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# Effect of aggregate and cementitious material on properties of lightweight self-consolidating concrete for prestressed members

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## HIGHLIGHTS

- Expanded clay and shale aggregate self-consolidating concretes were studied.
- High cementitious materials contents are required to achieve adequate flow.
- Type III cement was required for high early-age strength.
- Elastic moduli were closely predicted using the ACI Code equation.
- Measured shrinkage was less than 50% of ACI 209 predictions.

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## ABSTRACT

Forty-one concrete mixtures were used to examine the effects of cementitious material and aggregate type and content on flow and compressive strength of expanded clay and shale lightweight self-consolidating concrete. Type III cement was required to produce compressive strengths in excess of 28 MPa at one day, and high cementitious materials contents were required for adequate fresh and hardened properties. A limiting difference in slump and J-Ring flow of 100 mm is recommended for similar concrete mixtures. Moduli of elasticity measured for selected mixtures were accurately predicted by the ACI equation, and shrinkage was less than predicted by typical models.

## 1. Introduction

Structural lightweight concrete has characteristics which lead to benefits when used in certain applications due, in most cases, to its low self-weight. Precast/prestressed concrete members, building floor slabs, and bridge decks are examples. Lightweight concrete is defined as "concrete having a minimum 28-day compressive strength in excess of 17 MPa, an equilibrium density between 1120 kg/m$^3$ and 1920 kg/m$^3$, and consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate" [1]. The equilibrium density of structural lightweight concrete typically ranges between 1680 kg/m$^3$ and 1920 kg/m$^3$ [1]. Self-consolidating concrete (SCC) has become increasingly common in prestressed applications due to the possibility for reduced time, labor, and noise during construction and has been used in other areas for producing an improved surface finish in hard to vibrate areas [2]. Exact definitions may vary, but SCC should flow and fill forms under its own weight without vibration, remain homogeneous through long flow distances and vertical drops, and flow through congested areas without blockage or segregation [2]. Using lightweight aggregate in SCC produces the benefits of both lightweight concrete and SCC. Lightweight self-consolidating concrete (LWSCC) for bridge girders and other precast members has garnered more study in recent years due to a desire for weight reduction in long span girders and to fit with the increasingly common production methods used in precast plants [3]. Proper moisture control in the lightweight aggregate is important for LWSCC due to the relatively high absorption capacity of lightweight aggregates, and the increased potential

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for segregation of LWSCC with a large dosage of superplasticizer [3,4]. The relatively low strength of some lightweight aggregates can increase the difficulty of producing concrete with high compressive strengths, but most aggregates are adequate to achieve the strength required for typical structural concrete, and high strength concrete can be produced with proper aggregate selection.

Self-consolidating concrete combines the properties of a low yield stress allowing for high deformability of the fresh concrete with a moderate to high viscosity and high resistance to segregation [9]. It can therefore fill formwork and achieve adequate compaction without the need for vibratory consolidation. Use of a superplasticizer allows for a low water-cementitious material ratio ($w/cm$), which when combined with a relatively high cementitious material content is one method of producing a high paste viscosity [2,5,10,11]. Adequate viscosity is required to keep the aggregate particles in suspension and reduce friction between aggregate particles, especially in narrow sections and around closely spaced obstacles [11]. Other powder materials, such as supplementary cementitious materials and fillers, can be added to enhance cohesiveness and stability [9,11]. The combination of Type III cement and fly ash has been used successfully for SCC mixtures [5,12]. A viscosity modifying admixture (VMA) can be utilized instead of a high powder content to increase the paste viscosity when a more moderate $w/cm$ is used [2,9,11]. These two methods, referred to as "powder-type" and "VMA-type" SCC, are the basic methods of proportioning SCC. Most SCC mixtures contain much less coarse aggregate than conventional mixtures, which reduces the energy absorption caused by interaction between the aggregate particles, and in turn reduces the tendency for blockage [2,10,11]. The maximum aggregate size is usually smaller than for conventional concrete [5,11,12].

Most previous research identifies many of the same important factors to consider in the development of an SCC mix proportion. These include aggregate volume, particle size distribution, ratio of sand to total aggregate volume ($s/a$), water-cementitious materials ratio ($w/cm$), total powder content, total water content, and admixture dosages [2,4,9–11,13]. Kaszynska documented successful use of LWSCC mixtures derived from normal weight SCC mixtures and replacement of the normal weight aggregate with equal volumes of lightweight aggregate [14]. Success has been documented using the absolute volume method with specific gravity factors to proportion LWSCC as well [4].

