Pre-soaked Lightweight Fine Aggregates as Additives for Internal Curing in Concrete

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by Y. Wei and W. Hansen

Synopsis: High-performance concrete (i.e. water-cementitious ratio below 0.40) for bridge-deck applications has been shown to develop shrinkage-related cracking. This study explores the concept of internal curing using pre-soaked lightweight fine aggregate (LWFA) as partial replacement of sand for mitigating autogenous shrinkage and moisture warping. Concretes with water-cementitious ratios (w/c) of 0.35 and 0.45 containing LWFA to sand ratios of 20% and 40% by volume were investigated. Results show that pre-soaked LWFA is effective in mitigating autogenous shrinkage but also reduces slab uplift from moisture warping due to combined drying shrinkage at the top surface and wetting at the bottom surface.

Keywords: autogenous shrinkage; internal curing; moisture warping; self-desiccation shrinkage; self-induced stress

Biography:
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INTRODUCTION

Autogenous shrinkage is the macroscopic volume reduction of cementitious systems without moisture transfer to the environment. This property is a result of self-desiccation of pores within the hydrating cement paste thus increasing with degree of hydration.

Within days after pouring, the hydrating cement paste develops capillary discontinuity.[1, 2] This has been found to hinder moisture transport in cross sections greater than about 80 mm (3.2 in.).[3] Once this happens a moisture gradient can develop within the cross section any time the concrete is exposed to water at the free surface. Consequently, warping deformation can result in slabs if poor base-drainage conditions exist.[4, 5]

This paper presents new experimental results and test methods for quantifying autogenous shrinkage and warping and the effectiveness of internal curing by using pre-soaked LWFA in mitigating the shrinkage and associated tensile stresses.

RESEARCH SIGNIFICANCE

Low *w/c* (less than 0.40) bridge-deck concrete often develops shrinkage-related cracking. Cracking can affect the durability, especially in wet-freeze climate zones in North America, where deicing salts are used extensively during the winter. Low *w/c* mixes develop larger autogenous shrinkage. If this property can be mitigated through internal curing procedures, the advantages of using low *w/c* concrete can be better realized. Even higher *w/c* concretes such as highway mixes (*w/c* between 0.40 and 0.45) can benefit from internal curing procedures if they counteract self-desiccation by maintaining high internal pore humidity. In this study the use of water-soaked lightweight fine aggregate for internal curing and autogenous shrinkage control is further explored.

EXPERIMENTAL PROGRAM

Materials and experimental methods

A type I portland cement was used throughout. The chemical compositions of this type of cement are listed in **Table 1**. The sand-size expanded shale lightweight aggregate was obtained from a local manufacturer. This type of LWFA was found to have a bulk specific gravity of 1.8 and water content of 15% by weight obtained in a 24-hour pre-soaked condition. Two *w/c* ratios (0.35 and 0.45) and two LWFA contents (20% and 40%) by volume were used. The mix proportions for the 0.35 *w/c* concrete without LWFA and with 40% LWFA sand-volume replacement are shown in **Table 2**. For mix proportions of concrete with *w/c* = 0.45 (which is not listed in **Table 2**), the aggregate volume was maintained the same as *w/c* = 0.35 concrete.

Tests included heat of hydration of the portland cement paste, free and restrained autogenous deformation of concrete with a maximum aggregate size of 12.5 mm (1/2 in.), and moisture warping of concrete beams. Preliminary free autogenous deformation tests on concrete containing 25 mm (1 in.) maximum aggregate size were inconclusive. It was decided to remove the largest aggregate particles as they hindered the macroscopic measurement of autogenous shrinkage, probably due to particle to particle proximity.

Measurement of heat of hydration

Long-term (up to 21 days) isothermal heat rate was obtained for 0.35 and 0.45 *w/c* cement pastes at 23 ^oC (73 ^oF). Two specimens were tested for each mix and the average results were reported.

