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INTRODUCTION

GLOBAL WARMING AND CARBON DIOXIDE

Turn over the sheet of a newspaper today, or the glossy pages of a topical magazine, and you will find reference to greenhouse gases, global warming, rising sea levels and the rapidly receding polar ice caps somewhere on the page. These are not freak events due to transient or seasonal phenomena, such as solar flares, a meteorite shower, a tsunami, an earthquake or a volcanic eruption, after which the climate returns to normality. The increase in greenhouse gases is permanent, and has been building up over the past 500 years as a result of the burning of fossil fuels and the deforestation of vast tracts of land. Significant sources of greenhouse gases include the extraction of oil and gas, the excavation of mineral ore and precious stones, gas emissions of the internal combustion engine, discharges from the manufacture of industrial and household goods and the building of houses and offices.

As responsible designers and builders of the future, we all wish to find ways to sustain our planet and to reduce global warming by designing buildings that are energy efficient and by constructing buildings that have a small carbon footprint. It really is that simple, but getting to the core of the issue has been clouded by misconceptions, and the rather short-term outlook advocated in some published guidance notes may generate no real long-term benefits.

If we simply assess a raw material's embodied carbon dioxide (CO_2) and use that figure to find a green building solution, we may be ignoring many other major factors. This is true for all building materials, whether concrete, steel, timber or masonry. Timber, for example, may be carbon neutral, but it has to be felled, logged, cut, processed, treated, transported, assembled on site, supported on a foundation, framed with glass, pinned, glued, clad, roofed and lined to be useful. A building may contain miles of electrical cabling, plastic conduits and metal ducting for heating and ventilation, insulation, carpets, lighting, painted walls and ceilings, plaster and plasterboard linings, a sprinkler system, switches, plugs, boilers for heating water, and so forth. We need to measure the CO_2 emissions from all of these components as well.

And how are the components assembled during the construction of a building? It requires people, vehicles, scaffolding, machines and mechanical plant. People have to journey to and from their workplace every day, often by car, so how much CO_2 is contained in those car emissions? Materials are delivered to the site by road transport, and we may hire mechanical plant for excavation and for lifting and placing materials; this all requires fuel and creates CO_2 emissions. This is the bigger picture during the construction phase.

But the argument prevails that, because these components are common for buildings of the same height and plan area, why bother to measure all these items when there is a direct benefit from using a carbon-neutral material in the frame! It is the same argument put forward about the food we eat if we want to keep slim. It's the calorie count that's important, not the fact that the food is organic. Therefore, we must measure and assess all the CO_2 emissions in the construction phase, not just those of a few materials in isolation.

We also know that up to 95 per cent of the CO_2 emissions from a building are generated by the energy consumed during the life of the building and not by the materials used in its construction. This energy consumption is created by the need for heating, lighting and running electrical appliances, which will continue for 30 years or more for a typical building. It makes sense to also focus our green building design on the long-term reductions, such as by using thermal mass. In the future, as we specify more energy-efficient buildings and reduce our dependence on fossil fuels, CO_2 emissions in the construction phase will become just as critical.

A certain amount of greenhouse gas in the atmosphere, principally CO_2, is not at all bad for the planet, and in fact is essential for life – it is responsible for sustaining an average year-round temperature of 14 °C. This is due to the absorption by greenhouse gases of infrared radiation from the earth's surface. If there were no greenhouse gases in the atmosphere, the earth's temperature would plummet by 33 °C and we would not be able to survive. The greenhouse blanket has been created by the presence of methane, water vapour and CO_2 in the atmosphere, discharged by living creatures and microorganisms and from the decay of forests and greenery many thousands of years ago. But now, with the exponential rise in man-made greenhouse gases over the past decades, these gases can no longer be limited by natural reabsorption by algae, plants and plankton, and their levels are escalating out of control.

