# Use of Sand Lightweight Concrete and All Lightweight Concrete

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16. Abstract:

Lightweight concrete (LWC) has reduced density, enabling a reduced dead load compared to normal weight concrete, thus allowing longer spans, slender columns, fewer piers in new construction, and the use of existing substructures in rehabilitation projects. LWC in which both the coarse and fine aggregates are lightweight, called "All LWC," has an even greater reduction in density than "Sand LWC," where only the coarse aggregate is lightweight. LWC also has a low cracking potential at all ages mainly because of internal curing, a low modulus of elasticity, and a low coefficient of thermal expansion. Lightweight aggregates must be prewetted in order for these benefits to be achieved.

This study investigated All LWC and Sand LWC in the laboratory for use in bridge structures. LWCs with varying total cementitious material contents, supplementary cementitious material, and water–cementitious material ratios had satisfactory strengths for use in bridge structures. Differences in compressive strength between air-cured and moist-cured specimens were smaller than with normal weight concretes, which was attributed to internal curing that provided moisture for the hydration reactions. The reduced elastic modulus obtained enables lower stresses for a given deformation, helping to reduce bridge deck cracking. LWC with fibers had high tensile strength and ductility, which can control cracking, including that related to loads.

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**FINAL REPORT**

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## ABSTRACT

Lightweight concrete (LWC) has reduced density, enabling a reduced dead load compared to normal weight concrete, thus allowing longer spans, slender columns, fewer piers in new construction, and the use of existing substructures in rehabilitation projects. LWC in which both the coarse and fine aggregates are lightweight, called "All LWC," has an even greater reduction in density than "Sand LWC," where only the coarse aggregate is lightweight. LWC also has a low cracking potential at all ages mainly because of internal curing, a low modulus of elasticity, and a low coefficient of thermal expansion. Lightweight aggregates must be prewetted in order for these benefits to be achieved.

This study investigated All LWC and Sand LWC in the laboratory for use in bridge structures. LWCs with varying total cementitious material contents, supplementary cementitious material, and water–cementitious material ratios had satisfactory strengths for use in bridge structures. Differences in compressive strength between air-cured and moist-cured specimens were smaller than with normal weight concretes, which was attributed to internal curing that provided moisture for the hydration reactions. The reduced elastic modulus obtained enables lower stresses for a given deformation, helping to reduce bridge deck cracking. LWC with fibers had high tensile strength and ductility, which can control cracking, including that related to loads.

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## INTRODUCTION

Lightweight concrete (LWC) contains lightweight (LW) aggregates and has reduced density, which enables a reduction in dead weight. Thus, structures with longer spans, more slender columns, and fewer piers can be built using LWC. In addition, decks can be widened using the same substructure. Further, light timber decks in some cases can be replaced with low density LWC without the need to strengthen the substructure. There are two types of LWC: (1) Sand LWC, which contains LW coarse aggregate and normal weight (NW) sand with a maximum density of 120 $lb/ft^3$; and (2) All LWC, which contains both coarse and fine LW aggregates with a maximum density of 105 $lb/ft^3$. Concretes with varying density can be achieved by using a combination of LW and NW aggregates at different proportions.

LWC with prewetted LW aggregates provides internal curing and has a low modulus of elasticity and a low coefficient of thermal expansion, resulting in less cracking at early and later ages (Schindler et al., 2021). In addition to the proper selection of ingredients and proportions, good construction practices such as proper consolidation and curing are important in controlling cracking. Bridge decks with fewer and narrower cracks can be constructed with LWC and proper construction practices (Nair et al., 2017). Reducing the width and the occurrence of cracks restricts the infiltration of water and harmful solutions into concrete, thus improving durability. Internal curing can be helpful for concretes with marginal external curing and when autogenous shrinkage is expected. Early age cracking is generally caused by moisture and thermal deformations. The performance of concrete bridge decks is affected by early cracking (Schindler et al., 2021). Later age cracking can be due to drying shrinkage and loads. Internal curing helps to reduce drying shrinkage of concrete (Bentz and Weiss, 2011). Controlling early age cracking also reduces the amount of later age cracking, thus contributing to durability and sustainability (Byard et al., 2014; Darwin and Browning, 2008; Tankasala and Schindler, 2020). The benefits of internal curing are well recognized; the New York State Department of Transportation uses internal curing for all multispan bridge decks to reduce cracking and increase service life (Carpenter, 2019). To resist load related cracking, fibers may be needed, which can also help resist early age cracks.

The Virginia Department of Transportation (VDOT) successfully uses Sand LWC with a maximum density of 120 lb/ft$^3$ in bridge decks, overlays, and beams (Nair et al., 2017; Ozyildirim, 2008). LWC has been used in bridge decks in Virginia since 1959 (Ozyildirim et al., 2017). VDOT has also used All LWC, which had even lower density at a maximum value of 105 lb/ft$^3$, in one application on the Route 198 Bridge over Harper Creek (Schlussel et al., 2017).

VDOT can benefit from the wider use of LWC to control cracking, reduce dead load, improve structures in poor condition, address marginal curing in the field, and improve the durability of concrete structures. The low density of LWC would enable use in a variety of applications.

