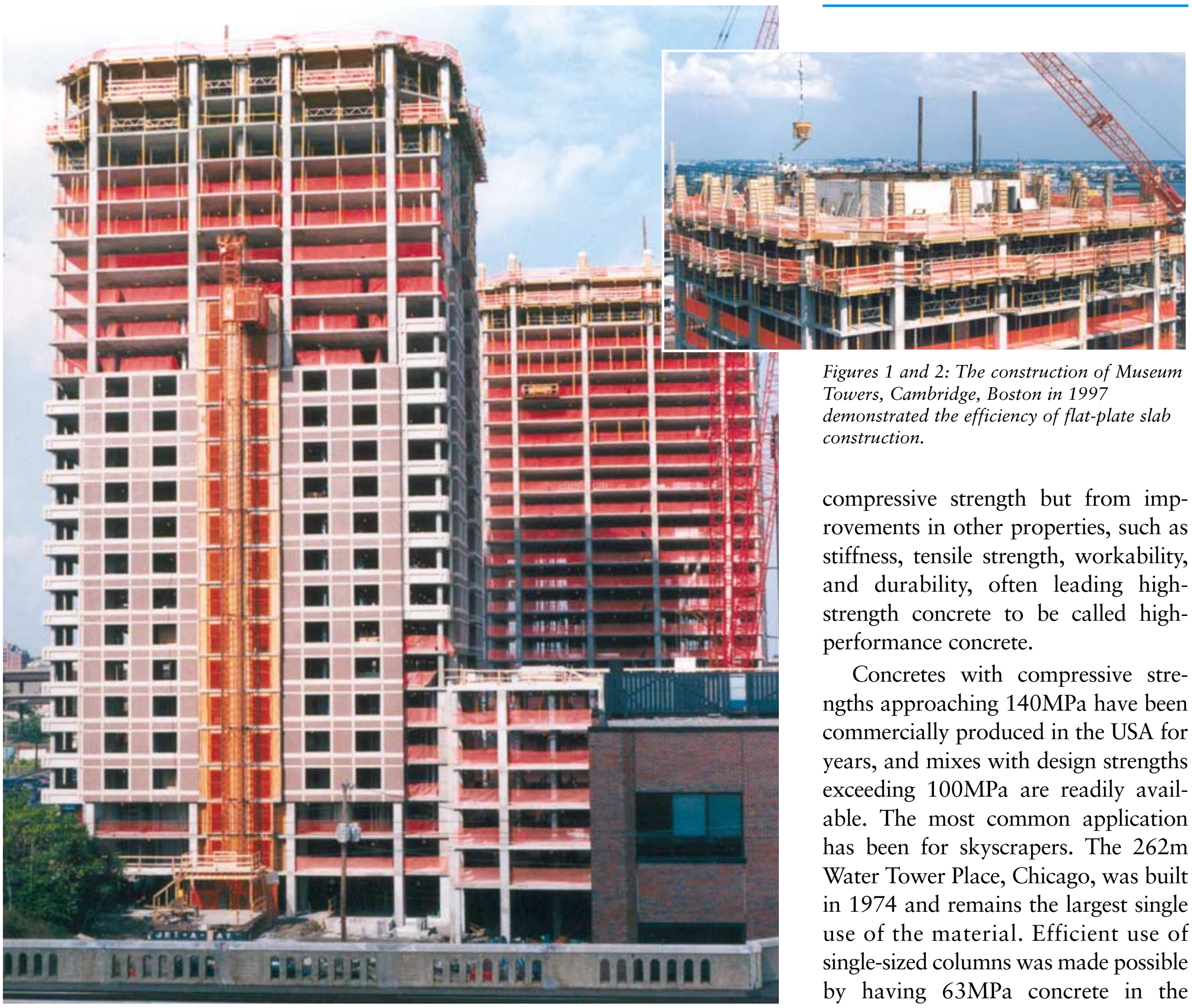

Figures 1 and 2: The construction of Museum Towers, Cambridge, Boston in 1997 demonstrated the efficiency of flat-plate slab construction.