Autogenous deformation measurements

Autogenous deformation measurements were carried out on both cement paste and concrete specimens with cross section dimensions of 60 mm (2.4 in.) by 100 mm (3.9 in.) and specimen length of 1000 mm (39.4 in.). The test setup is shown in **Fig. 1**. External drying was prevented by sealing the specimens right after casting to ensure sealed hydration. A neoprene sheet was placed between the mold and the sealed specimen in order to reduce external friction. The curing temperature was maintained at 23±2 ^{o}C (73±4 ^{o}F) by circulating constant-temperature water through the channels built-into the sides and bottom of the mold. A thermo-couple was embedded in the specimen to monitor temperature development during the test. One end of the specimen was fixed to the mold and the other end was free to move horizontally. The free end had an LVDT attached for measuring the linear autogenous deformation. The measurements were initiated after final set of the concrete. Two replicate specimens were tested and both values were reported.

Measurements of stress from restrained autogenous deformation

Self-induced stress in concrete was measured from a restraint test by using a temperature-stress-testing-machine (TSTM) equipped with servo-hydraulic control (**Fig. 2**). For this test the degree of restraint of the TSTM was determined to be 0.42. Degree of restraint has a large effect on the self-induced stress development.[6, 7, 8] Though the stress ratio (stress under a certain restraint/stress under a complete restraint condition) is not always proportional to the degree of restraint, it is considered acceptable to estimate the stress under 100% restraint using the measured stress assuming that the stress ratio is proportional to the degree of restraint.[8]

The specimen was sealed during the test to prevent external drying. The curing temperature was kept at about 23±2 ^{o}C (73±4 ^{o}F) by circulating water through copper pipes placed around the specimen. Testing was initiated after casting. Two replicate specimens were tested for each mix.

Moisture warping in concrete beams

Beam warping tests were conducted using a test procedure based on the work at Munich Technical University[4] as shown in **Fig. 3**. The test can determine beam uplift from simultaneous drying in the top portion and wetting in the bottom portion of the beam. The concrete beam is 2.3 m (7.5 ft) long, 0.2 m (8 in.) deep, and 0.15 m (6 in.) wide. One end of the beam is fixed and the other end is free to lift up. A dial-gauge was used to record the amount of warping at the free end over time. To facilitate a through-thickness moisture gradient, the other sides of beam were sealed using a water-proof paint. Beam warping tests were conducted in an environmental chamber maintained at constant relative humidity (50%) and temperature (23±2 ^{o}C/73±4 ^{o}F). Measurements were initiated at the age of 7 days when the beams have gained enough strength to lift up.

Split tensile strength

The split tensile strength of concrete cylinders was determined according to ASTM C496.

RESULTS AND DISCUSSIONS

Autogenous shrinkage in cement paste and concrete

Autogenous shrinkage is a property of hydration of cement paste. This is concluded from the results in **Fig. 4**. Autogenous shrinkage of cement paste is increasing substantially with decreasing *w/c* ratio. Although autogenous shrinkage is much smaller in concrete of same *w/c* ratio (**Fig. 5**) due to reduced cement paste volume and aggregate restraining effect, lower *w/c* (0.35) concrete is undergoing significant autogenous shrinkage, and thus is more prone to cracking.

Mitigation of autogenous shrinkage in concrete using pre-soaked LWFA

The results in **Fig. 5** show that pre-soaked LWFA is highly effective in reducing autogenous shrinkage, and that a smaller amount of LWFA is needed for higher *w/c*. Autogenous shrinkage during the first 28 days of sealed curing can be completely eliminated for the *w/c* of 0.35 concrete if 40% of the sand is replaced by LWFA. For a mix with *w/c* = 0.45, 20% LWFA is sufficient in preventing autogenous shrinkage.

Effect of internal curing on self-induced stress

The short-term and long-term development of self-induced stress along with autogenous deformation is plotted in **Fig. 6** for *w/c* = 0.35 concretes. According to the results, the self-induced tensile stress is completely eliminated in the 40% LWFA concrete, which is consistent with the free deformation results for the same mix. For the control mix, tensile cracking can be expected within 28 days in a fully restrained concrete element due to autogenous shrinkage alone (**Fig. 6d**). The direct tensile stress was obtained by breaking TSTM specimens, which is 70%-80% of the tested split tensile strength on 4 by 8 inch cylinders.

Mitigation of warping from internal curing

In slabs, moisture gradients from drying at the top surface and water suction at the bottom surface work together to cause uplift at joints and free edges. According to the experimental results on autogenous shrinkage, 20% pre-soaked LWFA replacement is capable of completely eliminating autogenous shrinkage in concrete with *w/c* of 0.45. To investigate if LWFA is also effective in reducing moisture warping, the same replacement and *w/c* were used for moisture warping measurements.