## PURPOSE AND SCOPE

The purpose of this study was to develop mix designs for Sand LWC and All LWC to enable consistent low density; satisfactory workability, strength, and permeability; and reduced cracking potential for use in bridge structures. Concretes with a minimum compressive strength of 4,000 psi were planned since that is the typical high strength specified for cast-in-place concretes in bridge structures and is widely used for decks. Substructure concrete typically has a minimum strength of 3,000 psi. Mixtures with a strength of 4,000 psi can be substituted for the 3,000 psi concretes; 3,000 psi concretes are easier to produce than 4,000 psi concretes. In the laboratory, Sand LWC and All LWC mixtures with varying total cementitious material contents, supplementary cementitious material (SCM) contents, and water–cementitious materials ratios (w/cm) were prepared and tested. The SCMs used were Class F fly ash and slag cement. Control mixtures with NW aggregates were prepared for comparison. To test the benefit of internal curing, LWC and NWC with partial replacement of the fine aggregate with LW fine aggregate were tested. Fibers were added to increase tensile strength and provide ductility.

## METHODS

After a literature survey and discussions with industry experts, mixtures for Phases 1 through 3 of the study were prepared and tested in the laboratory. Phase 1 mixtures were used to gather preliminary information to determine if low density and a minimum strength of 4,000 psi could be achieved with both coarse and fine LW aggregates and if internal curing was effective in strength development. In Phase 2, both Sand LWC and All LWC with different densities and mixture proportions were prepared and tested for fresh and hardened concrete properties. Phase 3 included the use of fibers with both Sand LWC and All LWC. Type I/II cements were used. The NW aggregates were siliceous, and the LW aggregates were expanded slate. The nominal maximum aggregate size of the NW coarse aggregate was 1 inch and that of the LW coarse aggregate was ¾ inch. The LW aggregates were prewetted before batching, and the moisture contents were determined. All mixtures contained an air-entraining admixture and a high-range water-reducing admixture.

The test procedure used in Phases 1, 2, and 3 is summarized in Table 1. In Phase 1, density, workability, and compressive strength were tested. The test for the coefficient of thermal expansion was also conducted for a few selected specimens.

**Table 1. Tests for Hardened Concrete Properties**

| Property | Test | Specimen Size (in) | No. of Specimens |
|---|---|---|---|
| Compressive strength | ASTM C39 | 4x8 | 2 each at 7, 28, and 56 days |
| Compressive strength | ASTM C39 | 4x8 | 2 at 28 days, air cured |
| Modulus of elasticity | ASTM C469 | 4x8 | 2 each at 7 days and 28 days |
| Splitting tensile strength | ASTM C496 | 4x8 | 2 each at 7 days and 28 days |
| Flexural strength | ASTM C1609 | 4x4x14 | 1 at 28 days |
| Permeability (chloride ion) | ASTM C1202 | 4x2 | 2 each |
| Length change | ASTM C157 | 3x3x11.25 | 2 each |
| Coefficient of thermal expansion | AASHTO T 336 | 4x8 | 1 each |

Specimens were moist cured at room temperature until testing with the following exceptions: specimens for tests of length change and splitting tensile strength underwent 1 week of moist curing followed by 28 days of drying, and specimens for the permeability test underwent moist curing of 1 week at 74°F and then 3 weeks at 100°F.

## Aggregate Preparation

LW aggregates were preconditioned to enable prewetting, and the surface moisture in the aggregates was determined for the batch weights.

### *LW Coarse Aggregate*

The LW coarse aggregate was soaked for at least 3 days and then drained for 2 days. If free moisture existed on the aggregate, that surface moisture was determined by using about 1 pound of wet LW coarse aggregate. Wet aggregate was towel dried to a saturated surface dry (SSD) condition and weighed. The absorption of the LW coarse aggregate was 5%.

Surface moisture of LW coarse aggregate (%) = [(Wet – SSD)*100 / SSD)]

### *LW Fine Aggregate*

The LW fine aggregate was soaked for at least 3 days and then drained for 1 day. It was still wet after draining. To calculate the surface moisture of LW fine aggregate, towel drying is not used since the fine particles would stick to the towel. About 0.8 to 0.9 pounds (350 to 400 grams) of the wet sample was weighed and then dried in the oven or on the hot plate. The absorption of LW fines used was 12%.

Surface moisture of LW fine aggregate (%) = [(Wet – Dry)*100/Dry] – Absorption (12%)

*NW Aggregate*

The NW coarse aggregates were soaked and drained and were in an SSD condition. The NW fine aggregate, a natural sand, was wet during batching. The surface moisture of the fine aggregate was calculated, and the correction for the mixture water was made.

## Phase 1 Mixtures

The mixture proportions for Phase 1 mixtures are given in Table 2. Concretes with varying density were planned. To determine the benefits of internal curing, two sets of specimens were made from each batch. The two different curing methods were used to determine the efficiency of internal curing. One set of specimens was kept in the molds covered for 1 day and then placed in the moist room. The second set was kept in the molds for 1 day with the top surface exposed and was then demolded and kept in the laboratory air.

