA-L 0.45 | | 22.00 | 26.37 | 42.63 | 47.67 | 54.97 | 64.13 |
| 50TI-50S LA-SL 0.45 | | 18.80 | 36.97 | 50.47 | 65.87 | 72.93 | 85.37 |
| 50TI-50S TX-G 0.45 | | 27.67 | 46.10 | 59.33 | 81.77 | 98.53 | 113.83 |
| 50TI-50S TX-L 0.45 | | 12.57 | 20.53 | 32.47 | 42.47 | 47.93 | 57.23 |
| 50TI-50S TX-SL 0.45 | | 22.37 | 31.97 | 57.83 | 64.80 | 66.93 | 79.77 |

*Specimen ID uses the following convention: Mix ID, LWA type, CA type, and w/cm ratio.

G: Gravel; L: Limestone; SL: Siliceous Limestone: w/cm: water-to-cementitious ratio; AL: Lightweight Aggregate from Alabama; LA: Lightweight Aggregate from Louisiana; TX: Lightweight Aggregate from Texas; C: Control (no lightweight aggregates).

**Table A4. Surface resistivity results for 30TI-30C-40S specimens over time**

*Cells color-coded to represent different chloride ion penetrability ratings*

*(Red: high; Yellow: moderate; Green: low; Blue: very low; Violet: negligible)*

| Specimen ID | w/cm | Surface Resistivity (kΩ-cm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Day 7 | Day 14 | Day 28 | Day 56 | Day 90 | Day 180 |
| 30TI-30C-40S C-G 0.35 | 0.35 | 9.07 | 18.57 | 40.07 | 83.97 | 130.60 | 237.07 |
| 30TI-30C-40S C-L 0.35 | | 23.60 | 37.17 | 64.07 | 99.37 | 114.77 | 129.13 |
| 30TI-30C-40S C-SL 0.35 | | 26.07 | 41.53 | 78.33 | 87.73 | 109.77 | 147.37 |
| 30TI-30C-40S AL-G 0.35 | | 16.37 | 27.80 | 61.27 | 105.23 | 141.93 | 222.30 |
| 30TI-30C-40S AL-L 0.35 | | 10.47 | 20.43 | 31.63 | 51.13 | 74.43 | 104.37 |
| 30TI-30C-40S AL-SL 0.35 | | 19.30 | 37.27 | 74.43 | 118.50 | 125.17 | 157.30 |
| 30TI-30C-40S LA-G 0.35 | | 16.37 | 33.37 | 62.40 | 138.67 | 163.20 | 262.67 |
| 30TI-30C-40S LA-L 0.35 | | 12.27 | 19.63 | 27.60 | 52.13 | 71.43 | 111.77 |
| 30TI-30C-40S LA-SL 0.35 | | 17.90 | 35.03 | 64.47 | 114.17 | 128.77 | 173.20 |
| 30TI-30C-40S TX-G 0.35 | | 23.23 | 44.10 | 69.10 | 127.73 | 171.80 | 222.80 |
| 30TI-30C-40S TX-L 0.35 | | 13.03 | 22.17 | 37.87 | 61.37 | 89.97 | 110.87 |
| 30TI-30C-40S TX-SL 0.35 | | 26.17 | 31.97 | 89.13 | 126.30 | 138.17 | 154.77 |
| 30TI-30C-40S C-G 0.45 | 0.45 | 5.97 | 10.53 | 20.07 | 40.77 | 74.87 | 152.00 |
| 30TI-30C-40S C-L 0.45 | | 16.37 | 26.13 | 41.90 | 76.63 | 83.03 | 103.33 |
| 30TI-30C-40S C-SL 0.45 | | 17.07 | 31.23 | 60.53 | 71.27 | 91.13 | 123.47 |
| 30TI-30C-40S AL-G 0.45 | | 9.33 | 15.07 | 35.03 | 62.57 | 95.43 | 162.93 |
| 30TI-30C-40S AL-L 0.45 | | 9.20 | 17.73 | 27.53 | 48.70 | 70.13 | 96.23 |
| 30TI-30C-40S AL-SL 0.45 | | 16.37 | 32.73 | 68.10 | 105.37 | 111.63 | 132.13 |
| 30TI-30C-40S LA-G 0.45 | | 9.97 | 16.87 | 31.27 | 69.97 | 97.93 | 170.50 |
| 30TI-30C-40S LA-L 0.45 | | 8.67 | 13.90 | 16.43 | 37.77 | 53.90 | 88.37 |
| 30TI-30C-40S LA-SL 0.45 | | 12.17 | 24.60 | 45.40 | 89.40 | 102.70 | 137.20 |
| 30TI-30C-40S TX-G 0.45 | | 13.90 | 26.00 | 42.23 | 81.97 | 126.00 | 177.40 |
| 30TI-30C-40S TX-L 0.45 | | 9.33 | 16.43 | 27.20 | 47.23 | 70.43 | 84.43 |
| 30TI-30C-40S TX-SL 0.45 | | 16.70 | 24.27 | 59.37 | 88.80 | 102.03 | 118.30 |

*Specimen ID uses the following convention: Mix ID, LWA type, CA type, and w/cm ratio.

G: Gravel; L: Limestone; SL: Siliceous Limestone: w/cm: water-to-cementitious ratio; AL: Lightweight Aggregate from Alabama; LA: Lightweight Aggregate from Louisiana; TX: Lightweight Aggregate from Texas; C: Control (no lightweight aggregates).

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