By and large, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have been banned as coolants for refrigeration and replaced by ecofriendly substitutes, and nitrous oxide emissions have been curbed by legislation and electrostatic screening. However, emissions of CO_2 are still far too high, so we must find simple yet effective ways of reducing them.

The long-term goal is to return to the levels of CO_2 emissions of, say, 1,000 years ago. It may take the next 50 to 100 years, and will require a worldwide agreement on the measures to be taken and a drastic change in Western lifestyles. The present target is a CO_2 concentration in the atmosphere of 300 parts per million (ppm) by volume. If we project forward using current emission levels, but including renewable energy sources and assuming that present policies prevail, we can expect a concentration of around 700 ppm of CO_2 by the year 2100. However, that would rise to 2,000 ppm if we assume the same population growth as in the past decade but we do nothing.

Put another way, that makes everyone in the world responsible on average for 4,200 kg of CO_2 per year at current emissions rates. However, in the USA, each person produces 20,000 kg of CO_2 per year on average – that is a huge deficit to make up. In India, the average is 800 kg per person, so they are in carbon credit, while in the UK the figure is 9,600 kg per person, so we are in deficit. In the Gulf States the average has risen to 90,000 kg per person.

So what are the biggest sources of CO_2 emissions, and how can designers and builders make a telling contribution to their reduction? Of the total CO_2 produced, 32 per cent comes from transport (mainly cars and commercial vehicles); 28 per cent from housing (mainly consumption of gas and electricity); 19 per cent from commerce (consuming mainly gas and electricity); and industrial processes and manufacturing account for 20 per cent. We can say from these figures that the building market is a major contributor to global CO_2 emissions.

Therefore, it is clear that the most significant improvement we can make is to design buildings that consume less energy. The section of this book on heating and cooling (in Chapter 2) will consider the long-term benefits of using passive cooling in summer and utilising concrete's thermal mass to reduce heating and cooling loads. Where economically viable, renewable energy sources could be considered, although they currently show a poor return on investment at today's energy prices. Terms such as admittance, fabric energy storage, embodied CO_2, thermal mass and many more will be fully explained.

Currently, *The Green Guide to Specification* (BRE Press, 2009) and other Building Research Establishment publications that focus on recommendations for sustainable construction consider, in the main, the embodied CO_2 of raw materials and largely ignore the transportation, process and construction CO_2. For example, the green rating of materials is given as A to E rankings, without any indication of the CO_2 per m^3 of the completed building. As a direct result of this, many specifications and designs for sustainable construction, particularly in housing, are written with a bias towards timber-frame construction. The whole CO_2 picture needs to be evaluated; otherwise, there may be no reduction, and even an increase, in CO_2 emissions in the long term.

In the section on assessing CO_2 emissions in construction (in Chapter 2), a simple yet robust approach has been developed to show how to map the carbon footprint of a project, accounting for material delivery mileage, factory production and assembly on site, as well as the embodied CO_2 of the raw and composite materials. There are cements with low embodied CO_2 that can be specified, as well as lightweight aggregates that reduce the thermal conductivity of concrete (so that no insulation is needed) and various other concrete options to help reduce and control CO_2 output. The key to this approach is the willingness and openness of the supply chain and the construction industry to provide data on a project-by-project basis.

The small but important group of companies that have assisted in providing the construction data for this book have shown how useful this can be in revealing which components are the most critical and what is the best way to manage CO_2 emissions. It is a balance between designing buildings with lower embodied CO_2, reducing material wastage and ensuring the lowest long-term energy consumption.

The contributions from the architects and engineers whose projects are detailed and illustrated in the case studies provide the hard evidence and practical information on how to deliver elegant, low-carbon, concrete building designs with success and at an affordable price.

HOW TO USE THIS BOOK

This book is divided into two parts. Part I covers in detail the materials and technology issues affecting the embodied CO_2 of buildings, while Part II presents real-world examples of sustainable concrete architecture.

