ESCS

SPECIFIED DENSITY CONCRETE

A TRANSITION FOR THE CONCRETE INDUSTRY

SHELBY CREEK BRIDGE (Precast)
Courtesy of the Precast/Prestressed Concrete Institute

HIBERNIA OFFSHORE PLATFORM (Ready Mixed)
Newfoundland, Canada

Buoyancy was improved by replacing 50% of the heavy coarse aggregate in the Gravity Base Structure with lightweight aggregate. With a mass of 1 million tons, the structure was towed and placed 200 miles (315 Km) southeast of St. John's, Newfoundland.

SPECIFIED DENSITY CONCRETE — A TRANSITION

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SUMMARY

Applications of Specified Density Concrete (SDC) are increasing in the US, Canada and Europe. The use of SDC is driven by engineers' decisions to optimize concrete density to improve structural efficiency (the strength to density ratio), reduce transportation cost, and to enhance the hydration of high cementitious concrete mixtures with very low w/c ratios <.40. Specific projects include bridges, marine structures, precast elements and consumer products with strength ranging from 20-70 Mpa (2900-10150 psi) and densities from 1200 to 2200 kg/m^3 (75 to 138 lb/ft^3). SDC is achieved by customizing the mixture proportion by replacing part of the ordinary Normal Density Aggregates (NDA) (>.2600 kg/m^3, SG >2.60) with either coarse or fine Low Density Aggregates (LDA) (generally <1600 kg/m^3, SG <1.60).

Examples of optimizing the design by using SDC include more structurally efficient members in bridges and buildings, improved buoyancy in marine structures, and reduced transportation costs of consumer products like wallboard, imitation stone, precast element, masonry, etc. SDC is defined as concrete with a range of density less than what is generally associated with Normal Density Concrete (NDC) and greater than the lowest density possible when using all LDA. This paper will focus on the 1800-2200 kg/m^3 (112-137 lb/f^{t3}) density range.

The American Concrete Institute Standard Building Code (ACI 318) provides structural engineers with adequate guidance when designing with structural LDC over the strength range of 20-35 Mpa (2900-5080 psi). ACI 318 precisely defines the differing engineering properties of NDC and LDC including reduced elastic modulus, reduced tensile shear and torsion capacities, increased development length...etc. The increased use of SDC is creating an urgent need for comprehensive, industry wide investigations into the physical properties and engineering characteristics of concretes with strength/density combinations outside of traditional ranges. Future code revisions should include a seamless transition of engineering criteria for concrete properties of all practical achievable strengths with density ranges from 1200-2500 kg/m^3 (75-156 lb/ft^3).

STRUCTURAL EFFICIENCY

There is a paradigm shift taking place in the way engineers design and specify concrete characteristics for structural efficient projects. No longer content to use the suggested "off-the-shelf" concrete mixtures routinely proposed for conventional applications, engineers now require "optimized" concrete performance to satisfy specific needs. These "custom tailored" concretes, often referred to as SDC, have been developed through the combined efforts of design professionals, material suppliers and concrete producers.

The systematic improvement in concretes placed in North American over the past eighty years is shown schematically in Fig. 1. Most increases came as a result of improvements in the cementitious matrix brought about by a new generation of admixtures (e.g. high range water reducers) and the incorporation of high quality pozzolana (silica fume, metakaolin, fly ash...etc.). However, history indicates that the first modern improvement came as a result of the use of LDC in the US lightweight concrete ship building program between 1917 and 1925.