It was found that LWFA in a pre-soaked condition is effective in reducing moisture warping in addition to eliminating autogenous shrinkage. As shown in **Fig. 7**, about 80% of moisture warping is reduced at the drying time of 16 days. The substantial reduction in moisture warping suggests that using LWFA decreases the moisture gradient along beam depth. Since the beam's bottom is in contact with water, RH at that portion is high with or without LWFA. However, the top portion of the beam with LWFA will have higher RH than that without LWFA possibly due to 1) the release of water from LWFA upon drying; and 2) faster consumption of water released from LWFA and higher degree of hydration than that in the interior of the concrete leaving a dense layer of concrete at the top portion which helps reduce the evaporation rate and consequently the moisture gradient along the beam depth. Water movement from LWFA to the hydrating cement paste will stop when the relative humidity in the pores of LWFA is equivalent to that in cement paste,[9] this may reduce the effectiveness of LWFA on reducing the moisture gradient if the slab top surface is exposed to drying for a long period.

CONCLUSIONS

Pre-soaked lightweight fine aggregate (LWFA) was found to be effective in reducing and even eliminating self-desiccation shrinkage in concretes with *w/c* ranging from 0.45 to 0.35. LWFA was used as partial replacement of regular sand by volume percentage range from 20% to 40%. These aggregates are effective in providing a source for internal curing by acting as internal reservoirs during hydration of the cement.

Tensile stresses from restrained autogenous shrinkage are significant in low *w/c* (0.35) concretes. Internal curing was found to be effective in eliminating these tensile stresses. Self-desiccation of pores and pore-discontinuity render a concrete cross section subject to a large warping deformation if one of the two opposing surfaces is exposed to wetting for an extended period. LWFA was found to be effective as well in reducing slab warping from combined drying within the top surface region and continued wetting from the base, a condition encountered if inadequate base drainage exists.

ACKNOWLEDGEMENTS

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Table 1 - Chemical compositions of portland Type I cement

% by weight	Cement (Type I)
SiO_2	20.4
Al_2O_3	5.04
Fe_2O_3	2.51
CaO	62.39
MgO	3.43
Na_2O	0.25
K_2O	0.67
Cl	0.03
SO_3	2.75
Total as Oxides	97.47
C_3S	53.66
C_2S	18.01
C_3A	9.11
C_4AF	7.64
Total as clinker Phases	88.42
Blaine (cm^2/g)	4290

Table 2 - Concrete mix proportion for *w/c*=0.35

Material	Control mix (0% LWFA)	IC mix for (40%LWFA)
Type I cement, kg/m^3 (lb/cyd)	557 (939)	557 (939)
Water, kg/m^3 (lb/cyd)	195 (329)	195 (329)
Limestone, kg/m^3 (lb/cyd)	431 (726)	431 (726)
Sand, kg/m^3 (lb/cyd)	1224 (2065)	724 (1220)
LWFA (pre-soaked), kg/m^3 (lb/cyd)	-	263 (443)
Water-reducing admixture, kg (lb)	2.23 (3.76)	2.23 (3.76)
AEA, kg (lb)	1.11 (1.87)	1.11 (1.87)

Note: AEA=air-entraining admixture

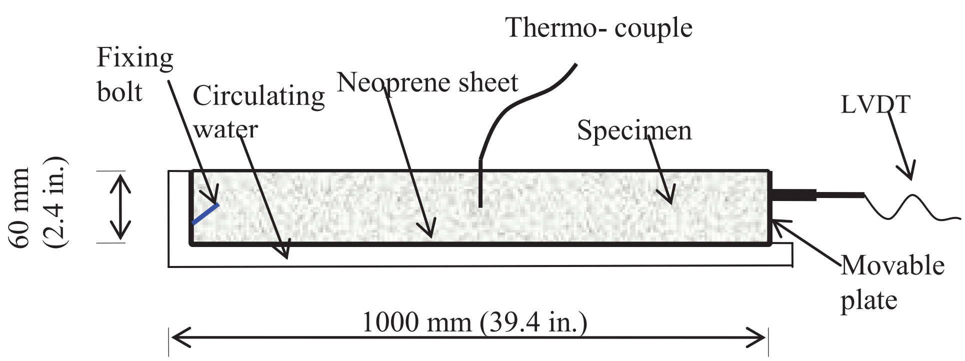


Figure 1 - Schematic illustration of linear measurements of autogenous deformation.

