TABLE 11 New Benicia-Martinez Bridge Lightweight Concrete Compressive Strength and Modulus of Elasticity Test Results [12]

Test	Age (Days)	Specimen Number 1	2	3	Average
Compressive Strength, psi	3	3,980	4,040	3,970	4,000
Modulus of Elasticity, ksi	3	---	3,000	3,000	3,000
Compressive Strength, psi	28	8,760	8,320	8,030	8,370
Modulus of Elasticity, ksi	28	---	3,940	3,760	3,850
Compressive Strength, psi	91	9,550	9,460	8,380	9,130
Modulus of Elasticity, ksi	91	---	3,910	3,900	3,910

Notes:
Specimens tested at an age of three days were cured in molds prior to test.
Specimens tested at an age of 28 and 91 days were cured in molds for three days, moist cured until an age of 14 days, and then air cured until test.

TABLE 12 New Benicia-Martinez Bridge Lightweight Concrete ASTM 512 Creep and Shrinkage Test [12]

Load Applied and Drying Started at an Age of Three Days

Days Loaded	Drying Shrinkage (millionths)	Load Induced Deformation* (millionths)	Specific Creep (µstrain/psi)	Creep Coefficient	Condition
0	0	619	0.00	0.00	Instantaneous Strain
1	30	909	0.18	0.47	Additional Strain Due to Creep
2	58	1011	0.24	0.63	" " " " "
3	63	1082	0.29	0.75	" " " " "
4	61	1108	0.31	0.79	" " " " "
5	80	1181	0.35	0.91	" " " " "
6	98	1229	0.38	0.99	" " " " "
7	142	1286	0.42	1.08	" " " " "
14	199	1402	0.49	1.26	" " " " "
21	257	1454	0.52	1.35	" " " " "
28	262	1481	0.54	1.39	" " " " "
59	302	1566	0.59	1.53	" " " " "
90	333	1600	0.61	1.58	" " " " "

Notes:

*Adjusted for drying shrinkage
Test specimens were 6" x 12" cylinders

Applied stress during creep test:	1,600 psi
Compressive strength at time of loading:	4,000 psi (ASTM C 39)
Modulus of elasticity at time of loading:	3,000 ksi (ASTM C 469)
Age at Loading:	Three days
Preload environment:	in molds
Loaded environment:	50% ± 4 relative humidity

TABLE 13 New Benicia-Martinez Bridge Lightweight Concrete ASTM 512 Creep and Shrinkage Test [12]

Load Applied at 28 Days, Drying Started at an Age of 14 Days

Days Loaded	Drying Shrinkage (millionths)	Load Induced Deformation* (millionths)	Specific Creep (μstrain/psi)	Creep Coefficient	Condition
0	0	643	0.00	0.00	Instantaneous Strain
1	0	787	0.06	0.22	Additional Strain Due to Creep
2	4	829	0.07	0.29	" " " " "
3	16	865	0.09	0.35	" " " " "
4	23	887	0.10	0.38	" " " " "
5	25	903	0.10	0.40	" " " " "
6	28	918	0.11	0.43	" " " " "
7	37	954	0.12	0.49	" " " " "
14	75	1027	0.15	0.60	" " " " "
21	97	1099	0.18	0.71	" " " " "
28	105	1108	0.19	0.73	" " " " "
59	173	1262	0.25	0.96	" " " " "
90	174	1258	0.25	0.96	" " " " "

Notes:

*Adjusted for drying shrinkage
Test specimens were 6" x 12" cylinders

Applied stress during creep test:	2,500 psi
Compressive strength at time of loading:	8,370 psi (ASTM C 39)
Modulus of elasticity at time of loading:	3,850 ksi (ASTM C 469)
Age at Loading:	28 days
Preload environment:	14 days moist, 14 days air dry
Loaded environment:	50% ± 4 relative humidity

TABLE 14 New Benicia-Martinez Bridge Lightweight Concrete ASTM 512 Creep and Shrinkage Test [12]

Load Applied at 91 Days, Drying Started at an Age of 14 Days

Days Loaded	Drying Shrinkage (millionths)	Load Induced Deformation* (millionths)	Specific Creep (μstrain/psi)	Creep Coefficient	Condition
0	0	673	0.00	0.00	Instantaneous Strain
1	38	753	0.03	0.12	Additional Strain Due to Creep
2	35	783	0.04	0.16	" " " " "
3	39	794	0.05	0.18	" " " " "
4	33	809	0.05	0.20	" " " " "
5	30	837	0.07	0.24	" " " " "
6	34	843	0.07	0.25	" " " " "
7	33	847	0.07	0.26	" " " " "
14	35	886	0.09	0.32	" " " " "
21	19	890	0.09	0.32	" " " " "
28	28	911	0.10	0.35	" " " " "
59	104	1065	0.16	0.58	" " " " "
90	114	1117	0.18	0.66	" " " " "