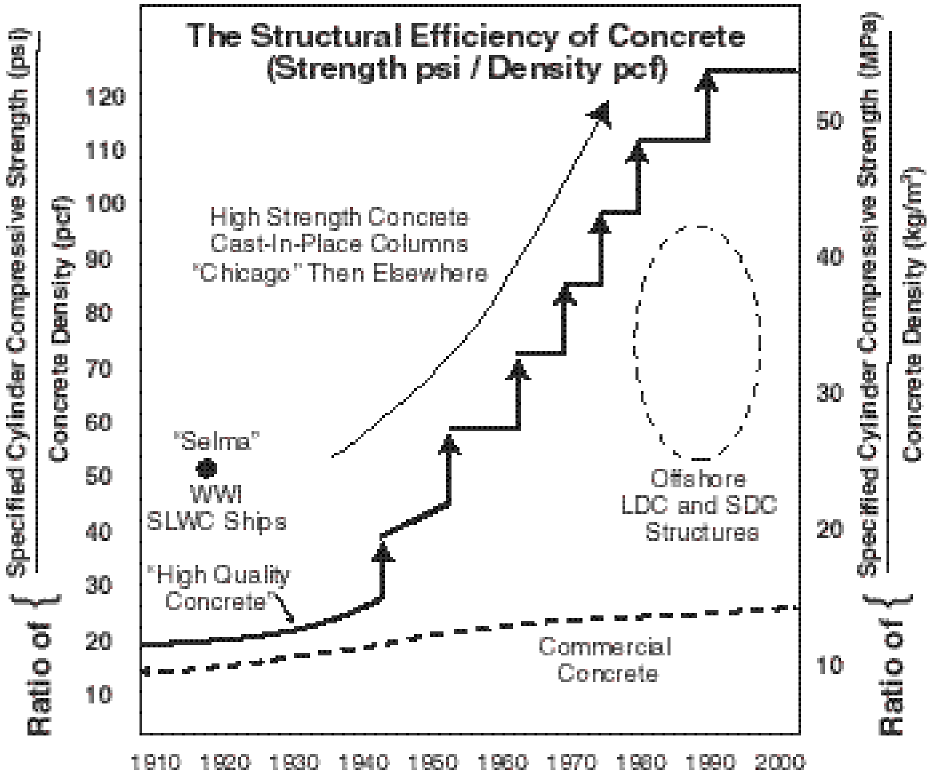


Figure 1. The Structural Efficiency of Concrete
The ratio of specified compressive strength to density (psi/lb ft^3)
through the recent history of construction.

MARINE STRUCTURES

Tarsiut Caisson Retained Island - 1981: The first arctic structure using SDC was the Tarsiut Caisson retained island built in Vancouver, Canada and barged to the Canadian Beaufort Sea. Four large prestressed concrete caissons 69 x 15 x 11 m high (226 x 50 x 35 ft) were constructed in a graving dock in Vancouver, towed around Alaska on a submersible barge, and founded on a berm of dredged sand 40 km (25 miles) from shore. The density of the SDC combined with the extremely high concentration of reinforcement was 2,240 kg/m^3 (140 lb/ft^3).

Heidron Floating Platform - 1996: Because of the deep water, 345m (1130 ft), above the Heidron oil fields, a decision was made to construct the first floating platform with High Strength Low Density Concrete (HSSDC). To improve buoyancy, the concept of HSSDC was introduced early in the planning stages. The hull of the floating platform, approximately 70,000 m^3 (91,000 yd^3) is constructed entirely of HSLDC with a maximum density of 2000 kg/m^3 (125 lb/ft^3). Heidron was built in Norway and towed to the North Sea.

Hibernia Oil Platform - 1998: Another significant application of SDC is in the Mobil Oil Hibernia offshore gravity based structure. To improve buoyancy of the largest floating structure built in North America, LDA replaced approximately 50% of the NDA (coarse fraction) in the high strength concrete (HSC) used. The resulting density was 2170 kg/m^3 (135 lb/ft$^{3)}$). Hibernia was built in Newfoundland, Canada, where the structure was floated out of dry dock and towed to a near by deep water harbor area where construction continued. When finished the more than one-million ton structure was towed to the Hibernia North Sea oil field site and set in place on the ocean floor. A comprehensive testing program was reported by Hoff et al. [1].