Removing barriers to high-strength concrete in Boston

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Introduction

The American Concrete Institute defines high-strength concrete as having compressive strength of 42MPa, but higher strengths are routinely attained for specific projects. In the Boston, Massachusetts region, the definition of high-strength concrete is 55MPa, as that has been regularly specified during construction of the Central Artery/Tunnel Project. This is the largest, most complex highway project in American history and consists of 161 lane miles of urban highway, of which almost half is below ground in a 7.5 mile corridor. Concrete of 55MPa has also been used on three metropolitan Boston building projects.

High-strength concrete has mainly been used for offshore oil platforms, high-rise buildings, and bridges. Other uses have included warehouses, parking garages, bridge deck overlays, dam spillways, bank vaults, and heavy-duty industrial floors. These applications benefit not only from the higher compressive strength but from improvements in other properties, such as stiffness, tensile strength, workability, and durability, often leading high-strength concrete to be called high-performance concrete.

Concretes with compressive strengths approaching 140MPa have been commercially produced in the USA for years, and mixes with design strengths exceeding 100MPa are readily available. The most common application has been for skyscrapers. The 262m Water Tower Place, Chicago, was built in 1974 and remains the largest single use of the material. Efficient use of single-sized columns was made possible by having 63MPa concrete in the lower columns and reducing the strength further up the building, allowing the columns to have the same cross-sectional dimensions at the base and at the top. In Two Union Square, Seattle, built in 1988, 130MPa concrete in columns was used to transfer loads by reduced-size sections and to increase stiffness to reduce sway.

Despite the many advantages to be derived from the use of high-strength concrete and the extent to which it has been adopted throughout the USA, concrete with a minimum strength of 55MPa has still not been widely specified in the Boston area. Experience from one region of the country cannot be directly transferred to another; the raw materials for producing the concrete must be local, and the concrete contractors and quality control/quality assurance personnel need the relevant practical experience. Five requirements need to be simultaneously satisfied for higher strengths to be used:

- Ready-mixed concrete suppliers must be able to deliver the concrete consistently
- Concrete contractors must be familiar with placing the material
- Quality assurance and quality control facilities must be able to analyse it
- Engineers must be aware of the special provisions for use of high-strength concrete
- The owner/developer must have confidence in each sector of the team.

The Boston situation

In Boston, during the past 20 years, steel-frame structures have been favoured over reinforced concrete, leading to stagnation of concrete technological progress in the region. Recently, height restrictions on buildings near the waterfront and the requirement for more floor space to make construction projects economically feasible have made flat-plate floor slabs the building system of choice. In 1997, the completion of Museum Towers in Cambridge, across the Charles River from downtown Boston, demonstrated the efficiency of the flat-plate floor slab system and led the way for further developments (see Figures 1 and 2). In the Boston area, three notable recent projects have used 55MPa concrete in their columns: 75 Sidney Street, Cambridge; 165 Tremont Street, Boston; and the 125m-high Millennium Project in Boston.

To increase specification of concrete in the area above 55MPa, the Reinforced Concrete Construction Committee (RC^3), a local organisation of contractors, producers, engineers, developers and contractors dedicated to the promotion of the use of quality concrete use, challenged three metropolitan Boston ready-mixed concrete suppliers. Their task was to deliver concrete with specified strengths of 70 and 85MPa concrete to a remote site. The concrete was to remain in the truck for at least an hour and have a minimum slump of 200mm at discharge.

The remote site was a concrete testing laboratory, licensed by the Commonwealth of Massachusetts. Field and laboratory personnel holding a Massachusetts Field Class A licence performed tests on the fresh concrete, including slump, air content, and temperature.