Chapter 1 describes the various materials and products (and their manufacture and processing) that are common in reinforced concrete and concrete masonry construction. At the end of each descriptive section, the embodied CO_2 of the material is given. If a CO_2 material audit has been undertaken by the manufacturer the CO_2 figure quoted will be accurate for that product or process. In all other cases, the CO_2 figures shown are based on the published data summarised in Table A.1 (see the Appendix to Part I), based on desk research. The CO_2 values are not product-specific for a particular supplier – a steel fabricator or brick manufacturer, for example – nor are they validated for transport or production CO_2; rather, they are generalised best-fit approximations from published data and therefore contain some degree of inaccuracy. Table A.2 (see the Appendix to Part I) presents validated CO_2 data for specific manufacturers' products.

The Construction CO_2 Audit shows how to calculate a building's total CO_2 emission at the end of the construction phase. This will give valuable insight and better understanding about which building elements bump up CO_2 and which frame materials offer better CO_2 management in both the short term and the long term.

Chapter 2 covers heating and cooling of buildings, and how to use concrete's thermal mass to reduce long-term energy consumption in residential and office building. Various forms of concrete construction are reviewed, along with different ways to heat and cool office buildings, from using passive and naturally ventilated systems to chilled beams and forced ventilation systems, including ducted air, radiant cooling and ground source heat pumps.

Part II contains twenty-four superbly illustrated and detailed case studies, from private houses to apartment buildings, from schools to universities, galleries to museums, visitor centres to office buildings. Each case study has a statement on the building's energy efficiency, energy rating and CO_2 emmisions. This is the compelling evidence that sustainable concrete architecture is the future for low-energy, green building design and why architects and designers should turn to concrete for their solutions.

THE NEW HERBARIUM AND LIBRARY WING, ROYAL BOTANIC GARDENS, KEW

Lara Michael, Edward Cullinan Architects

The Royal Botanic Gardens at Kew hold one of the world's largest and most important collections of samples of plant diversity. However, many are stored in overcrowded and unsuitable accommodation, which poses a threat to their continued survival. It is for these reasons that Kew wished to build a new wing as an extension to the herbarium.

The new herbarium building is a large repository for the national archive of dried and preserved plant and seed specimens. For more than a hundred years the ever-growing collection has been housed in period buildings with natural ventilation and widely fluctuating temperature and humidity. Key aspects of the brief were to introduce stability into the environmental conditions, to ensure temperature levels that would resist animal infestation and to provide secure fire-resistant containment, with a design life to match the existing buildings. These requirements led the team very quickly to the conclusion that concrete would really be the only sustainable long-term solution to meet these objectives.

The new wing to the herbarium and library provides 5,000 m^2 of increased storage space in controlled climatic environments, a state-of-the-art pest decontamination unit with walk-in freezer rooms chilled to temperatures of minus 40 °C, north-lit study spaces for viewing and illustrating the collection and space to provide reading rooms and further study spaces. In addition, the new facility provides better access for large groups to gather and to be taken on tours without disturbing the scientists at work, and it meets all the design criteria of respecting and maintaining Kew Gardens' World Heritage Site status while protecting the TROBI champion trees on the site.

The design

The core of the new wing is a four-storey, brick-clad, concrete frame treasure-box containing the precious specimens, which are stored within ceiling-high, purpose-made mobile shelves. These archive rooms are kept at a constant 15 °C – a temperature that is cool enough to prevent any herb pests from reproducing. As the contents are best examined in daylight, these areas are located on the perimeter of each floor and screened by an undulating timber façade on one side, brickwork on another and trellised with greenery that clings to the concrete treasure-box.

Right
Shadows cast by the *brise soleil* move across the south-facing offices on sunny days

Far right
Study bays are provided in the undulating corridor to the west of the archives, which are within the brick-clad treasure-box

Below
View towards the north elevation of the drum. The timber rainscreen cladding undulates with the wavy corridor along the west elevation

The main workspace for graphics, editing and computer staff is located on the top floor, within the large open-plan concrete vaulted roof.