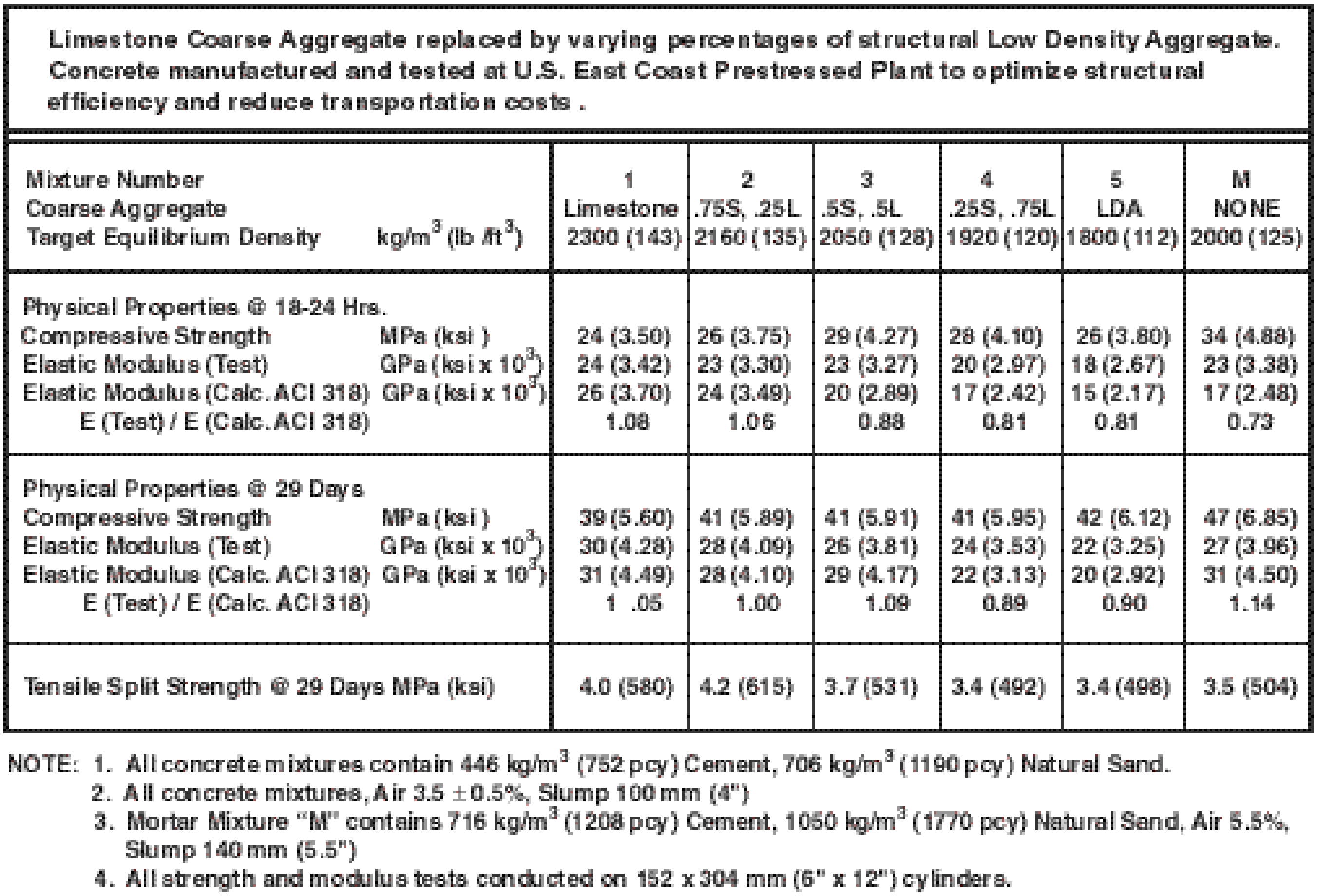
Bridges: Numerous bridges in North America and Europe have utilized SDC. Examples are the Shelby Creek Bridge, Kentucky, density 2080 kg/m^3 (130 lb/ft^3) [2] as well as numerous long span precast bulb tee bridge girders placed in Ohio and Indiana, 2000-2160 kg/m^3 (125-135 lb/ft^3). A series of major long-span Norwegian prestressed box-girder bridges [3,4], also incorporated HSLDC, for example, the entire bridge span (Boknasundet, 1990), the central part of long main spans (Raftsundet, 1998) and side spans that balanced NDC in main spans, (Sandhornia,1989). The Raftsundet Bridge, located north of the Arctic Circle in Norway, is of box girder construction utilizing HSLDC for 220M (721 ft) of the main span length of 298m (1023 ft). At the time of construction this bridge was the longest span bridge of this type in the world.

REDUCED TRANSPORTATION COST

The concept of specified density concrete is not new. Almost 20 years ago a precast manufacturer evaluated the trade-offs between the physical properties and the transportation costs. Mixes included a typically used limestone “control” concrete paralleled by other mixtures in which 25, 50, 75 and 100% of the ND limestone coarse aggregate was replaced by an equal absolute volume of an LDA. This resulted in 5,11, 15 and 21 percent reductions in density respectively. Results of the testing programs are shown in Table 1 and Fig. 2. Figure 3 demonstrates that for the particular LDA and limestone tested, these replacement levels had little effect on early or 28 day compressive strengths.