**Table 2. Phase 1 Preliminary Mixtures (lb/yd$^3$)**

| Batch | Mix[a] | Cement | Fly Ash | NWCA | LWCA | NWFA | LWFA | w/cm | Density[b] |
|---|---|---|---|---|---|---|---|---|---|
| B1 | NWC 600 | 480 | 120 | 1804 | --- | 1,171 | --- | 0.45 | 142.4 |
| B2 | Sand LWC 650 | 520 | 130 | --- | 875 | 1,255 | --- | 0.45 | 113.4 |
| B3 | All LWC 600 | 480 | 120 | --- | 875 | --- | 949 | 0.44 | 99.6 |
| B4 | All LWC 650 | 520 | 130 | --- | 850 | --- | 898 | 0.45 | 99.6 |
| B5 | All LWC 725 | 580 | 145 | --- | 875 | --- | 876 | 0.36 | 101.4 |
| B6 | All LWC 850 | 680 | 170 | --- | 875 | --- | 794 | 0.31 | 103.03 |

NWCA = normal weight coarse aggregate; LWCA = lightweight coarse aggregate; NWFA = normal weight fine aggregate; LWFA = lightweight fine aggregate; w/cm = water–cementitious materials ratio; NWC = normal weight concrete; LWC = lightweight concrete; --- = not applicable.
Fly ash replaced 20% of the total cementitious materials.
[a] The number denotes the total cementitious materials content.
[b] Design density in lb/ft$^3$.

## Phase 2 Mixtures

Based on the literature survey, the results for the preliminary mixtures in Phase 1, and discussions with the industry, the mixture proportions in Table 3 were planned for Phase 2 mixtures including Sand LWC, All LWC, NWC with NW sand, and NWC with some of the NW sand replaced with LW sand for internal curing. The cementitious materials content and the w/cm were varied to maintain a similar water content and workability.

**Table 3. Phase 2 Mixture Proportions (lb/yd$^3$)**

| Batch | Mix | Cement | Fly Ash | Slag | NWC | LWCA | NWFA | LWFA | w/cm | Density[c] |
|---|---|---|---|---|---|---|---|---|---|---|
| B7 | Sand LWC 600 | 480 | 120 | --- | --- | 875 | 1,371 | --- | 0.44 | 115.2 |
| B8 | Sand LWC 725 | 580 | 145 | --- | --- | 875 | 1,258 | --- | 0.36 | 115.6 |
| B9 | Sand LWC 850 | 680 | 170 | --- | --- | 875 | 1,146 | --- | 0.31 | 116.1 |
| B10 | Sand LWC 600 | 360 | --- | 240 | --- | 875 | 1,403 | --- | 0.44 | 116.4 |
| B11 | Sand LWC 725 | 435 | --- | 290 | --- | 875 | 1,297 | --- | 0.36 | 117.1 |
| B12 | Sand LWC 850 | 510 | --- | 340 | --- | 875 | 1,191 | --- | 0.31 | 117.8 |
| B13 | All LWC 600 | 480 | 120 | --- | --- | 875 | --- | 949 | 0.44 | 99.6 |
| B14 | All LWC 725 | 580 | 145 | --- | --- | 875 | --- | 872 | 0.36 | 101.3 |
| B15 | All LWC 850 | 680 | 170 | --- | --- | 875 | --- | 732 | 0.35[a] | 102.0 |
| B16 | All LWC 600 | 360 | --- | 240 | --- | 875 | --- | 971 | 0.44 | 100.4 |
| B17 | All LWC 725 | 435 | --- | 290 | --- | 875 | --- | 898 | 0.36 | 102.3 |
| B18 | All LWC 850 | 510 | --- | 340 | --- | 875 | --- | 825 | 0.35[a] | 104.2 |
| B19 | NWC 600 | 480 | 120 | --- | 1,804 | --- | 1,249 | --- | 0.40 | 144.2 |
| B20 | NWC 600 | 360 | --- | 240 | 1,804 | --- | 1,203 | --- | 0.45 | 143.6 |
| B21 | NWC 600 IC[b] | 480 | 120 | --- | 1,804 | --- | 556 | 480 | 0.40 | 136.3 |
| B22 | NWC 600 IC[b] | 360 | --- | 240 | 1804 | --- | 553 | 450 | 0.45 | 136.2 |

NWCA = normal weight coarse aggregate; LWCA = lightweight coarse aggregate; NWFA = normal weight fine aggregate; LWFA = lightweight fine aggregate; w/cm = water-cementitious materials ratio; LWC = lightweight concrete; --- = not applicable; NWC = normal weight concrete.
Fly ash replaced 20% and slag cement 40% of the total cementitious materials.
[a] B15 and B18 were stiff mixtures and water was added, increasing the w/cm to 0.35 from the initial design of 0.31 for similar workability.
[b] Contains LWFA for internal curing.
[c] Design density in lb/ft$^3$.

For each batch, 1.7 ft$^3$ of concrete was prepared in a pan-type mixer. The specimens were moist cured until testing except for the specimens tested for length change (drying shrinkage) and splitting tensile strength, which were moist cured for 7 days and then air dried in accordance with ASTM C496. In Batches 21 and 22, LW fine aggregate for internal curing replaced 30% by volume of the fine aggregate.