The circular drum entrance and staircase link the new building to the existing herbarium, and provide orientation and reception facilities for the herbarium, library, arts and archives building as a whole. The public places, such as the reading room, the open-plan botanist room and training room, are gathered in the drum. The finely cast concrete main staircase to the rear of the drum curves up and around the fair-faced lift shaft walls to enjoy the warmth from south-facing glazing, while the collection is protected from direct sunlight.

The in-situ concrete structure was chosen to support the heavy rolling loads from the shelving racks, and the floor soffits stabilise the temperature fluctuations while the thermal mass helps to maintain the internal temperature at 15 °C. Natural materials, such as carpets and timber, are ideal breeding grounds for pests, so choosing clean hard finishes, such as a concrete topping to the floors and fair-faced concrete walls, exposed soffits and fair-faced blockwork walls finished with a dust sealer, became an obvious choice. The concrete topping also allowed us to exploit its thermal mass by incorporating heating pipes within its build-up to heat the naturally ventilated spaces.

We wanted the fair-faced concrete to be of an excellent quality and invited David Bennett to join the design team to produce the visual concrete specification and to oversee all the site work. This specification focused on the concrete mix, the formwork and all aspects of concrete workmanship.

The site is within a conservation area and is a World Heritage Site. The listed buildings of the existing herbarium, along with the positioning of the new drum, now frame a southern courtyard with an existing hornbeam tree in the centre. Colours in the original bricks on these buildings are picked up in the new wing, with the colour of Kew Palace influencing the choice of the striking red brick, laid in Flemish bond.

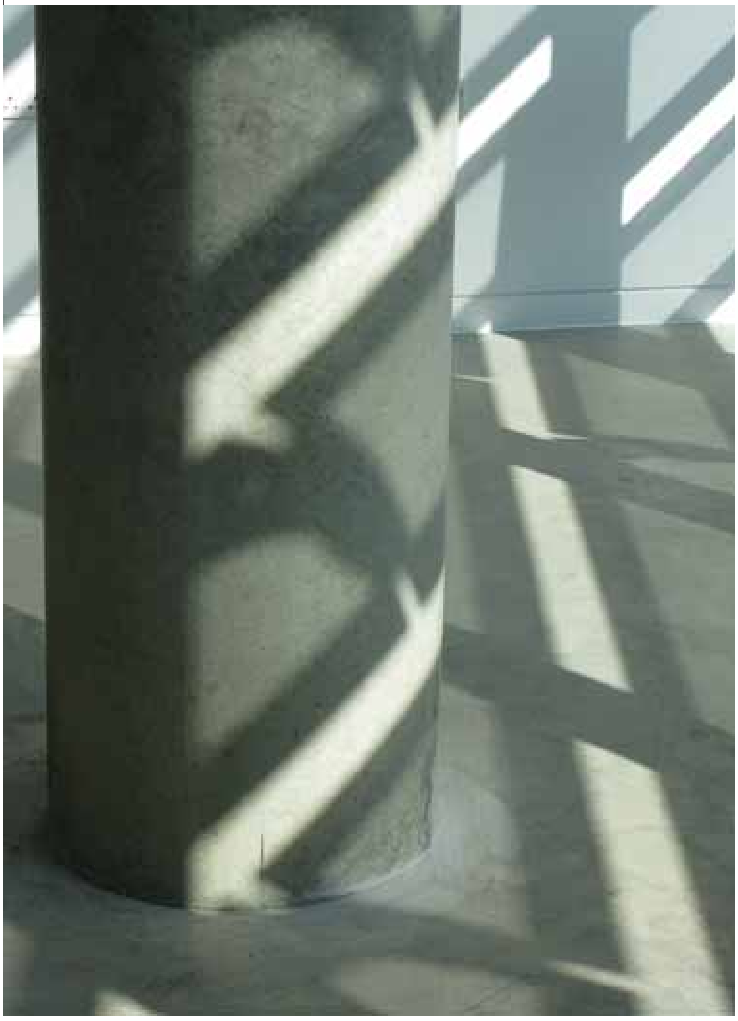
We originally wanted a green roof and to collect the rainwater but the client was not keen on the maintenance involved. A high priority in the client's brief was for a robust roof with absolutely no possibility of leaks. With a precedent of zinc on the roof to part of the existing herbarium, we specified Rheinzink. We used SpectraPlan for the waterproof membrane on roof areas and Ruberoid at ground areas because of their guarantees.

