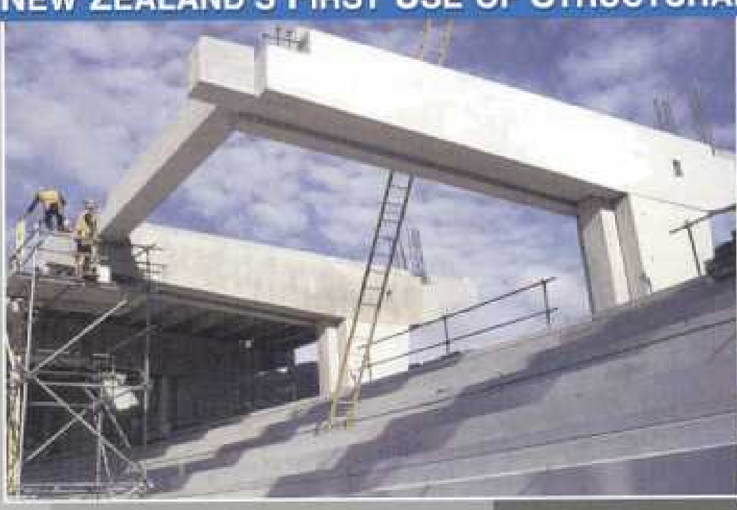
WELLINGTON STADIUM

4,000 Precast Lightweight Concrete Components Provide Seismic and Economic Solutions

NEW ZEALAND'S FIRST USE OF STRUCTURAL LIGHTWEIGHT CONCRETE



The Wellington Stadium

New Zealand's First Use of High Strength Lightweight Precast Concrete

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STRUCTURAL ENGINEER
Holmes Consulting Group

LIGHTWEIGHT PRODUCER
TXI Pacific Custom Materials, Inc., CA

CONTRACTOR
Fletcher Construction Ltd.

PRECAST SUPPLIER
Stresscrete

OWNER
The Wellington Stadium Development Trust

ARCHITECTS
HOK– Lobb (Brisbane)
Warren & Mahoney

CONCRETE SUPPLIER
Firth Industries

TEST RESULTS
Lightweight Aggregate Concrete:
Average Cube Strength:
44 MPa
(6380 psi)
Density
1,845 kg/m^3
(115 lb/ft^3)

Exterior of 40,000-seat Wellington Stadium nearing completion

1.0 SYNOPSIS

The recently completed Wellington Stadium, with a seating capacity of 40,000, is New Zealand's first purpose-built modern sports stadium. It is also the first major structure in New Zealand to be built with lightweight aggregate concrete. Expanded shale aggregate, imported from California, was used to produce lightweight concrete for all the precast components in the main stadium bowl structure. Concrete with a cylinder strength of 35 MPa was chosen for durability reasons, and also to achieve an overnight strength of 25 MPa for the efficient production of pre-tensioned units for the bleachers, long span inclined raker beams and pre-finished double tee flooring.

As the structure is located in close proximity to active earthquake fault lines, an innovative seismic damping system was used to ensure that the structure is not subjected to high ductility demands. Lightweight concrete, with a density of 1850 kg/m^3, reduced the seismic loads and offered a number of other design and construction advantages for the difficult site conditions, but it also created a few surprises for the precast concrete manufacturer and for the contractor.

This paper explains where cost savings can be achieved through the use of lightweight concrete and gives some insights into the issues involved in introducing the material into a new market.

2.0 THE SITE AND BUILDING LAYOUT

The stadium is sited in a prominent location on the harbour edge, in close proximity to the main Wellington railway station, the Parliament buildings and the main business area. The ground, which was once a marshalling yards for trains serving the port and city, consists of poorly consolidated fill, dredged from Wellington Harbour in the late 1800's when Wellington was developed as New Zealand's capital city. Proximity to the central railway station, and to downtown parking was a key factor in the choice of the site. Apart from the engineering challenge of weak ground, the site is exposed to wind blown sea spray and is located just a few hundred metres from one of the country's most active and violent seismic fault lines.