## Phase 3 Mixtures

Steel fibers with hooked ends were added to minimize cracking and restrict crack widths. The fibers were 2.4 inches long, were glued, and had an aspect ratio of 80. Two batches of Sand LWC similar to that in B9 from Phase 2 were tested with two dosages, 0.6% and 0.7% by volume fibers, and one batch of All LWC similar to B14 was tested with a dosage of 0.7%. The mixture proportions are shown in Table 4. The total cementitious materials content was 725 lb/yd$^3$ to enable the inclusion of fibers.

**Table 4. Phase 3 Mixture Proportions (lb/yd$^3$)**

| Batch | Mix | Cement | Fly Ash | Fiber[a] | LWCA | NWFA | LWFA | w/cm | Density[b] |
|---|---|---|---|---|---|---|---|---|---|
| B23 | Sand LWC | 580 | 145 | 0.6 | 875 | 1258 | --- | 0.36 | 115.6 |
| B24 | Sand LWC | 580 | 145 | 0.7 | 875 | 1258 | --- | 0.36 | 115.6 |
| B25 | All LWC | 580 | 145 | 0.7 | 875 | --- | 871 | 0.36 | 101.3 |

LWCA = lightweight coarse aggregate; NWFA = normal weight fine aggregate; LWFA = lightweight fine aggregate; w/cm = water–cementitious materials ratio; LWC = lightweight concrete; --- = not applicable.
[a] Fiber dosage in percent by volume.
[b] Design density in lb/ft$^3$.

## RESULTS AND DISCUSSION

### Phase 1 Mixtures

Phase 1 mixtures had satisfactory workability, with slump values ranging from 3 to 6 inches and air contents ranging from 4.5% to 7.2%. Densities were within the limits for Sand LWC and All LWC. Compressive strengths of moist-cured cylinders at 28 days exceeded 4,000 psi except for B4 at 3,780 psi, as shown in Table 5. The 28-day compressive strength data for different curing methods, moist cured and air cured, are provided in Table 5 for Batches 1 through 6.

In All LWC and Sand LWC, the difference in strength between the air-cured and moist-cured specimens was less than that found for the NWC specimens, as shown in Figure 1, indicating the effectiveness of internal curing.

**Table 5. 28-Day Compressive Strength With Different Curing Methods**

| Batch | Mix | Moist (psi) | Air (psi) | Air/Moist (%) |
|---|---|---|---|---|
| B1 | NWC 600 | 4,600 | 2,710 | 60 |
| B2 | Sand LWC 650 | 4,810 | 3,910 | 81 |
| B3 | All LWC 600 | 4,660 | 3,370 | 72 |
| B4 | All LWC 650 | 3,780 | 3,050 | 81 |
| B5 | All LWC 725 | 7,750 | 6,280 | 81 |
| B6 | All LWC 850 | 9,760 | 9,070 | 93 |

NWC = normal weight concrete; LWC = lightweight concrete.

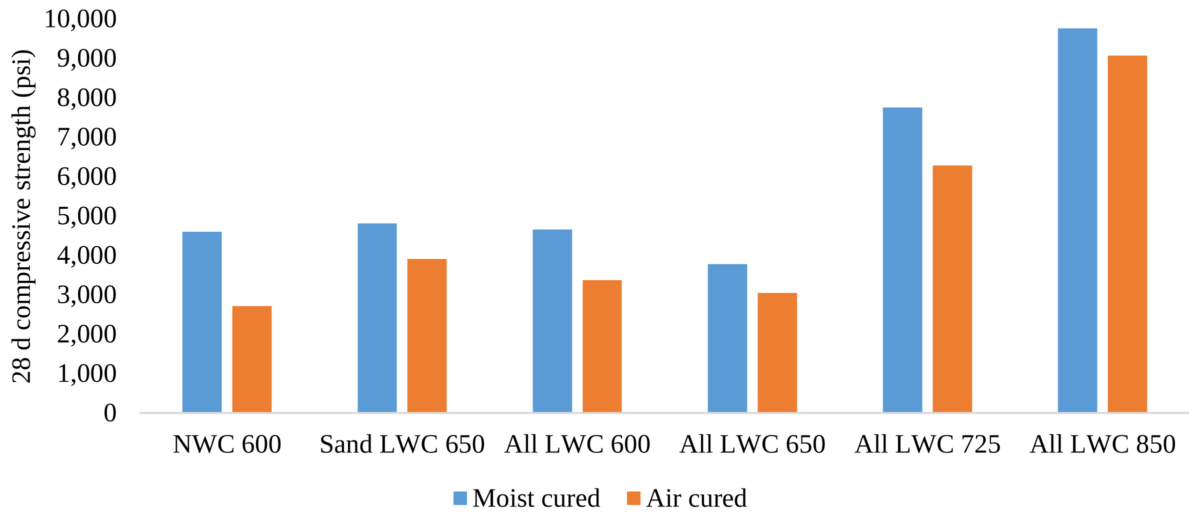


**Figure 1. 28-day Compressive Strength With Different Curing Methods in Phase 1. NWC = normal weight concrete; LWC = lightweight concrete.**

## Phase 2 Mixtures

Fresh and hardened concrete properties for the Phase 2 mixtures are given in Table 6 and Table 7, respectively.