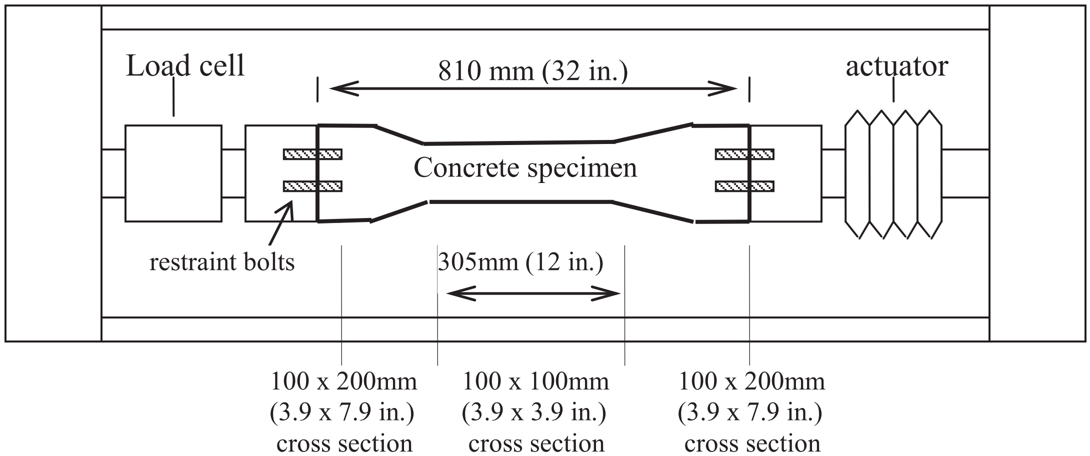


Figure 2 - Top view of the restrained autogenous shrinkage test.