The structural layout consists of an oval bowl around the playing field (roofed only over the spectator seating) and is connected by a two-level open walkway and parking building to the railway station. At the southern end of the oval there is a four-storey administration building that also forms part of the main stand [Figure 1].

Figure 1 – The Completed Stadium

3.0 FACTORS FAVOURING LIGHTWEIGHT CONCRETE CONSTRUCTION

Where it is commercially available, lightweight concrete is commonly used for Stadia construction around the world. While structural lightweight concrete had never before been used in New Zealand, many factors combined to influence the choice in favour of lightweight concrete for this project.

3.1 Poor Foundation Conditions – Extensive piling was required to support the stadium structure on firm strata some eight to twelve metres below the ground. Other site remediation measures were also taken to protect the site, and the structure, from damage due to soil liquefaction during a major earthquake. Reducing the weight of the building resulted in substantial savings in the foundations by minimizing both the number of piles and their diameter. The choice of lightweight concrete also reduced the financial risk in extending the piles if actual load capacities were less than the values predicted from the test bore information.

3.2 *Severe Earthquake Forces* – Seismologists predict that there is a one-in-ten chance of a major earthquake affecting the city of Wellington in the next 50 years. Geological evidence suggests that the Wellington Fault, which is located just a few hundred metres from the site, jumps 5 to 6 meters every 400 to 700 years. Reducing the concrete density reduced the design seismic forces in direct proportion to the reduction in mass.

3.3 Durability – Wellington has a well-deserved reputation as New Zealand's windiest city. Frequent storms carry salt spray across the site from the nearby harbor. The exceptional durability of lightweight concrete meant that future maintenance costs would be reduced. This had a significant impact on the financial viability of the stadium.

3.4 Rapid Construction – Deadlines imposed by major sporting and entertainment events gave an advantage to the contractor if the project was completed in 20 months. This favoured precast concrete construction, which has been New Zealand's preferred construction method for many years. With the nearest precast factory some 60 km away, the use of lightweight reduced the transport costs for the 4,000 individual precast components. It also ensured that even the largest pieces of concrete could be transported on standard truck and trailer units, avoiding the need for special transporters, pilot vehicles, permits and other expenses.

3.5 Space Utilization – The Architects favoured long clear spans for the primary support structure. This allowed more versatility in the use of the space under the seating, which impacted on the financial viability of the whole project. Reducing the self weight of the raker beams, bleachers and floor units, allowed columns to be eliminated and reduced the reinforcement in the units that was required to support their own weight.

3.6 Jointing – Joints in precast concrete are always costly. The use of lightweight concrete allowed larger pieces of precast concrete to be transported and lifted into place. The triple-riser bleacher units reduced the cost of circumferential joint waterproofing by two-thirds, while combining the raker beam and upper column into one precast element eliminated a very costly moment resisting connection that was repeated sixty-two times around the structure. Larger sized components also required fewer crane lifts and resulted in higher productivity on the site.

3.7 Crane Capacity – Limiting components to 32 tons kept precast components within the lifting capacity and reach of the available cranes in Wellington. The advantage of not having to transport and rig special heavy-lift cranes was a significant cost saving. There were similar cost and program advantages in being able to place most of the floor and bleacher units with rail-mounted tower cranes.

3.8 Reduced Site Work – Lightweight concrete allowed the contractor the option of pre-finishing the double tee floor units in the precast factory. This eliminated the need to place and finish a layer of structural topping concrete on the site and reduced the risk of delays due to wet weather — a factor that allowed the structure to be completed well ahead of the original program. The double tees, with the additional weight of a thickened top flange, were still within the lifting capacity of the tower cranes. Diaphragm action was maintained by a combination of welded and grouted connections.

3.9 Innovative Spirit – An additional factor in the introducing structural lightweight concrete for this project was the progressive spirit of the Stadium Development Trust. This group of committed sports enthusiasts, from the business community of Wellington, had emphasized their desire to take advantage of all innovative ideas that could reduce cost without compromising quality. The Contractor, Fletcher Construction also welcomed lightweight concrete as a means of differentiating their bid from other contractor's bids based on more traditional construction materials. The precaster and concrete supplier viewed the project as an opportunity to learn more about structural lightweight concrete, a material with a lot of potential in high seismic zones.