**Table 6. Fresh Concrete Properties of Phase 2 Mixtures**

| Batch No. | Mix | Slump (in) | Air (%) | Fresh Density (lb/ft$^3$) |
|---|---|---|---|---|
| B7 | Sand LWC 600 | 5 | 7 | 116.1 |
| B8 | Sand LWC 725 | 5.5 | 5 | 118.9 |
| B9 | Sand LWC 850 | 3 | 4.5 | 122.1 |
| B10 | Sand LWC 600 | 3 | 4.5 | 117.4 |
| B11 | Sand LWC 725 | 3.5 | 5 | 119.3 |
| B12 | Sand LWC 850 | 4 | 5 | 120.9 |
| B13 | All LWC 600 | 5.75 | 7.25 | 103.6 |
| B14 | All LWC 725 | 5 | 5.5 | 101.6 |
| B15 | All LWC 850 | 7 | 8.5 | 101.6 |
| B16 | All LWC 600 | 3 | 7 | 101.6 |
| B17 | All LWC 725 | 8.5 | 8 | 101.6 |
| B18 | All LWC 850 | 6 | 7 | 104.4 |
| B19 | NWC 600 | 2.75 | 7 | 148.2 |
| B20 | NWC 600 | 7 | 7.4 | 144.2 |
| B21 | NWC 600 IC[a] | 3.75 | 7 | 135.3 |
| B22 | NWC 600 IC[a] | 4 | 9 | 137.8 |

LWC = lightweight concrete; NWC = normal weight concrete.
[a] Contains lightweight fine aggregate for internal curing.

All batches were workable and easily consolidated using mechanical vibration; however, in some cases, the mixture was harsh for hand finishing, especially when All LWC was used. For example, B7 was a bit grainy and B8 was sticky. B9 and B13 were very coarse. The harshness was reduced using admixtures. In B9 and B12, the density was slightly higher than 120 lb/yd$^3$; however, the batches had air contents on the low side. Increasing the air content would make those mixtures meet the design density. All LWC had densities less than the maximum design value of 105 lb/ft$^3$.

In LWC, the compressive strengths of moist-cured specimens exceeded 4,940 psi and those of air-cured specimens exceeded 4,240 psi at 28 days, as shown in Table 7, indicating satisfactory strengths for bridge deck concretes, which require a minimum compressive strength of 4,000 psi. In general, the lowest modulus of elasticity was obtained in All LWC. The highest modulus of elasticity value was 4.02 million psi for the Sand LWC containing 850 lb/yd$^3$ of total cementitious material; this mixture had a 28-day compressive strength of 8,540 psi. The theoretical modulus of elasticity for a NWC with this compressive strength would be 5.27 million psi, calculated using 57,000 times the square root of the compressive strength. The NWC tested also had a modulus of elasticity less than expected based on the theoretical equation. This was attributable to the type of aggregate used in this study, which was a granite aggregate. The low modulus of elasticity is beneficial in reducing the cracking potential.

Differences in compressive strength for the curing methods, i.e., moist cured and air cured, are shown in Figure 2 and Table 8. In LWC, the difference in strength between the air-cured and moist-cured specimens was small, indicating the effectiveness of the internal curing. Similarly, the NWC with a low w/cm of 0.40 was also able to retain a high amount of strength when air cured. However, the NWC with a higher w/cm of 0.45 had the largest difference in strength between moist- and air-cured specimens.

The permeability values were low and mostly very low, indicating high resistance to the penetration of chlorides. These values were similar to permeability values obtained in the laboratory and the field from the same class of concrete with either NWC or LWC. The Sand LWC and the NWC with granite aggregates had similar values, expected of typical concretes containing granite aggregates, which is 5.3 millionths per °F (Kosmatka and Wilson, 2011).

Shrinkage data are displayed in Figure 3. The length change after 7 days of moist curing is given. The 28-day values were less than the 0.035% used for VDOT low shrinkage bridge deck concretes (VDOT, 2020). The maximum value at 6 months of drying was less than 0.045%. This value is much lower than the maximum shrinkage value of 0.07% at 4 months recommended by Babaei and Fouladgar for low cracking bridge decks (Babaei and Fouladgar, 1997).