One of our aims was to try to source materials locally and so we used locally grown western red cedar for our cladding. By lifting the timber cladding one floor off the ground, and with careful detailing to ensure adequate ventilation and to allow rainwater to run off, and providing end-grain protection in terms of preservatives to the trellis and zinc caps to the cladding, we anticipate that the timber cladding will have a life of at least 50 years, as TRADA experts suggest.

As the building is primarily climate-controlled, most areas of the building are sealed, so logically we relished the idea of floor-to-ceiling glass. We wanted to minimise the number of joints, which carry the possibility of failure, and found that the Schüco system provided us with what we wanted without having to design bespoke mullions. We have tried to make the most of the views of the beautiful trees and the river beyond. The wavy corridor accommodating study spaces undulates around the TROBI champion trees to the north of the drum. Botanists and other researchers are now able to work with views out through the leaves of these trees.

The interiors are minimal. We have used Sto acoustic recycled-glass suspended ceiling boards with a trowel-finish in the flat ceiling areas and a sprayed-finish on the suspended curved acoustic panels in the vaulted space. Where access is required, we have opted for ceiling planks that have a similar texture to the Sto boards. In the circulation spaces we have chosen to use a polished plaster finish which is tough so that decorating maintenance is reduced. In keeping with our pallet of natural colours, we have opted for warmer metals, such as bronze, and the dark chocolate brown and bronze metals of the interior are a clean contrast to the pale umber of the exterior mullion caps.

Externally, we were fortunate to have the ideal client to choose a selection of plants to climb up the trellis, and consideration is being given to displaying the collection of ivy on Ferry Lane wall, opposite the large ground-floor window to the east.



The building fabric

For almost any building the construction of the building fabric and the design of the façade have a much more profound effect on the internal environment and energy efficiency than the design of any of the engineering systems it contains. Although it is possible to design heating plant (or air-conditioning systems) to deal with high heat losses in winter (or high solar gains in summer), the comfort levels are rarely as good as those that are achieved when the building fabric has been designed to shield the occupants from these two extremes.

The objective in winter is to maintain a warm, condensation-free environment with minimal consumption of energy for heating and lighting. In order to achieve this, the building fabric must be designed to minimise heat losses, to exploit passive solar gain and to maximise the use of available daylight.

The parameters having the most effect on the winter performance of a building are:

- insulation levels – measured by the U-value
- thermal mass – achieved by exposing the concrete frame
- infiltration levels – determined by the airtightness of the building construction
- fenestration and solar control – useful for providing passive gain and natural daylight, but with a heat loss penalty which must be minimised.

Implementing the lower U-values can reduce the fabric heat loss by almost one-third. Improving the airtightness of the building can also make a significant difference to the heat loss.

Construction

Long-term reductions in terms of CO_2 emissions were addressed during the consideration of the design approach. Reducing CO_2 emissions in the short term was achieved by reducing embodied CO_2 through recycling formwork, minimising waste and reducing the delivery transport emissions by sourcing materials locally.

Reuse of formwork

The design consists of straight fair-faced walls and soffits and curved walls and a vaulted roof. The formwork shutters for the basement walls were reused seven to eight times. The columns and sheer walls had between ten and fifteen reuses and were refaced where required. The flat soffits were less efficient as there are a number of deep down-stand beams and the bolt hole layouts meant that cut pieces of plywood could not be reused once they had been drilled. New plywood was brought in for the fair-faced vaulted soffit on the third floor, but generally the soffit sheets were reused between three and four times.