Because of weight limits on roads, this precast producer developed the lower density SDC mixtures that reduced the weights of members allowing an increased number of precast elements per truck. By adjusting the density of the concrete, precasters are able to maximize the number of concrete elements on a truck without exceeding highway load limits. This reduces the number of truck loads which lowers project cost. Opportunities for increased trucking efficiency are greater when transporting smaller concrete products (e.g. hollow core plank, wallboard, precast steps, imitation stone...etc.).

Table 1. Physical Properties of Concrete Mixtures



Limestone Coarse Aggregate replaced by varying percentages of structural Low Density Aggregate. Concrete manufactured and tested at U.S. East Coast Prestressed Plant to optimize structural efficiency and reduce transportation costs .

Mixture Number		1	2	3	4	5	M
Coarse Aggregate		Limestone	.75S, .25L	.5S, .5L	.25S, .75L	LDA	NONE
Target Equilibrium Density	kg/m^3 (lb /ft^3)	2300 (143)	2160 (135)	2050 (128)	1920 (120)	1800 (112)	2000 (125)
Physical Properties @ 18-24 Hrs.							
Compressive Strength	MPa (ksi)	24 (3.50)	26 (3.75)	29 (4.27)	28 (4.10)	26 (3.80)	34 (4.88)
Elastic Modulus (Test)	GPa (ksi x 10^3)	24 (3.42)	23 (3.30)	23 (3.27)	20 (2.97)	18 (2.67)	23 (3.38)
Elastic Modulus (Calc. ACI 318)	GPa (ksi x 10^3)	26 (3.70)	24 (3.49)	20 (2.89)	17 (2.42)	15 (2.17)	17 (2.48)
E (Test) / E (Calc. ACI 318)		1.08	1.06	0.88	0.81	0.81	0.73
Physical Properties @ 29 Days							
Compressive Strength	MPa (ksi)	39 (5.60)	41 (5.89)	41 (5.91)	41 (5.95)	42 (6.12)	47 (6.85)
Elastic Modulus (Test)	GPa (ksi x 10^3)	30 (4.28)	28 (4.09)	26 (3.81)	24 (3.53)	22 (3.25)	27 (3.96)
Elastic Modulus (Calc. ACI 318)	GPa (ksi x 10^3)	31 (4.49)	28 (4.10)	29 (4.17)	22 (3.13)	20 (2.92)	31 (4.50)
E (Test) / E (Calc. ACI 318)		1 .05	1.00	1.09	0.89	0.90	1.14
Tensile Split Strength @ 29 Days MPa (ksi)		4.0 (580)	4.2 (615)	3.7 (531)	3.4 (492)	3.4 (498)	3.5 (504)

NOTE:
1. All concrete mixtures contain 446 kg/m^3 (752 pcy) Cement, 706 kg/m^3 (1190 pcy) Natural Sand.
2. All concrete mixtures, Air 3.5 ±0.5%, Slump 100 mm (4")
3. Mortar Mixture "M" contains 716 kg/m^3 (1208 pcy) Cement, 1050 kg/m^3 (1770 pcy) Natural Sand, Air 5.5%, Slump 140 mm (5.5")
4. All strength and modulus tests conducted on 152 x 304 mm (6" x 12") cylinders.