4.0 DESIGN

The use of lightweight concrete was initially proposed by Stresscrete, the precast concrete supplier. But it was also readily accepted by the project structural consultants, Holmes Consulting Group, who were impressed by the potential of the product to reduce cost and responded enthusiastically to the challenge of a new material. In the final analysis, the choice was between a structure of lightweight concrete, or one of steel. Normal weight concrete was ruled out early in the final design process.

There were no difficulties with the design, but in terms of practical constructability, both Holmes Group and Stresscrete agree that for future projects, more generous seating (88 mm rather than 75 mm) would be a sensible precaution. The concern is the fragility of the seating edges of heat cured lightweight precast concrete at an early age, as it is cooling and drying.

4.1 Compliance with Standards – The New Zealand Concrete Structures Standard [1] had anticipated the introduction of structural lightweight concrete and contains modification factors for the use of structural lightweight concrete within the ranges of 1,400 to 2,500 kg/m^3 (88-156 lb/ft^3). However, because the seismic performance of lightweight concrete had not been well researched under cyclic earthquake loadings, the Standard requires that lightweight concrete shall not be used in structures designed for a ductility demand greater than 1.25 times yield. This was not a constraint for the design team at Holmes Consulting Group as the form of the structural system, and the unique seismic damping built into the bleacher and double tee fixing, meant no parts of the precast lightweight concrete required high ductility.

Sufficient research has now been completed to allow the use of lightweight concrete in components requiring full ductility. One of those research projects, by C.J. Allington has been described in Reference 2.

4.2 Novated Design – The nature of the novated design and build contract that the Wellington Stadium Development Trust adopted for this project made it an ideal opportunity to introduce lightweight concrete to New Zealand. The successful bidder for the construction contract, Fletcher Construction Ltd, took over the design contract and the project Architects and Engineers of the original scheme concept were retained by Fletcher to complete a final design that could be built for the the guaranteed maximum sum of the bid. The precast concrete supplier therefore had the opportunity to work through the design with the main contractor and the Structural Engineers to evaluate all the cost savings from the foundation bearing strata up. Lightweight concrete was measured against alternative construction in structural steel and in conventional weight concrete. Where the cost savings justified its use for the stadium bowl structure (Figure 2), lightweight concrete was used. The four-storey administration building at the southern end of the oval was more economical in structural steel, while the two-storey carpark and walkway link to the railway station is built of conventional weight precast concrete.

4.3 Partial Prestress Design – All pretensioned units were designed as partially prestressed sections to limit the initial camber, to reduce camber variations, and to minimize long term creep shortening. This approach ensured very good fit of the installed floors and bleachers where there was no cast-in-place topping concrete to cover camber variations.

4.4 Load Tests – Laboratory scale mixes and tests aimed at determining the concrete properties are meaningful to Structural Engineers, but contractors, their clients, and precast factory staff, require real load tests. These also provided verification of the performance of end support details, member shear strengths and the final failure modes of the units.

(a) Double Tee Tests: This unit performed as predicted at the ultimate limit state, and the flange support reinforcing details provided excellent crack control at the serviceability limit state. The flexural failure mode was a yield failure of the prestressing tendons, but before collapse the load was repositioned to fail the unit in shear and to test the end support detail to destruction.

(b) Bleacher Test: The triple-riser unit also behaved as predicted by the design calculations. The unit deflected about its minor axis, parallel to the raker beam slope, and the end support details provided very good crack control at the serviceability limit state.

(c) Upper Bleacher (Lever 4): This is a complex unit to analyze, with a mix of simple support to the hammerhead assembly and cantilever action carrying the front edge loads. Again the load tests verified the design assumptions, and the performance of the lightweight concrete.

5.0 PRECAST CONCRETE PRODUCTION

The decision to pre-tension the bleacher and flooring units was dictated by cost considerations and the Architect's desire to maximize the spacing of the support frames. To achieve the required properties for the efficient production of pre-tensioned components, expanded clay, and shale aggregates were considered. These materials met the required concrete properties, had a long history of regular use for the production of precast, prestressed concrete and could be shipped from California at an economic price.