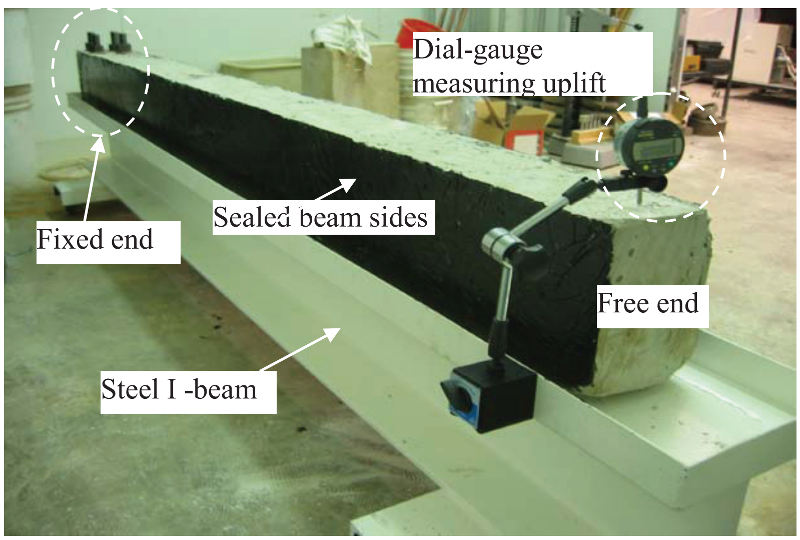
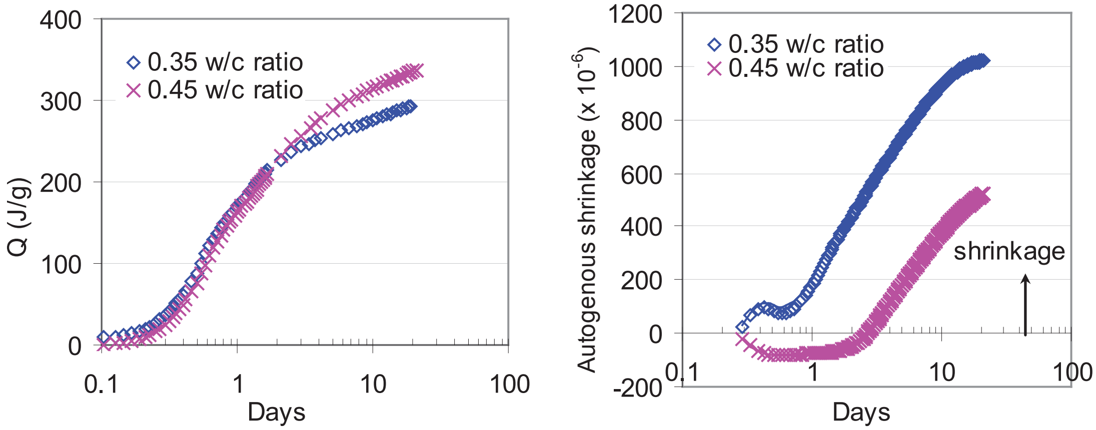
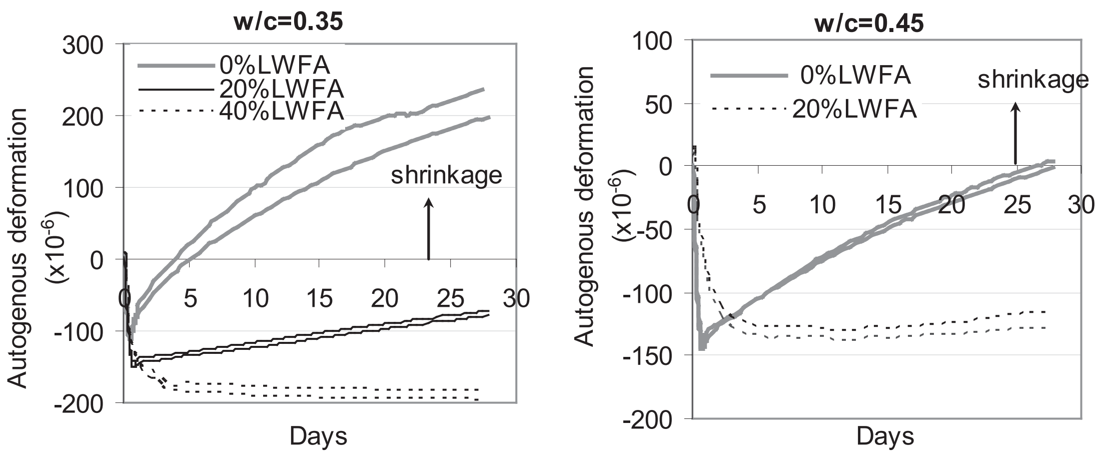


Figure 3 - U of M beam warping test setup.



(a) (b)

Figure 4 - Development of (a) heat of hydration; and (b) autogenous shrinkage of cement paste.



(a) (b)

Figure 5 - Measured autogenous deformation of control and LWFA concrete with two replicate specimens tested for each mixture: (a) *w/c* = 0.35; (b) *w/c* = 0.45.