Recommendations from NCHRP Report 628 stated that SCC used for precast bridge girders should have a slump flow between 600 mm and 735 mm, J-Ring flow between 545 mm and 660 mm, and difference between slump flow and J-Ring flow of less than 75 mm [5]. A $w/cm$ of between 0.34 and 0.40 was recommended along with a $s/a$ between 0.46 and 0.50 and a maximum aggregate size of less than 12.5 mm [5]. Wall [3] provided general guidelines for lightweight SCC for bridge girders consisting of a slump flow between 560 mm and 660 mm, maximum $w/cm$ of 0.40, cement content between 415 kg/m$^3$ and 504 kg/m$^3$, 32% absolute volume of coarse aggregate, air content between 4.5% and 7.5%, a nominal maximum coarse aggregate size of 12.5 mm, and a compressive strength of 55 MPa. These bridge girder mixtures were reported to have a density 80 kg/m$^3$ to 160 kg/m$^3$ greater than typical lightweight concrete due to the increased cement content, lower $w/cm$, and reduced coarse aggregate content required for SCC [3,6]. Hubertova and Hela [7] recommended that the specification for LWSCC $T_{50}$ should be increased from the range of 2–5 s implied by ACI 237 [15] to account for the reduced kinetic energy resulting from the reduced density of the material. LWSCC with a $T_{50}$ of 7 s was successfully used by Dymond et al. [6].

This paper describes expanded clay and expanded shale aggregate LWSCC mixtures that were tested for use in a larger project concerning bond of 15.2 mm diameter prestressing strands cast in lightweight SCC with a targeted fresh density of 1920 kg/m$^3$. These two aggregates were chosen as representative of the aggregates typically used in the region where the study was conducted. Variations of the different ideas and recommendations from previous research described previously in this section were used to define the important variables and to produce the mix designs examined in this project. Targeted mixture properties were selected based on variations of the same previous research [3,5–7].

Mixtures with compressive strengths of 28 MPa and 41 MPa at one day of age ($f'_{ci}$) and corresponding compressive strengths of 41 MPa and 48 MPa at 28 days of age ($f'_c$) were the end goal for the project. Fresh concrete properties including slump flow of 610 mm to 760 mm, $T_{50}$ between 2 s and 7 s, difference between slump flow and J-Ring ($\Delta$) less than 75 mm, and visual stability index (VSI) of 1.0 or less were targeted as well. Effects of water-cementitious materials ratio ($w/cm$), cementitious materials type and content, and coarse aggregate type and content on both compressive strength and fresh concrete properties were examined. Elastic modulus was measured for selected mixtures and values were compared to the ACI [8] prediction equation. Prestress losses were measured out to an age of 28 days for a series of prestressed members cast with the same mixtures tested for elastic modulus and free shrinkage was measured out to an age of 16 weeks.

## 2. Materials and methods

Concrete mixtures were tested using two lightweight aggregates. These included expanded clay with a nominal maximum size of 12.5 mm manufactured in Louisiana and expanded shale with a nominal maximum size of 19 mm manufactured in Missouri. Specific gravity factors ($SG$) and absorption capacities ($AC$) were determined for each of the lightweight aggregates using the guidelines in the appendix of ACI 211.2, Standard Practice for Selecting Proportions for Structural Lightweight Concrete [16]. Specific gravity was determined using the pycnometer method on samples soaked in water for 24 h. The SG for the expanded clay was 1.25 and was 1.41 for the expanded shale. Aggregate absorption was determined using the centrifuge method described in ACI 211.2 [16], with measured values of 15.0% for the expanded clay and 9.3% for the expanded shale. Locally available river sand with a specific gravity of 2.60 and absorption capacity of 0.48% was used for each concrete mixture along with a polycarboxylate-based high range water reducer (HRWR). Cementitious materials included Type I and Type III cement, class C fly ash, and condensed silica fume (CSF).

The relatively short soaking times may not have produced a true representation of absorption, but subsequent aggregate preparation followed the specifications used to determine absorption capacity in order to provide a consistent comparison. The lightweight aggregates were immersed in water for a period of time between 12 and 24 h prior to concrete batching to ensure that the aggregates were sufficiently saturated to not absorb a substantial amount of the mixing water. The aggregate was then drained with the intention of removing as much free water as possible and producing repeatable moisture contents. Due to the high absorption of the lightweight coarse aggregate, the moisture content could not be determined overnight prior to concrete batching like that for conventional aggregates. An estimate of coarse aggregate moisture content was made based on the bulk density of the presoaked aggregate and experience. A sample was taken from the presoaked aggregate to determine the actual moisture content for later comparison to the estimate. As experience with the aggregates increased, it was possible to make a reasonable estimate, but never exact prediction, of the aggregate moisture content.

Three cementitious material contents were tested with expanded clay, and five cementitious material contents were examined for the expanded shale mixtures. Within the constraints of these cementitious material contents, $w/cm$, HRWR dosage, volumetric sand to total aggregate ratio ($s/a$), and supplementary cementitious material contents were varied. Mixtures were designated using a system consisting of a 1 or 3 for Type I and Type III cement, followed by C or S for clay or shale, then the cement content in kg/m$^3$, and the mix number for that combination. For example, mix 1C564-2 indicates variation 2 of an expanded clay mixture using Type I cement and 564 kg/m$^3$ of cementitious material. The initial expanded clay LWSCC mix design was based on work done previously at the University of Arkansas [17]. The LWSCC mixtures with higher cement contents were based on results obtained during testing of the first two series of mixtures and previous research concerned with development of high-strength normal weight SCC mixtures [18]. The expanded shale mixtures were chosen based on the results of testing the expanded clay mixtures. Since relatively high strengths were desired at one day and the lightweight aggregate was weaker than conventional aggregate, only the powder-type method of developing SCC was utilized.