The imported expanded shale aggregate, supplied by TXI Pacific Custom Materials Inc. had a bulk density of 800 kg/m^3 (50 lb/ft^3) and a moisture content that varied from 16% to 26%. In the precast yard, concrete could be placed in the moulds within 30 minutes of mixing, but to ensure that there was no significant slump loss due to the aggregate absorption, the surge storage pile was pre-wet by sprinklers. The mix contained natural river sand and 5% entrained air to meet the specified strength and density requirements given in Table 1.

Because of the variable aggregate moisture content, the concrete supplier, Firth Industries Ltd., elected to volume batch the lightweight aggregate. This was done by means of a profiling plate attached to the front end of the feed hopper as it fed the aggregate onto the belt, and counting mechanism on the belt end drum. The batch could dial up the required liters of lightweight aggregate, independent of the moisture content. Daily checks verified the accuracy of this system. There were no problems with the yield of the mix. Subsequent trials with weigh batching have proven that volume batching, while desirable, is not essential.

5.1 Placing and Finishing – Having been warned that over-vibration of the lightweight concrete could cause the aggregate to float, making it difficult to finish, the production team approached the new concrete with some degree of nervousness. In reality, the cement rich lightweight mix proved so much easier to screed and trowel than conventional precast mixes that production crews preferred working the lightweight concrete.

5.2 Spalling and Chipping – The propensity for heat-cured lightweight concrete to chip and spall while cooling caused some problems. Forms for lightweight precast components had to be manufactured to exacting standards of straightness than the New Zealand precast industry would normally use, and the draw (or taper) on the end plates and rebate formers had to be more generous. The thermal stresses within the section, as a heat-cured precast unit cools to ambient conditions, caused high tension at the surface that could cause large thin slabs of concrete to spall off if the unit were not handled carefully. Differential moisture contents due to surface drying effects while the interior is still moist also claimed to reduce the tensile splitting strength. After the precast units had cooled and cured they were more robust, but corners and edges were still vulnerable if mishandled.

5.3 Anchorage – Load tests for proprietary lifting devices and drilled-in anchors were carried out in the precasting factory, and on the site, to ensure that there were no unforeseen problems. Swiftlift lifting anchors were able to develop their full rated capacity and failure modes were identical to normal weight concrete.

Because the speed and ease with which drill-in anchors could be installed in the lightweight concrete, the contractor decided to install the anchors for the seat and handrail fixings on-site. This simplified the production of the bleacher units and was a decision that was applauded by the precaster, Stresscrete. The crew installing the seats did, however, complain that the lightweight concrete, in spite of its "softness," seemed to be more abrasive than normal density concrete and caused more rapid bit wear.

5.4 Color – The large dark patches that occurred on the surface of some of the lightweight concrete units as they dried under cool moist conditions were a surprise. The condition was only temporary and rapidly faded as the humidity dropped and the weather warmed. An explanation of this effect is that lightweight aggregate concrete is more impermeable than normal weight concrete due to the chemical reaction between the aggregate particles and the cement paste. The cement paste, as it cures, has a high affinity for absorbing water and will draw what it needs from inside the aggregate. Once the cement has hydrated however the rest of the water trapped in the porous aggregate has to be drawn through the concrete by vapor pressure as moisture evaporates from the surface of the concrete.

Water vapour will be drawn to the surface where most of the evaporation is taking place. That will be the sunny side, the windward side, or to a more open troweled surface rather than an off-the-form surface. If the concrete surface temperature drops below the dew point, water vapour will condense under the surface before it can evaporate, resulting in a dark colour. As the movement of water vapour through concrete follows the path of least resistance, the dark colour will be patchy. The temperate climate in New Zealand during the winter proved to be ideal conditions for the appearance of the dark patches.