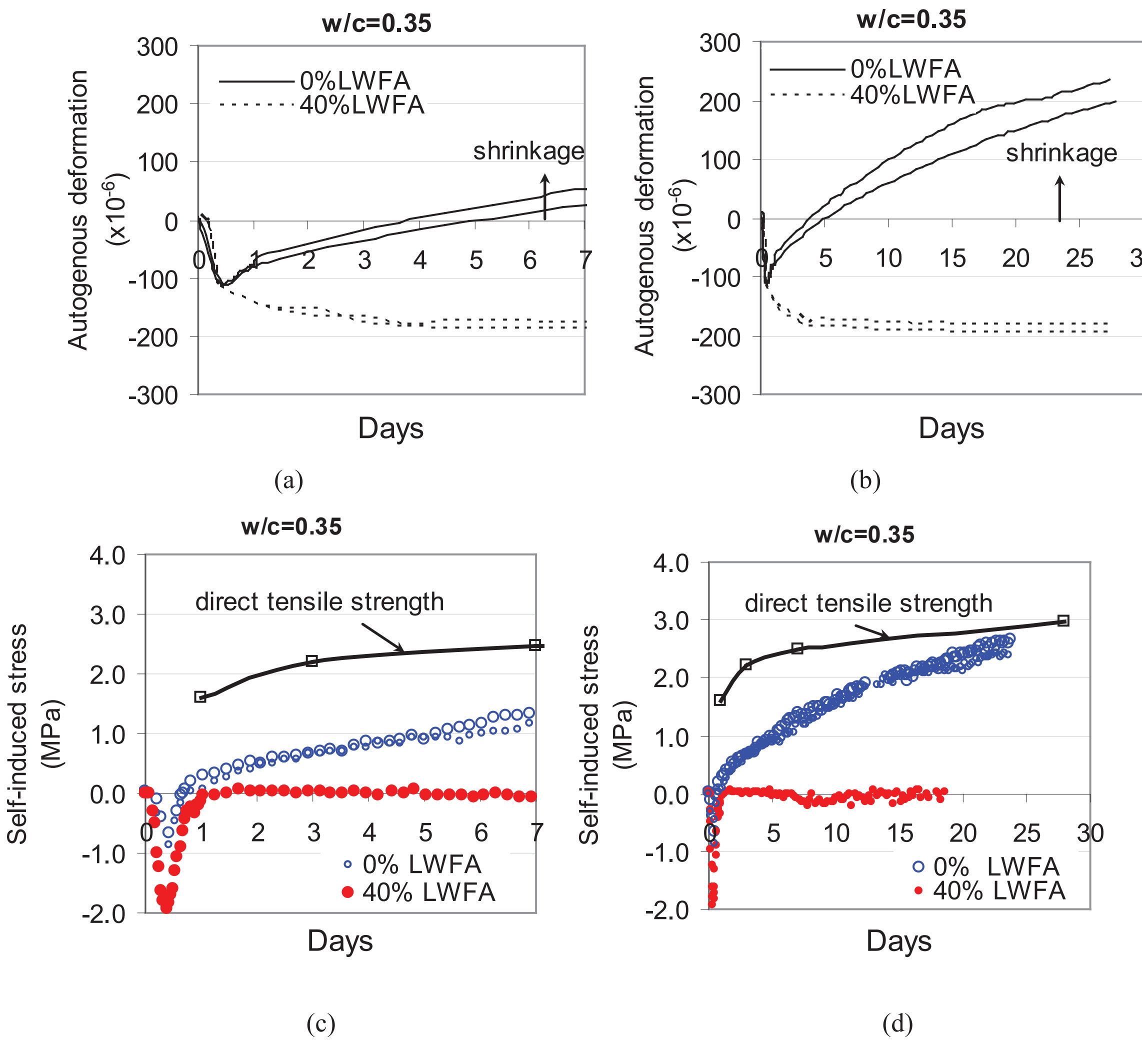


Figure 6 – Free autogenous deformation and self-induced stress of control and LWFA concretes with *w/c* = 0.35: (a, c) short-term; and (b, d) long-term.

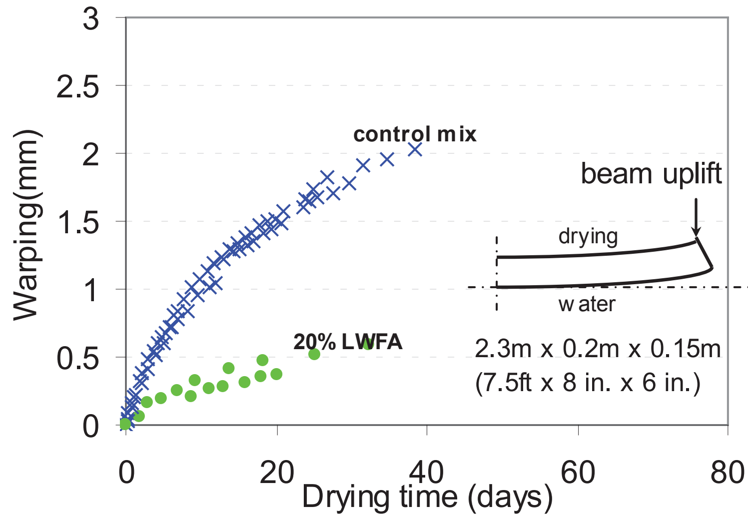


Figure 7 – Measured development of beam warping (internal curing vs. no internal curing) for *w/c* = 0.45 concrete.