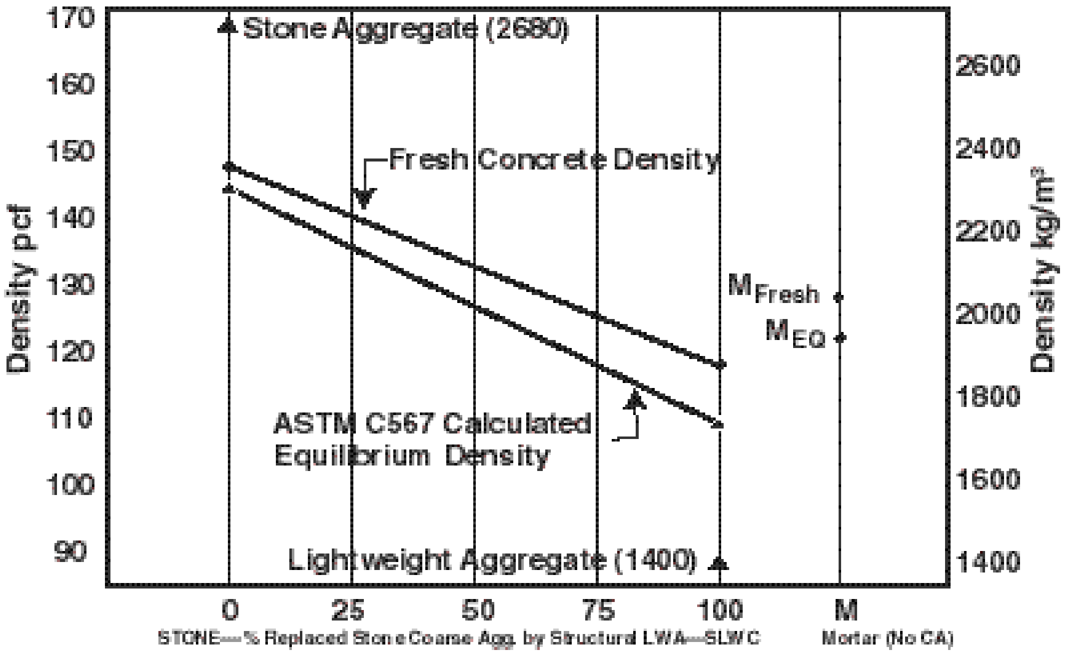


Figure 2. Fresh and ASTM C567 Calculated Equilibrium Concrete Density with varying replacement of limestone coarse aggregate with LDA

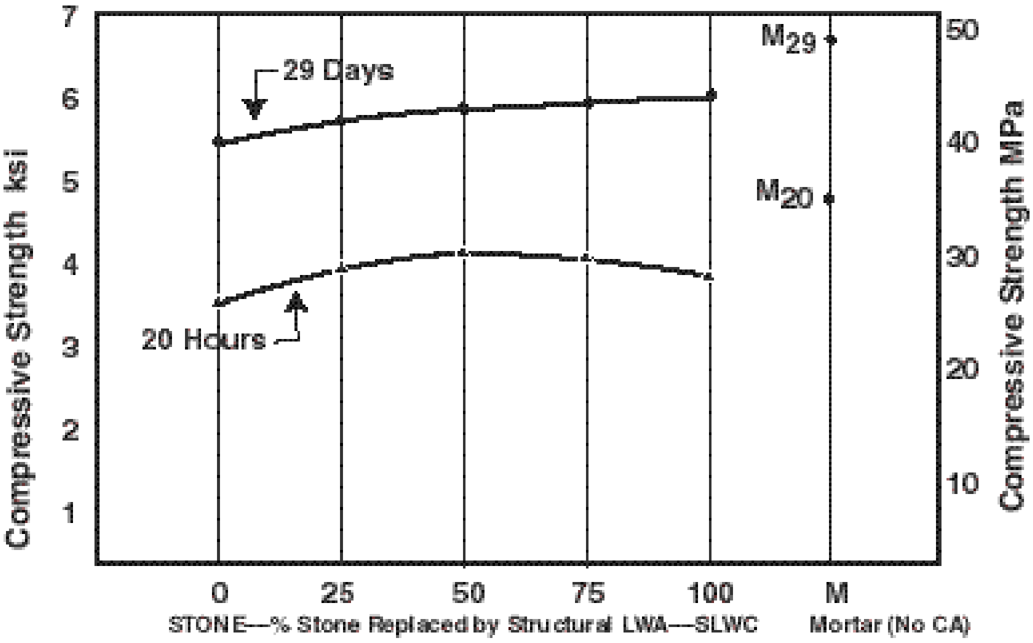


Figure 3. Compressive Strength 152Ø x 304 mm (6" x 12") Cylinders with varying replacements of Limestone Coarse Aggregate with LDA

Concretes containing LDA have lower modulus of elasticity at both early and later ages. Since exact modulus data at release (18 hrs. ±) is crucial to strand location, camber and deflection control, it is essential to determine the properties directly from the proposed concrete mixture. It is also important to realize that even with NDA's at the same density, the modulus of elasticity can vary considerably. Table 1 reveals that for the "control" limestone NDC, the tested elastic modulus correlated with the computed value using the ACI 318 formula $Ec=33w^{1.5}\sqrt{Fc}$. For LDC at earlier ages and with compressive strengths over 35 MPa (5080 psi), the ACI formula clearly over estimates the value of the elastic modulus.