Notes:

*Adjusted for drying shrinkage
Test specimens were 6" x 12" cylinders

Applied stress during creep test:	2,500 psi
Compressive strength at time of loading:	9,130 psi (ASTM C 39)
Modulus of elasticity at time of loading:	3,910 ksi (ASTM C 469)
Age at Loading:	91 days
Preload environment:	14 days moist, 77 days air dry
Loaded environment:	50% $\pm$ 4 relative humidity

Design, Development and Use of the Concrete for the Superstructure of the Viaduct Section of the Docklands Light Railway Extension, London

by J.M. Best, S.R. Maynard, and E.A. Kay

Synopsis: Design and construction of elements of Docklands Light Railway City Airport Extension in London are described. The scheme is 4.4km long and consists of sections at-grade, on embankment, on viaduct and in trough cuttings. Durability design was carried out to the new European Standard EN 206 and its British application document BS 8500. The paper concentrates on the concrete for the segments of the viaduct. A particular aspect of segment production was the need to meet high early strengths under winter working conditions in order to achieve 24 hour mould turn round and to meet the project schedule. In-situ strength for striking and lifting purposes was established by using the results of pull-out tests calibrated against cubes cured under the same conditions as the segments.

Keywords: concrete; durability; precasting; railways; testing

James Best has been a Senior Engineer with Halcrow Group Ltd for 3-years. He has involvement on the Docklands Light Rail City Airport Extension scheme as the Viaduct Design Team Leader, responsible for the design of the viaduct substructures and superstructure.

Simon Maynard has been a Materials and Geotechnical Engineer with AMEC Construction Services for five years. He has been involved with development of the structural mixes for the Dockland's Light Railway Extension scheme and continues to provide technical assistance to site, during the construction phase of the project.

Ted Kay is an Advisory Engineer with the Concrete Society and was until recently a Principal Engineer in Halcrow's Construction Materials Section. He has over a quarter of a century's experience of specifying concrete for durability in some of the harshest environments on the planet including six years in residence in the Middle East. He has worked on a large variety of projects including bridges, airports, marine works, coastal protection and wastewater treatment.

INTRODUCTION

The Docklands Light Railway (DLR) City Airport Extension project extends an existing light rail network from Canning Town to London City Airport in the heart of London's Dockland area. This provides an essential connection between the airport and the London Underground and national railway networks. The overall length of the scheme is 4.4 km and consists of at-grade rail, embankments, 2.8 km of elevated viaduct and trough cuttings. The viaduct consists of precast, externally post-tensioned concrete segments arranged in simply-supported spans.

This paper describes the project in general and concentrates mainly on the design, development and use of the concrete for the superstructure of the viaduct section of the route.

DESCRIPTION OF SCHEME

Parties Involved

The project was commissioned by Docklands Light Railway as a Design, Build, Finance and Maintain project. The scheme was released for tender in 2001, and awarded to the concessionaire City Airport Rail Enterprises (CARE) in February 2003. The Design and Build Contract element of the scheme was let to AMEC for a fixed price of £140M ($255M).

Details of the parties involved are as follows:

Concessionaire	CARE comprising AMEC Group Ltd and Royal Bank of Scotland
Design and Build Contractor	AMEC Group Ltd
Detailed designer for AMEC including civil, structural and systems design	Halcrow Group Ltd

Objective

The objective of the construction of DLR City Airport Extension scheme is to extend the existing light rail network to London City Airport and so provide an essential connection between the airport and the London Underground and national railway networks and to provide for further extension to Woolwich Arsenal.

The scheme includes 3 intermediate stations which, it is hoped, will promote development and attract business to the south of the Royal Docks by improving access to the centre of London from this location. This area is currently experiencing extensive redevelopment including both industrial and residential elements.

Scheme Route

The scheme is situated in the docklands area of East London, and runs to the north of the River Thames as shown in Figure 1. It consists of 0.30km (990 ft) of at grade railway, 0.26km (855 ft) of railway on embankment, 2.93km (1.82 miles) of elevated viaduct and 0.87km (2855 ft) of railway in sub-surface U-trough structure.

The western end of the scheme connects into the existing DLR Becton Line at Canning Town station. The line then runs at-grade through an existing underpass under the Lower Lea approach structure, and then rises on earth embankment to the Thames Wharf Structure. The elevated route continues south of the North Woolwich Road and follows, in part, the alignment of the Silverlink Tramway, which was decommissioned in the mid-1960's. Planned proposals for a third Blackwall Crossing, either as a tunnel or an overbridge constrain the alignment of the viaduct around the west abutment. Other constraints include industrial units, the North Woolwich Roundabout, an existing railway line, road accesses and provisions for car parking. The alignment remains elevated at London City Airport station, then dips down to the a subsurface U-trough structure south of the King George V Dock, and the scope of the concession agreement terminates at King George V station, which is incorporated in the trough structure.