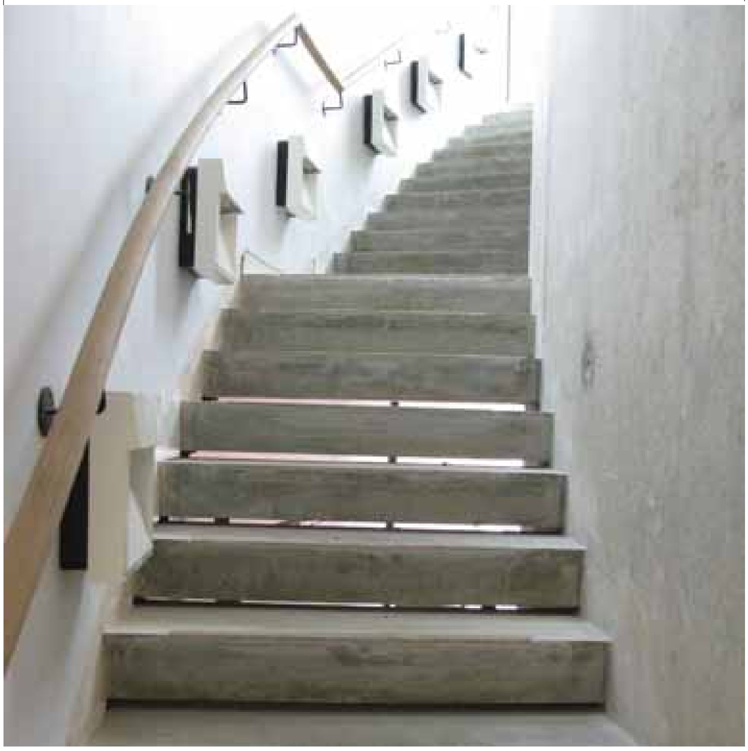
Prior to starting on site, our structural engineer, Buro Happold, reviewed whether the floor slabs could be post-tensioned to assist in the speed and safety of the construction by trying to eliminate all of the down-stand beams, but this proved not to be practical.

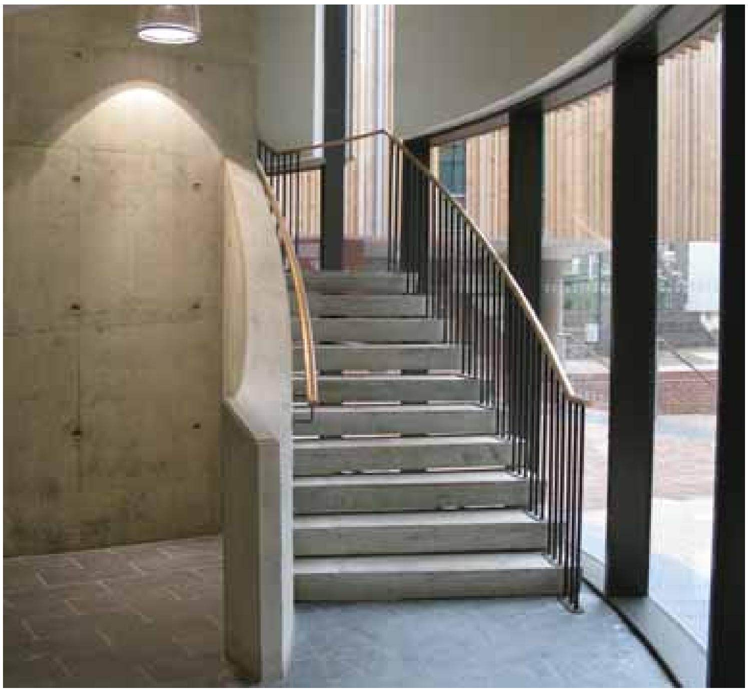
The birch ply shutters for the curved wall at stair 3 were reused three times, and the lift-shaft shutters were used four times, i.e. reused at each floor level.