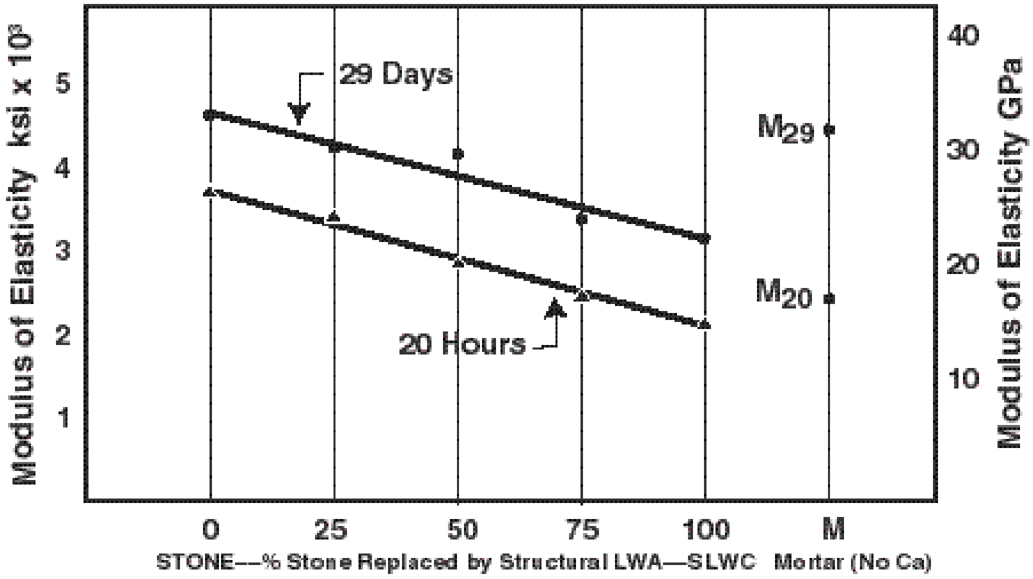
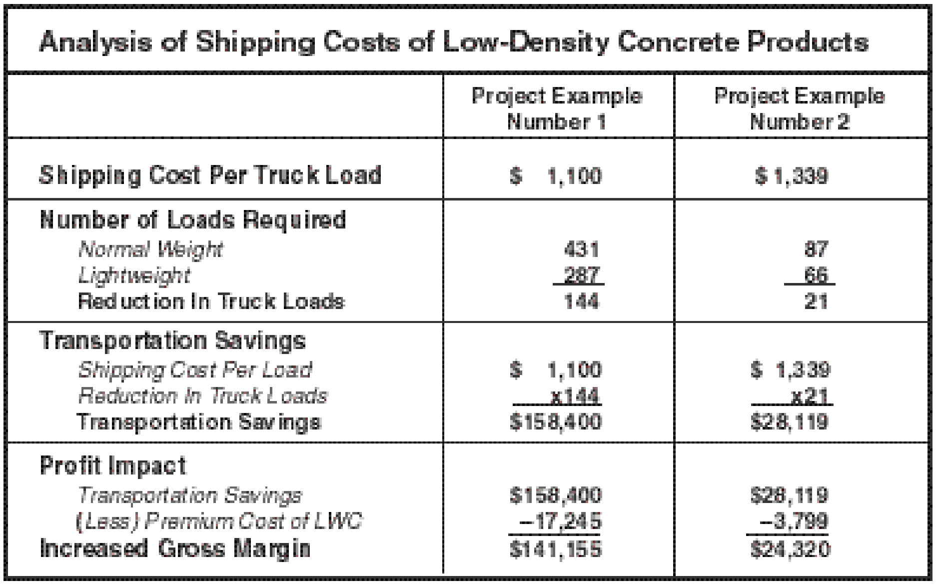


Figure 4. Modulus of Elasticity 152 x 304 mm (6" x 12") Cylinders with varying replacements of limestone NDA with LDA

Two trucking studies conducted at a U.S. precast plant are shown in Table 2. These studies demonstrated that the transportation cost savings were seven times more than the additional cost of LDA. Savings vary with the size and weight of the product and are most significant for the smaller consumer type products. For example, one manufacturer of wallboard has shipped product to all 48 mainland US states from one manufacturing facility. Reductions in shipping costs are possible when shipping by rail or barge, but are most often realized in trucking where highway loads limits are posted.