The feature station at London City Airport is an elevated structure that permits integration between the DLR line, London City Airport and local buses and taxis. Two further elevated stations at West Silvertown and Pontoon Dock provide passenger access from the viaduct to residential and industrial developments along the route.

Trains and Track

The extension will operate the same trains as those running on the existing DLR network. These consist of two-car articulated coaches, giving a total train length of 58m (190 ft) with provision for three-car vehicles. The trains are automatic and so are controlled and monitored through induction loops on the track. They are electrified and are powered via a third rail mounted on the trackslab. Trains operate on two tracks; a down-line and an up-line. The rails are continuous welded track with rail expansion joints at special structures.

THE VIADUCT

The viaduct consists of three structural types; simply supported segmental spans, three balanced cantilever structures and precast prestressed-beam composite concrete deck.

Segment Geometry

The precast segments have a constant width of 10.03m (33 ft) which was determined to meet UK Government standards (1) for safe clearances. The width allows for two trains, two maintenance walkways and for the cant and throw effects, as shown in Figure 2 The segment depth was developed to give an efficient prestressed section whilst maintaining the permitted headroom to access roads under the viaduct. The segment length was developed to suit the span modules and was set at 3.1m (10.2 ft). This gave typical segment weights for standard segments, deviator segments and end diaphragm segments of 36, 41 and 52-tons respectively.

The segments were match cast to include variations in plan and elevation alignment, but did not have an applied super-elevation. Train cants were introduced through trackslabs cast insitu on the completed spans.

Standard Simply Supported Spans

Just under 2km (1.25 miles) of the project is made up of simply supported spans using precast concrete segments with external prestressing tendons. The spans are typically 37m (121.4 ft) long, but vary to suit access roads and other alignment constraints. The variation in span length was accommodated by altering the number of segments in a span rather than the segment length. The number and type of segments used per span are given in Table **1**.

The simply supported spans were stressed using 6 tendons with varying strand numbers depending on the span length. The strand consisted of 15mm diameter 7-wire super strand complying with ASTM A 416-85, and was run in PTFE plastic ducting. The anchorages were cast into the end units, and were stressed from one end. Following stressing the strands were cropped, the anchorages capped, and the tendons grouted.

Station Extensions

At two locations along the route, West Silvertown and Pontoon Dock, the standard viaduct units were modified to accommodate in-line stations. The segment cantilevers were elongated and propped, as shown in Figure 3. The platforms were formed by precast units that were tied to the segments by an insitu stitch. The platforms are partially covered with glazing, and are accessed via external lift and stair towers.

Due to the increased load the station span lengths had reduced span lengths, typically 27.7m (91 ft), and used the same segment types but with modified cantilever extensions. Additional modifications were required to the reinforcement to accommodate the station prop.

Balanced Cantilever Structures

Balanced cantilever structures were used to span obstructions which were beyond the range of the simply supported spans. This occured in three locations; Blackwall Crossing, Pontoon Dock and Connaught Crossing.

The planned proposal for a third Blackwall Crossing, either as a tunnel or an overbridge meant that the viaduct must span an exclusion zone set-aside for the third crossing. This resulted in a three-span balanced cantilever with span lengths of 46.6, 57.4 and 46.5m (153,188 and 153 ft). The Pontoon Dock balanced cantilever structure was required to span landscaped gardens in the Green Dock and a car-parking area, resulting in a four-span structure with span lengths of 30.4, 49, 46 and 30.4m (33, 161, 151 and 33 ft). An existing road and rail corridor resulted in the third balanced cantilever structure, Connaught Road Crossing, which straddles the Connaught Road and a Network Rail Silverlink line. The Connaught Road Crossing structure is a four-span structure with span lengths of 36, 54.6, 54.6 and 36m (118, 179, 179 and 118 ft).

As with the simply supported spans, the balanced cantilever structure used only a few precast segment types that were repeated in various arrangements to suit the prestressing requirements. The balanced cantilever segments also increased in depth by 600mm (23.6 in) to form a haunch adjacent to the piers. Balanced cantilever segments were typically 2.85m (9.4 ft) long and varied in weight from 38ton for a span unit to 81t for the pier units.