5.5 Camber Variation – The variation in camber between the pretensioned, pre-finished double tees and between bleacher units was much less than Stresscrete had experienced with similar units cast from normal weight concrete. This was attributed to the very uniform properties of the manufactured lightweight aggregate, and to the rigorous production controls that the factory staff instituted while they learned to handle this new material.

5.6 Surface Finishes – Air voids trapped on the vertical formed faces of the precast units were slightly larger than would be expected with normal weight aggregates. Attempts to reduce these by adjusting the mix design and trying alternative release agents were not very successful, but self-compacting mix design philosophies were not attempted.

6.0 CONSTRUCTION

The structural concept did not require any structural lightweight concrete to be cast on the stadium site. The only issues the contractor had were the fragility of the corners and edges of those units that had not fully cured and dried before they were erected, and the need to allow the precast bleachers and double tees to shrink and creep before the joints were concreted.

The fragility of the relatively fresh precast concrete made it easy for the site erection crew to knock pieces off the precast where there was a lack of fit between the precast and structural steel details, for example. This practice was discouraged, but it was easier to use a hammer than a saw when the units were hanging on the crane hook.

7.0 DURABILITY

The chloride ion permeability and the resistivity of the lightweight concrete were tested, but this was more for interest than necessity. The markedly superior durability performance of structures built from expanded clay or shale aggregate is well documented and has been attributed to three unique properties:

Pozzolanic Action: The kiln-fired aggregate is mildly pozzolanic. Cement hydration products form silicates that actually grow across the paste-aggregate boundary, creating dense, impermeable concrete in spite of the porous nature of the aggregates. Under a microscope the exact aggregate paste boundary of the stadium concrete was very difficult to detect. In contrast, the aggregate to paste boundary in equivalent strength normal-density concrete is marked by an easily defined, relatively weak layer that can allow chloride ions to penetrate the concrete.

Water Absorption: The ability of lightweight aggregates to absorb water prevents the accumulation of bleed water on the underside of aggregate particles. In normal weight concrete this water layer increases the water/cement ratio of the paste in a critical location and provides a path of weakness for chloride ions to penetrate the concrete. Another feature of the water absorbing properties of lightweight aggregate particles is their ability to slowly release this water for almost perfect curing of the cement paste: lightweight concretes can be self-curing. It is well known that better curing enhances concrete durability.

Reduced Stress Concentration: The stiffness of lightweight aggregate particles is very similar to the stiffness of the hardened cement matrix. Under load, lightweight concrete has the ability to sustain higher compressive stress levels before the onset of micro-cracking. Micro-cracks contribute to the chloride ion permeability of normal weight concrete.

8.0 SERVICEABILITY PROPERTIES

Lightweight concrete typically has a lower modulus of elasticity, higher creep, and higher shrinkage than normal density concrete of the same strength. These properties are manageable, both in design terms, and in practical terms. Tests were done to establish the numerical value of these properties [Table 1] and the designers selected member sizes, reinforcement and construction details that could perform adequately at the required serviceability limit states. In precast concrete construction, higher creep can offset higher shrinkage by reducing restraint forces. The use of precast components also allowed most of the shrinkage to occur before the final connections were made.

For the pre-tensioned, precast elements, cambers and deflections, and crack widths under load tests have been as predicted. In the completed structure, the seismic damping connection details allowed creep and shrinkage to occur unrestrained at each inclined raker beam. These joints have been monitored and are behaving as predicted.

ALKALI-AGGREGATE REACTIVITY

The lightweight aggregate chosen for the stadium project has a long history of use as a concrete aggregate in the USA. This information was considered to be more meaningful than any short term tests for alkali reactivity. As North America cements typically have a higher alkali content than currently available New Zealand-made cements, the imported aggregate was not tested. Research has also shown that the large pore space in lightweight aggregates can provide a reservoir to reduce the expansive effect of alkali-silica gel resulting from reactive sands.

10.0 CONCLUSIONS

The successful completion of the Wellington Stadium has been a learning process for the designers, the contractor and the precaster. The lessons were as follows:

1. Minimum seating lengths for simply supported lightweight concrete precast floor and bleacher units should be 85 mm (3$^3/_8$"). This is 10 mm ($^3/_8$") more than is common practice in New Zealand for normal weight concrete. This is a precaution to account for edge spalling in heat cured units that are likely to be mishandled.