Table 2.



Analysis of Shipping Costs of Low-Density Concrete Products

	Project Example Number 1	Project Example Number 2
Shipping Cost Per Truck Load	$ 1,100	$ 1,339
Number of Loads Required		
Normal Weight	431	87
Lightweight	287	66
Reduction In Truck Loads	144	21
Transportation Savings		
Shipping Cost Per Load	$ 1,100	$ 1,339
Reduction In Truck Loads	x144	x21
Transportation Savings	$158,400	$28,119
Profit Impact		
Transportation Savings	$158,400	$28,119
(Less) Premium Cost of LWC	−17,245	−3,799
Increased Gross Margin	$141,155	$24,320

Courtesy of Big River Industries, Inc.

ENHANCED HYDRATION DUE TO INTERNAL CURING

LDA containing high internal moisture contents may be substituted for NDA to provide “internal curing” in concrete containing a high volume of cementitious materials. High cementitious concretes are vulnerable to self-desiccation and benefit significantly from the added internal moisture. This application is significantly helpful for vertical members and concretes containing high volumes of silica fume that are sensitive to curing procedures. In this application, density reduction is a by-product.

Time dependent improvement in the quality of concrete containing LDA is greater than that with NDA. The reason is better hydration of the cementitious fraction provided by moisture available from the slowly released reservoir of water absorbed within the pores of the lightweight aggregate. This process of “internal curing” is made possible when the moisture content of LDA aggregate, at the time of mixing is in excess of that achieved in a one day soak. The fact that absorbed moisture in LDA batched with a high degree of saturation (percent of internal pore volume occupied by water) was available for internal curing has been known for several decades, and first documented in 1967 by R. Campbell and Bob Tobin [5]. Their comprehensive program compared strengths of cores taken from field cured exposed slabs with test results obtained from laboratory specimens cured strictly in accordance with ASTM procedures. Their tests confirmed that availability of absorbed moisture in LDA produced a more forgiving concrete that was less sensitive to poor field curing conditions.

In a series of papers addressing long term service performance of LDC, Holm and Bremner [6, 7, 8, 9] repeatedly cited the improved integrity of the LDA/matrix interface, attributing the improved quality to internal curing, pozzolanic activity at the contact zone, and reduction in stress concentrations resulting from elastic compatibility of the concrete phases.

It appears that Philleo [10] in 1991 was the first to recognize the potential benefits to high performance NDC possible with the addition of LDA containing high volumes of absorbed moisture. Weber and Reinhardt [11] have also conclusively demonstrated reduced sensitivity to poor curing conditions in HSNDC containing an adequate volume of high moisture content LDA.

The benefits of "internal curing" are increasingly important when pozzolans (silica fume, fly ash, metokaolin, calcined shales, clays and the fines of LDA) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is contingent upon the availability of moisture. Additionally, "internal curing" provided by absorbed water minimizes the "plastic" (early) shrinkage due to rapid drying of concretes exposed to unfavorable drying conditions.

The benefits of "internal curing" go far beyond the improvements in long-term strength gain. In the opinion of the authors, the principal contribution of "internal curing" rests in the reduction of permeability that develops from a significant extension in the time of curing. Powers [12] showed that extending time of curing increased the volume of cementitious products formed which caused the capillaries to become segmented and discontinuous.

One interesting demonstration of the practicality of providing internal curing with LDA was in the construction of secondary containment slab-on-grade. In this application, high performance, low permeability concrete containing high moisture content LDA and high volumes of silica fume were used successfully. The containment slabs were under steel storage tanks that contained hazardous waste fuels at production plants in the US. To lower concrete permeability to values acceptable to the permitting authorities, high volume additions of silica fume were essential. To minimize sensitivity to curing for concretes placed in hot weather, special precautions were taken to provide Low Density Coarse Aggregate (LDCA) with a relatively high degree of saturation. Despite high ambient temperatures, concrete construction proceeded without incident. No visible surface cracking has been observed after several years of exposure. This concrete provides an industrial grade barrier that resists deterioration due to freezing and thawing, chemical attack, and ultraviolet rays that attack troweled- on thin mortar alternatives. These secondary containment slabs can stand up to forklift traffic, movement of pallets and heavy duty commercial exposure, and require minimum maintenance while meeting environmental containment standards.