Precast Beam Structures

Due to restrictions on headroom, precast prestressed beams with a composite in-situ deck slab were used in the landmark station structure at London City Airport. At this station, the passengers access the trains from an island platform, so the precast beam also provided the flexibility to split the up and down lines either side of the platform. A cross section through the station structure is shown in Figure 4.

Casting of Segments

Segment production was critical to the project programme and so segments were cast on site in a casting shed. The shed contained 3 moulds dedicated to the simply supported span segments and 2 moulds to the balanced cantilever structure segments. In addition, there were four beds for the reinforcement fabrication, two for the simply supported span segments and two for the balanced cantilever segments.

The concrete mix was also developed to allow early mould strike times to promote segment production. This is discussed further in a later section of this paper.

Substructures

The viaduct is supported on pile groups of 4 to 21 continuous flight auger (CFA) piles of 900 (35.4 in) and 600mm (23.6 in) diameter. Pile lengths, numbers and diameters varied according to the soils, which are made up of varying thicknesses of made ground, Lambeth Beds, Thanet Sands, Thames Gravels, and London Clay.

Piers have a single octagonal stem with a width of 1.7m (5.6 ft). The pier stem flares towards the top to provide a surface for the bearings and to provide sufficient space for the legs of the erection gantry. Drains of 350mm (13.8 in) diameter were cast into several of the piers to connect the deck drainage into the subsurface drains.

DURABILITY DESIGN

Basis of Durability Design

The concrete structures on Docklands Light Railway Extension were amongst the first structures designed by Halcrow where the durability provisions of the new European Standard EN 206 (2) and its British application document BS 8500 (3) were employed. EN 206 breaks new ground in that it lists exposure classes in terms of predominant deterioration processes. For example “corrosion induced by carbonation”. It is also innovative in that it recognises that different cement types can afford different degrees of protection against chloride-related reinforcement corrosion. In addition, it acknowledges that different types of structure may have different intended working lives.

As an example of the approach to durability in BS 8500, Table 2 shows the carbonation exposure classes and the requirements in terms of cover to reinforcement and concrete parameters for an intended working life in excess of 100 years. BS 8500 also gives requirements for concrete exposed to chlorides (both de-icing salts and the sea) for an intended working life in excess of fifty years, freezing and thawing and aggressive ground. Unfortunately, BS 8500 indicates that the current state of knowledge does not permit recommendations to be made with confidence on the cover to reinforcement for structures exposed to chlorides with intended lives in excess of 50 years. However, it does suggest that, as a first estimate, the tabulated cover values for intended working life of at least 50 years should be increased by 15mm where intended working lives of at least 100 years are required. Structures on the project are to have a design life of 120 years.

Durability Design of Viaduct Superstructure

The exposure conditions which applied to the viaduct superstructure were:

Interior	XC3 and XC4	Corrosion induced by carbonation – moderate humidity or cyclic wet and dry
Exterior	XC3 and XC4	Corrosion induced by carbonation – moderate humidity or cyclic wet and dry.
	XD1	Corrosion induced by chlorides from de-icing salts – moderate humidity
	XF2	Moderate water saturation with de-icing salts.

These exposure conditions led to the requirements shown in Table 3. The highest strength grade amongst the permitted mixes is C50 (cube), with maximum water cement ratio of 0.45 and cover to reinforcement of (40 + Δc)mm for the XD1 exposure condition on the external surfaces and (30 + Δc)mm for the XC3 and XC4 exposure condition on the inside of the units. Δc is also a new concept introduced in EN 206; it is a tolerance on cover usually between 10 and 15mm) set by the designer and related to the manner of construction.

A compressive strength of 60N/mm^2 was required for structural reasons and also to gain high early strength to permit early stripping of the moulds. This being the case the maximum water cement ratio was set at 0.4 but the cover requirements were maintained as above in recognition of the long service life requirements for structures associated with railways. The tolerance on cover, Δc, was taken as 5mm in view of the close degree of control which could be achieved in the precast situation.

DEVELOPMENT OF MIXES

Background

During the tender phase of the project, Ready Mixed Concrete Ltd (RMC) was identified as the project's concrete supply chain partner. Following award of the scheme, all development work on the segment concrete mixes was carried out in collaboration with RMC's technical department, based in Fulham, London.

For the reasons noted above, the project-specific United Kingdom Highways Agency Series 1700 concrete specification, stipulates a viaduct segment concrete design strength of 60N/mm^2, a minimum cement content of 425kg/m^3 and a maximum water cement ratio of 0.4.

Due to the cantilever wing design of the viaduct segments, the removal of the supporting mould and the subsequent lifting of the segments were governed by two minimum strength requirements.

(1) Striking of segment mould (12-14hours after casting) – 13.5N/mm^2

(2) Lifting of segment (36 hours after casting) - 17.5N/mm^2