2. Forms for double tees must be well built and in very good condition. Slight bowing in the web sides, between support stiffeners, can cause the units to bind and spall during de-tensioning.

3. End plates and rebate formers should have generous tapers to aid removal without excessive impact.

4. Precast units should be allowed time to cool, and preferably dry to the point where surface shrinkage stress are minimized, before being transported to the site.

5. Erection crews must be trained to avoid edge impact, or stress from crowbars used to lever the units into final alignment.

6. While the lightweight concrete is easy to drill, it can be very abrasive and may cause higher than normal bit wear.

7. Creep and shrinkage of expanded shale lightweight concrete is very similar to Wellington's normal weight concrete.

8. Do not underestimate communication and training. In their crusade to save the world from innovative ideas, some people will resort to extraordinary behavior. Lightweight concrete will initially be blamed for any problems that occur.

The ultimate compliment for lightweight concrete has come from the factory and site labor forces. Their verdict is, "It's just like normal concrete!" Only the crane operator reading his load indicator can tell the difference.

11.0 ACKNOWLEDGMENTS

Owner	The Wellington Stadium Development Trust
Contractor	Fletcher Construction, Ltd.
Architects	HOK – Lobb (Brisbane)
Structural Engineer	Holmes Consulting Group
Precast Concrete	Firth Industries
LWA Supplier	TXI - Pacific Custom Materials, Inc. (California)

12.0 REFERENCES

1 Standards New Zealand, Concrete Structures Standard, NZS 3101: 1995

2 Allington, C.J., Bull, D.K., McSaveney, L., Ductile Response of Lightweight Aggregate Concrete Members, Second International Symposium on Structural Lightweight Aggregate Concrete, 18-22 June, 2000, Kristiansand, Norway.

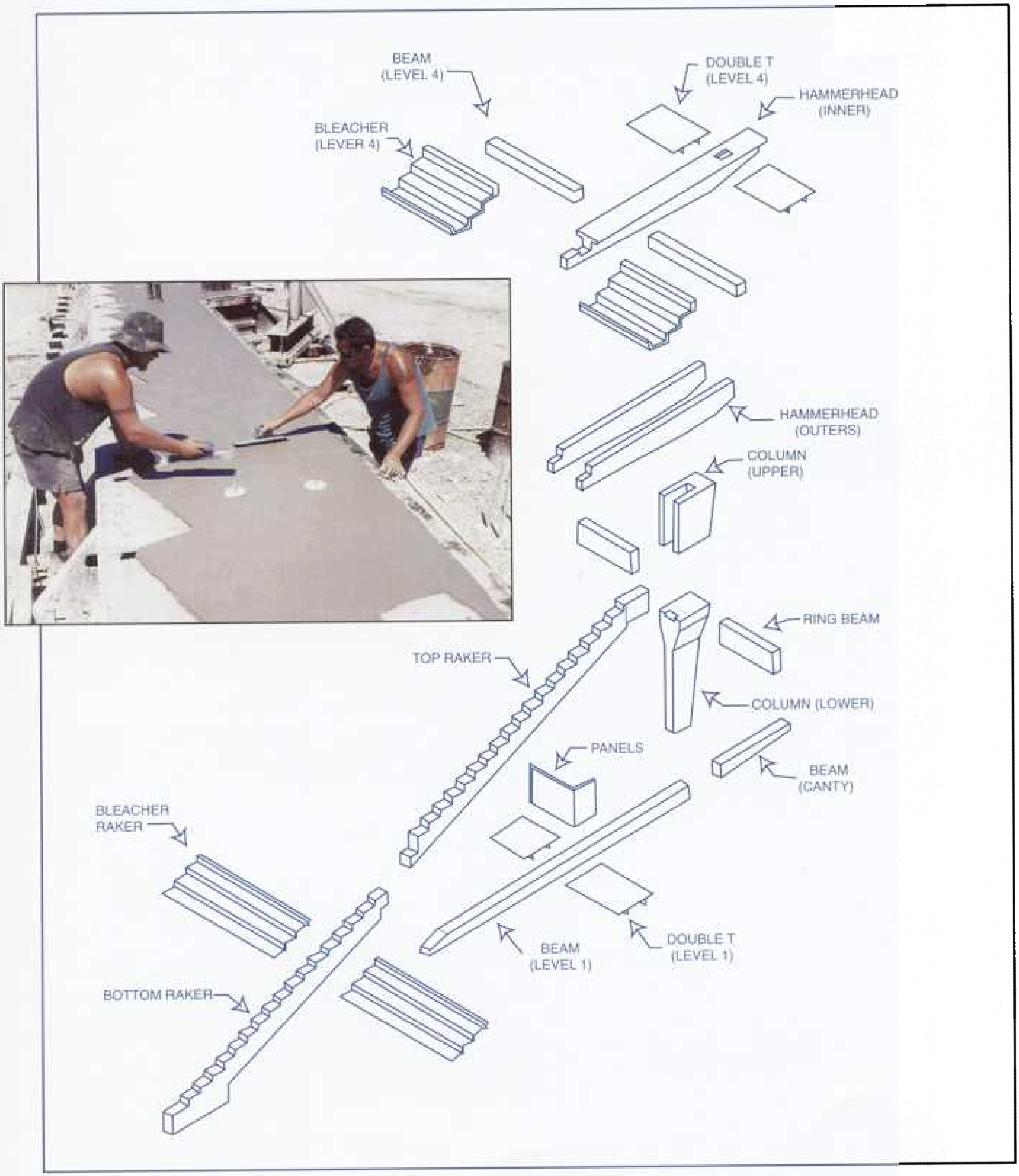
3 Park, R., McSaveney, L.G., Johnstone, P.G., Wellington Stadium Precast Lightweight Concrete Members: Material Properties and Load Tests Results, IPENZ Technical Conference, July, 1999, Auckland, New Zealand.