Internal curing is typically provided by LDCA in high performance concrete applications. However, Low Density Fine Aggregate (LDFA) is more effective in distributing available moisture for internal curing. As Bentz [13) has pointed out, a much more efficient spatial distribution could be accomplished by partial replacement of the sand fraction with LDFA.

MAXIMUM STRENGTH CEILING

Concrete mixtures have a “strength ceiling” where there is a very little increase in compressive or tensile strength, despite improvements in binder quality or increasing cementitious content. When concrete (LDC or NDC) reach this ceiling, the strength of the coarse aggregate particle or the quality of the interfacial contact zone will determine the limiting strength. After reaching the strength ceiling, a very strong NDC will demonstrate a small positive slope of the strength/binder relationship. In contrast, the slope will be somewhat less with LDC. In concretes containing highly expanded LDA there will be a flat line with essentially no further increase in strength. Beyond the strength ceiling increasing binder content is ineffective for LDC and NDC. In some areas it is not unusual to observe an overlap in the envelope of strength/binder relationships when concretes containing a strong LDA are compared to concretes containing a moderately strong NDA.

The strength/cementitious content curves of LDC using different LDA will have differing shapes and maximums. These differences are due to the structural strength of the different vitreous ceramic LDA’s and the characteristics of the pore system developed during the expansion process. The producers goal is to manufacture a high-quality, structural grade LDA which has a system of well distributed pores of moderate size (5-300m) surrounded by a strong, relatively crack-free vitreous ceramic matrix. The size, shape, volume and distribution of the vesicular pores will determine the LDA particle strength (compressive and tensile). In general, greater pore volume will correlate with lower strength potential, however there are exceptions and each material needs to be individually investigated.

POST-ELASTIC STRAIN CAPACITY

Because the interfacial bond between the LDA and the surrounding matrix is greater than the LDA particle strength, the failure plane will pass through both LDA and matrix. In contrast, the tensile strength of a strong NDA particle exceeds the matrix tensile strength, and consequently the failure surface generally will pass around the NDA. The failure plane in NDC is usually through the contact zone (NDA/matrix interface) which is often weakened by the accumulation of bleed water.

With LDC at common strength levels 20-35 Mpa (2900-5080 psi) the similar tensile strength and elastic rigidity of the two components (LDA and matrix) will minimize stress concentrations and micro-cracking. This contrasts with extremely high strength NDC containing a very strong NDA, where the aggregates remain intact after the matrix fails and provide a measure of additional post-elastic strain capacity and a greater resistance to splitting. Because of the lower splitting strength and reduced post-elastic strain capacity of LDC it appears prudent to limit the coefficients for which the ACI 318 requirements modify the NDC for shear, tension, torsion, development length and seismic design criteria to 35 Mpa (5080 psi) for concretes containing LDA. Significantly higher compressive strength LDC’s and SDC’s have been specified, approved and successfully used on several major projects after a comprehensive testing program conducted on a specific mixtures demonstrated that higher values were achievable. As pointed out by Rabbat, et al. [14] the seismic behavior of LDC will be similar to that of NDC for strengths up to 6.0 ksi provided careful attention is given to the amount, placement and detailing of confining steel reinforcement.

RECOMMENDATIONS

- Recognizing the fact that concrete is heavy, and because construction generally involves transportation, design professionals may consider SDC to improve structural efficiency and lower transportation costs.
- To assure an adequate curing regime that improves internal integrity and performance, designers may consider the addition of LDA containing high moisture content to NDC to enhance hydration through internal curing.
- There is now an urgent need for comprehensive, industry wide investigations into the physical and engineering properties of structural concretes with strength/density combinations outside of traditional ranges.
- Future code revisions should develop a seamless transition of criteria for engineering properties for concretes of all practical combinations of achievable strengths with density ranges from 1200-2500 kg/m^3 (75-156 lb/ft^3)

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