Ready-mixed concrete supplier	**RM-1**		**RM-2**		**RM-3**	
Specified strength, f_c (MPa)	70	85	70	85	70	85
Cement (kg/m^3)	445	445	415	561	393	457
Class F pfa (kg/m^3)	101	89	–	–	–	–
Ggbs (kg/m^3)	–	–	208	–	263	196
Fine aggregate (kg/m^3)	748	754	558	564	653	659
Coarse aggregate (kg/m^3)	1009	1009	1068	1068	1133	1139
Added water (kg/m^3)	101	115	121	101	90	95
Calcium nitrite (litres/m^3)	20	20	15	–	15	–
Silica fume (litres/m^3)	–	–	–	74	–	–
Superplasticiser (litres/m^3)	2.9	2.4	2.0	2.0	4.3	4.3
Mid-range water reducer (litres/m^3)	2.1	–	–	–	–	–
Water reducer/retarder (litres/m^3)	0.7	1.0	1.7	1.6	–	1.3

Table 1: Mix designs.

Cylindrical test specimens were cast, cured, and tested for compressive strength at 7, 14, 28, and 56 days.

The results

The mix designs used by the three ready-mixed concrete suppliers are given in Table 1. The cements used were equivalent to ASTM Type II, with the exceptions of the 85MPa mixes for RM-1 and RM-3 which were cements with interground silica fume. RM-2 used a slurry-based silica fume (70% water by volume). RM-1 and RM-2 each used Ossipee sand while RM-3 used Heffron sand. All producers used Lynn stone for the coarse aggregate, RM-1 using 9.5mm nominal maximum aggregate size, with RM-2 and RM-3 using 12.5mm coarse aggregates. Calcium nitrite, a corrosion-inhibiting admixture that also increases concrete compressive strengths, was used in some mixes. All mixes contained a superplasticiser (ASTM C494 Type F) and most included a water-reducer/retarder (ASTM C494 Type D). One also used a mid-range water-reducer (ASTM C494 Type A).

For testing, 100 × 200mm cylinders were adopted instead of standard 150 × 300mm cylinders, which would require a testing machine with a capacity of 2200kN. The normally available 1100kN machines have the capacity to test 130MPa concrete in 100mm diameter cylinders. Table 2 provides the results from the test programme. In addition to the specified compressive strength, (f_c), the required compressive strength, (f_{cr}), is also given. For concrete with f_c greater than 35MPa, ACI 318 requires that $f_c = 1.10f_c + 5$MPa when data is not available to establish a standard deviation. Although the results are less than ideal, they demonstrate the capability of producing 70 and 85MPa concrete using readily available materials under field conditions.

The future

Further trials will be carried out to establish the exact mix designs that will provide acceptable strength levels without over-design. This demonstration project has indicated that, in the Boston region, 85MPa concrete can be delivered by ready-mixed concrete suppliers and be properly tested, removing two main impediments to the specification of the material. The next step will be to pour mock columns during the construction of a building to provide the necessary experience for contractors in handling and curing high-strength concrete. Cores taken from the columns should persuade the engineers and owners/developers that the in-situ strength is satisfactory. ■

Ready-mixed concrete supplier	**RM-1**		**RM-2**		**RM-3**	
Specified strength, f_c (MPa)	70	85	70	85	70	85
Required strength, f_c (MPa)	82	98.5	82	98.5	82	98.5
Age at sampling (hr:min)	1:23	1:33	1:00	1:08	1:21	1:09
Slump (mm)	265	215	195	200	200	255
Air content (%)	2.1	3.0	1.9	1.8	2.0	1.8
Concrete temperature (°C)	18	17	16	15	28	13
Density (kg/m^3)	2370	2420	2470	2440	2420	2450
Compressive strength (MPa)						
7 days	63.6	61.4	71.9	68.6	75.4	84.1
14 days	71.6	78.0	99.8	87.1	92.6	103.9
28 days	93.4	89.0	106.5	93.6	93.1	111.8
56 days	101.1	96.5	124.6	98.2	95.7	116.7

Table 2: Test results.