Table 1
Concrete Properties for the Wellington Stadium (BRANZ Tests)

Property	Specified or Assumed	Test Results	Comments
Strength	Transfer of prestress: 25 MPa At 28 Days: 35 MPa	18 hours heat cured, 24 to 30 MPa Average strength 44 MPa	***fib*** TG8.1 recommend a mean compressive strength within 90 days, 5 MPa higher than the specified cylinder strength at 28 days.
Density	1850 kg/m^3	1845 kg/m^3	Test result is oven dried plus 50 kg/m^3 for permanently retained moisture.
Modulus of Elasticity	19.1 GPa	20 GPa at 28 days	Similar to normal weight concrete cast from some softer NZ volcanic aggregates.
Creep	Long term assumed creep factor 2.3	Measured value 1.8 after 3 months. Long term predicted value 3.0 from the CEB model	Prestressed designs adjusted to reduce long term losses. Seating details allow for creep shortening.
Shrinkage	840 microstrain long term	14 day – 400 microstrain 28 day – 590 56 day – 730 CEB prediction of long term value, 1250 microstrain	Heat cured results. Prestressed designs adjusted to reduce long term losses. Seating details allow for some movement.
Modulus of Rupture	Not specified, but NZS3101 gives 4.02 MPa for 35 MPa Concrete	5.2 MPa at 28 days Standard Cured 4.8 MPa Heat Cured	Flexural beam tests
Chloride Ion Diffusion	Equivalent to 40 MPa General Purpose cement concrete	4796 Coulombs Standard Cured 4562 Heat Cured	Tested at 28 days. 4400 Coulombs is typical for Wellington concretes.
Resistivity	Equivalent to 40 MPa GP cement concrete (7,700 Ohm cm for Wellington GP concretes)	SSD 12,030 Ohm cm Dry 13,570 Ohm cm	Tested at 56 days. Tested at 63 days.

NOTE: $kg/m^3 \div 16 = lb/ft^3$ MPa x 145 = psi

Figure 2
Lightweight Concrete
Precast Elements • Wellington Stadium



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