**Table 7. Hardened Concrete Properties of Phase 2 Mixtures**

| Batch | Mix | Compressive Strength (psi) | | | | Splitting Tensile Strength (psi) | | Modulus of Rupture (psi) | Modulus of Elasticity ($10^6$ psi) | | Coefficient of Thermal Expansion ($10^{-6}$/°F) | Permeability (C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 7-day (Moist) | 28-day (Moist) | 28-day (Dry) | 56-day (Moist) | 7-day | 28-day | 28-day | 7-day | 28-day | | |
| B7 | Sand LWC 600 | 4,070 | 4,940 | 4,560 | 5,510 | 290 | 340 | 610 | 2.74 | 2.98 | --- | 507 |
| B8 | Sand LWC 725 | 6,110 | 7,700 | 6,190 | 7,510 | 325 | 495 | 415 | 3.40 | 3.32 | --- | 512 |
| B9 | Sand LWC 850 | 6,710 | 8,700 | 7,560 | 9,300 | 535 | 515 | 845 | 3.24 | 3.72 | --- | 189 |
| B10 | Sand LWC 600 | 7,650 | 7,990 | 5,890 | 8,280 | 450 | 600 | 620 | 3.59 | 3.62 | 5.047 | 251 |
| B11 | Sand LWC 725 | 8,680 | 8,510 | 7,500 | 8,440 | 620 | 625 | 535 | 3.52 | 3.61 | --- | 324 |
| B12 | Sand LWC 850 | 8,130 | 8,540 | 7,290 | 9,370 | 480 | 520 | 850 | 3.62 | 4.02 | --- | 382 |
| B13 | All LWC 600 | 3,860 | 5,120 | 4,240 | 5,070 | 325 | 370 | 550 | 2.60 | 3.07 | --- | 1413 |
| B14 | All LWC 725 | 5,230 | 6,090 | 5,440 | 6,160 | 295 | 420 | 600 | 2.78 | 2.84 | --- | --- |
| B15 | All LWC 850 | 6,350 | 7,440 | 7,200 | 7,400 | 350 | 590 | 635 | 3.10 | --- | 5.258 | --- |
| B16 | All LWC 600 | 4,310 | 5,190 | 4,430 | 6,880 | 345 | 315 | 535 | 2.36 | 2.58 | 3.854 | --- |
| B17 | All LWC 725 | 6,320 | 7,375 | 4,890 | 7,540 | 410 | 470 | 720 | 2.56 | 2.59 | --- | 140 |
| B18 | All LWC 850 | 8,330 | 8,460 | 5,500 | 8,150 | 545 | 565 | 700 | 2.96 | 3.13 | --- | 134 |
| B19 | NWC 600 | 5,900 | 7,140 | 5,900 | 7,090 | 555 | 530 | 645 | 3.46 | 3.77 | 5.593 | 825 |
| B20 | NWC 600 | 2,540 | 4,420 | 1,950 | 4580 | --- | 455 | 555 | 2.13 | 3.05 | 5.339 | 1164 |
| B21 | NWC 600 IC[a] | 4,260 | 4,910 | 4,350 | 6,290 | 365 | 490 | 525 | 2.36 | --- | --- | 732 |
| B22 | NWC 600 IC[a] | 2,780 | 4,540 | 4,040 | 5,990 | --- | 475 | 640 | 2.34 | 2.71 | 4.987 | 665 |

LWC = lightweight concrete; NWC = normal weight concrete; --- = not tested.
[a] Contains lightweight fine aggregate for internal curing.

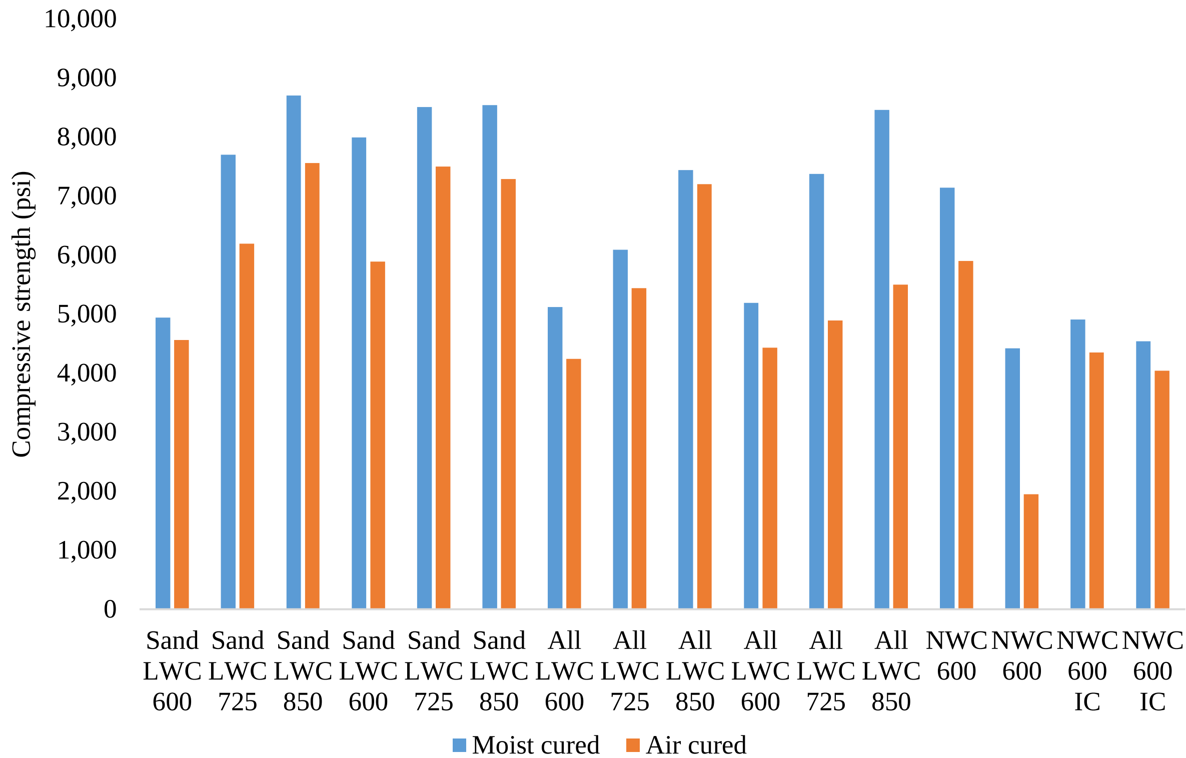


**Figure 2. 28-day Compressive Strength With Different Curing Methods in Phase 2. LWC = lightweight concrete; NWC = normal weight concrete.**

**Table 8. 28-Day Compressive Strength (psi) With Two Different Curing Methods in Phase 2**

| Batch | Concrete | Moist (psi) | Air (psi) | Air/Moist (%) |
|---|---|---|---|---|
| B7 | Sand LWC 600 | 4,940 | 4,560 | 92 |
| B8 | Sand LWC 725 | 7,700 | 6,190 | 80 |
| B9 | Sand LWC 850 | 8,700 | 7,560 | 87 |
| B10 | Sand LWC 600 | 7,990 | 5,890 | 74 |
| B11 | Sand LWC 725 | 8,510 | 7,500 | 88 |
| B12 | Sand LWC 850 | 8,540 | 7,290 | 85 |
| B13 | All LWC 600 | 5,120 | 4,240 | 83 |
| B14 | All LWC 725 | 6,090 | 5,440 | 89 |
| B15 | All LWC 850 | 7,790 | 6,220 | 80 |
| B16 | All LWC 600 | 5,190 | 4,430 | 85 |
| B17 | All LWC 725 | 7,375 | 4,890 | 66 |
| B18 | All LWC 850 | 8,460 | 5,500 | 65 |
| B19 | NWC 600 | 7,140 | 5,900 | 83 |
| B20 | NWC 600 | 4,420 | 1,950 | 44 |
| B21[a] | NWC 600 IC | 4,910 | 4,350 | 89 |
| B22[a] | NWC 600 IC | 4,540 | 4,040 | 89 |

LWC = lightweight concrete; NWC = normal weight concrete.

[a] Contains lightweight fine aggregate for internal curing.

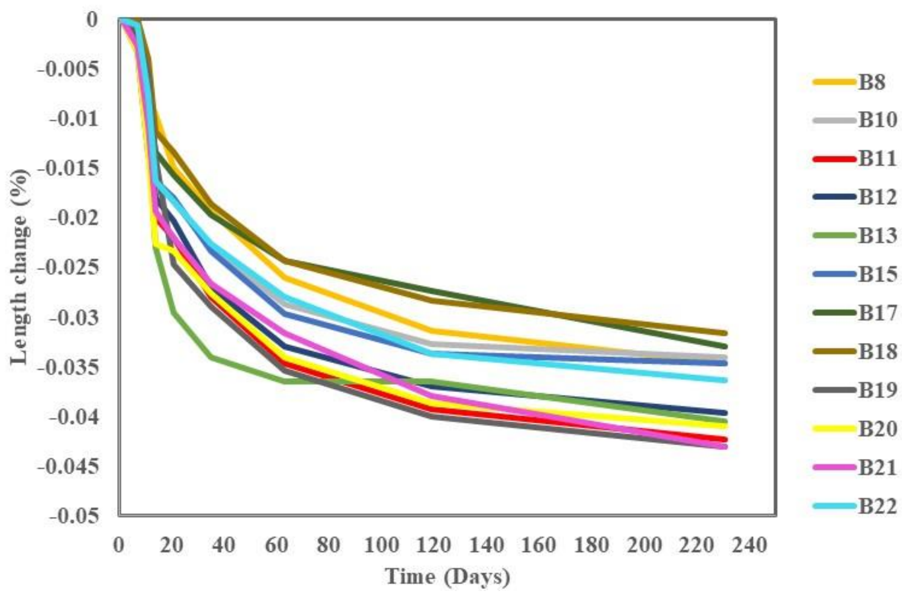


**Figure 3. Length Change Data After 7 Days of Moist Curing**

## Phase 3 Mixtures

Fresh and hardened properties of concretes with fibers for the Phase 3 mixtures are given in Table 9 and Table 10, respectively. The 7-day flexural strengths are shown in Figure 4 and Table 11. Deflection hardening was observed that would keep crack widths tight when they occur. Fibers help increase the tensile strength of LWC and provide ductility, both of which help in controlling cracking in fresh and hardened concretes.

**Table 9. Fresh Concrete Properties of Phase 3 Mixtures**

| Batch | Slump (in) | Air (%) | Density ($lb/ft^3$) |
|---|---|---|---|
| B23 | 4 | 6.25 | 112.85 |
| B24 | 3 | 6.5 | 120.08 |
| B25 | 4 | 7.0 | 102.34 |

**Table 10. Hardened Properties of Phase 3 Mixtures**

| Batch | Compressive Strength (psi) | | | Splitting Tensile Strength (psi) | Modulus of Elasticity ($10^6$) | |
|---|---|---|---|---|---|---|
| | 7-day (moist) | 28-day (moist) | 56-day (moist) | 28-day | 7-day | 28-day |
| B23 | 4,890 | 5,720 | 6,220 | 680 | 2.97 | 3.10 |
| B24 | 5,260 | 6,400 | 6,930 | 800 | --- | 3.14 |
| B25 | 3,060 | 4,440 | 5,060 | 500 | 1.62 | 2.10 |

--- = not tested.

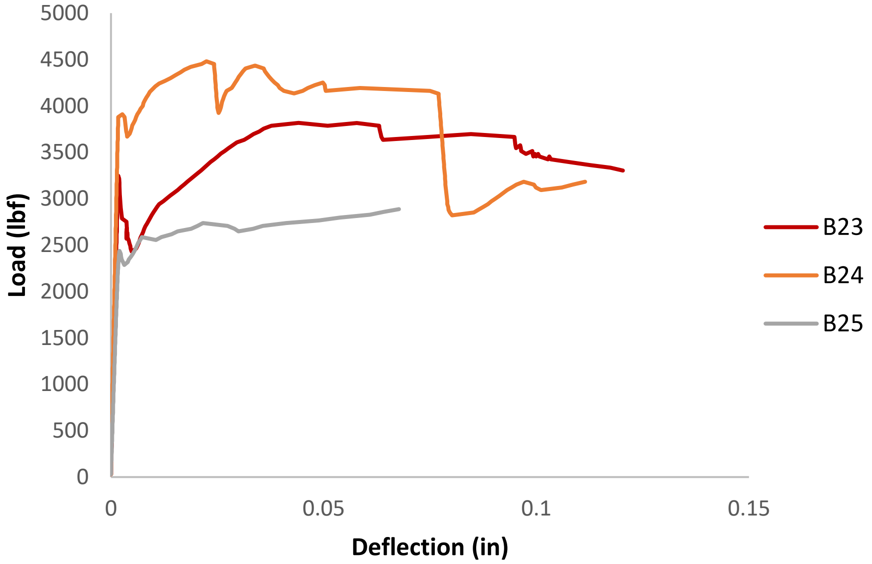


**Figure 4. Load vs. Deflection at 28 Days**

**Table 11. Flexural Test Data at 28 Days (psi) for Phase 3**

| Batch No. | Maximum Strength | First-Peak Strength | Residual Strength at Span/600 | Residual Strength at Span/300 | Residual Strength at Span/150 |
|---|---|---|---|---|---|
| B23 | 760 | 571 | 603 | 710 | 693 |
| B24 | 870 | 727 | 835 | 780 | 529 |
| B25 | 605 | 445 | 508 | 513 | --- |

--- = not tested.

## CONCLUSIONS

- *Both Sand LWC and All LWC have lower density than NWC and provide satisfactory strengths appropriate for bridge structures.* All LWC has lower density than Sand LWC.

- *LWC with prewetted LW aggregates has small differences in compressive strength between air-cured and moist-cured specimens, indicating the effectiveness of internal curing.* Proper external curing is critical; however, internal curing would help in cases with marginal curing and when autogenous shrinkage is expected.

- *Shrinkage of Sand LWC and All LWC is low, as desired for reduced cracking in bridge deck concretes.*

- *LWC has reduced elastic modulus values compared to NWC at the same total cementitious materials content, which would help in reducing bridge deck cracking.* NWC also has reduced elastic modulus values that are lower than predicted by the theoretical equation. This is due to the characteristics of the aggregate used in this study.

- *Permeability of Sand LWC, All LWC, and NWC can be very low or low, attributable to the SCMs and low w/cm, indicating high resistance to penetration of chlorides.* A maximum w/cm of 0.45 was used in the study.

- *The coefficient of thermal expansion is lowest in All LWC, which would minimize the cracking potential due to temperature.*

- *Fibers help increase the tensile strength of LWC and provide ductility, both of which help to control cracking in fresh and hardened concretes.*

## RECOMMENDATION

1. *VDOT's Structure and Bridge Division should consider low density LWC including both Sand LWC or All LWC in bridge decks and overlays whenever feasible and practical.*

# IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

## Implementation

VTRC will work with VDOT's Materials Division to update Section 217.12 of VDOT's *Road and Bridge Specifications* by September 2025. VDOT's Structure and Bridge Division will encourage demonstration projects with All LWC.

## Benefits

The cost of LWC material is higher than that of similar NWC material; however, the benefits in reduced dead load and improved cracking resistance and durability are expected to make LWC cost-effective throughout the life cycle of structures. In addition, the availability and wider use of a competing LWC material would lead to a reduced cost. Further, the increase in the material cost is a small fraction of the total cost of a project.

Eleven percent (2,353) of Virginia's bridges have timber decks, and 36% of Virginia's structurally deficient bridges (285 of 799) have timber decks, as presented at the 2020 meeting of VTRC's Concrete Research Advisory Committee. LWC decks would be an appropriate replacement for aging timber decks since there would not be an increase in dead loads on the existing foundation and thus no need to replace the existing substructure. This would result in great cost-savings. Further, since LWC decks are more durable than timber decks, the service life of the bridge would be extended.

Many times, curing in the field has been less than satisfactory because of the time of the application of the curing material, the effectiveness of the curing method, or the limited duration of curing—as in patch repairs. Further, many times, wind removes the curing materials over the concrete placement. Internal curing could compensate for the weaknesses or limitations of regular curing. The New York State Department of Transportation has been using internal curing in their high performance concrete by including LWA to address bridge deck cracking and has indicated that their experimental results showed a 70% reduction in cracking, including several multispan bridges that showed no cracking (Carpenter, 2019). If environmental stresses in combination with the loads on the members are expected to cause cracking, fibers can be included in the LWC mixtures.

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