There were two sets of birch ply shutters for the main stair beam/balustrade, and these were used three times each. They were sanded and resealed after each use. New top and bottom shutters had to be cut for each pour because each beam is slightly different in geometry since the floor-to-floor levels were not regularised as the drum floor levels were tying-in to the existing building.

All timber and plywood used was FSC-certified. However, the timber came from Scandinavia and the plywood from Latvia, all supplied by Laver Timberworld, based in Reading, Bucks. At the end of the project all reusable timber and plywood was transferred to other projects for use in ground beams by the concrete subcontractor, Toureen Mangan. Unusable pieces were placed in dedicated timber skips for removal from site by the main contractor, Willmott Dixon.

The requirement for back screwing the wall shutters to achieve a fair-faced concrete surface free of nail and screw heads meant that twice as many plywood sheets were required for each formwork panel. This added to labour time and costs for the initial shutter construction, but this contingency was considered at the preconstruction stage





Left
The southern stair follows the same design principles as the concrete stair within the drum – precast treads are cantilevered off the curved in-situ concrete wall

Middle
Finely cast concrete detail, where the top of the balustrade meets the lift shaft of the stair within the drum – the bronze handrail contrasts with the concrete balustrade

Bottom
Main staircase leading from the ground floor inside the drum

and built into the plan. The wall construction would have been quicker without the precise tie bolt layouts, enabling the use of proprietary panel systems with preformed tie holes; however, this would have resulted in a greater amount of remedial work, the infilling of unwanted bolt holes and extra cost.

The concrete materials were sourced as follows:

- cement from Rugby, Warwickshire (overnight by road)
- limestone aggregate from Shepton Mallet, Somerset (rail transport)
- sand from Dagenham, Kent (by road).

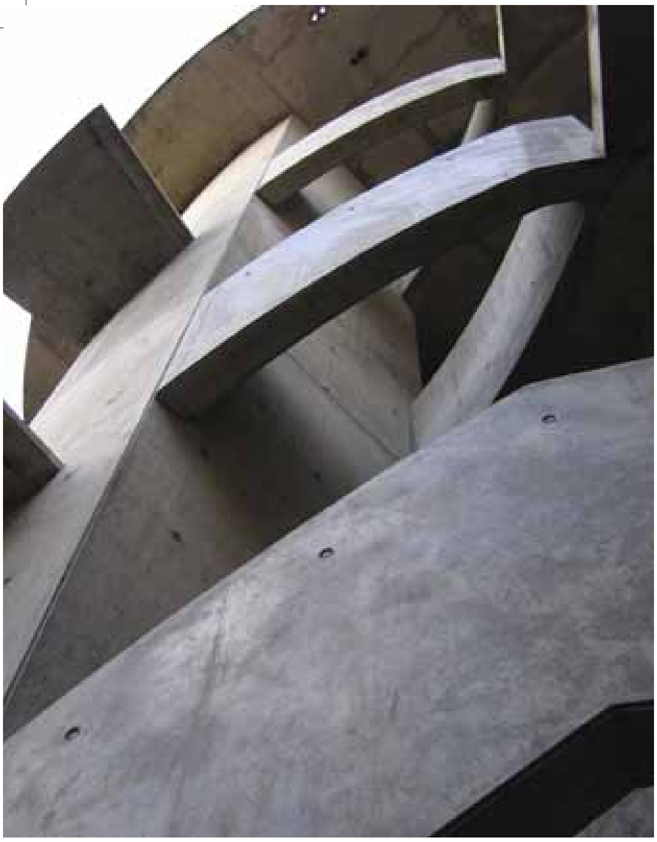
Ready-mixed concrete was delivered from London Concrete, which is based two miles from the site at Kew.

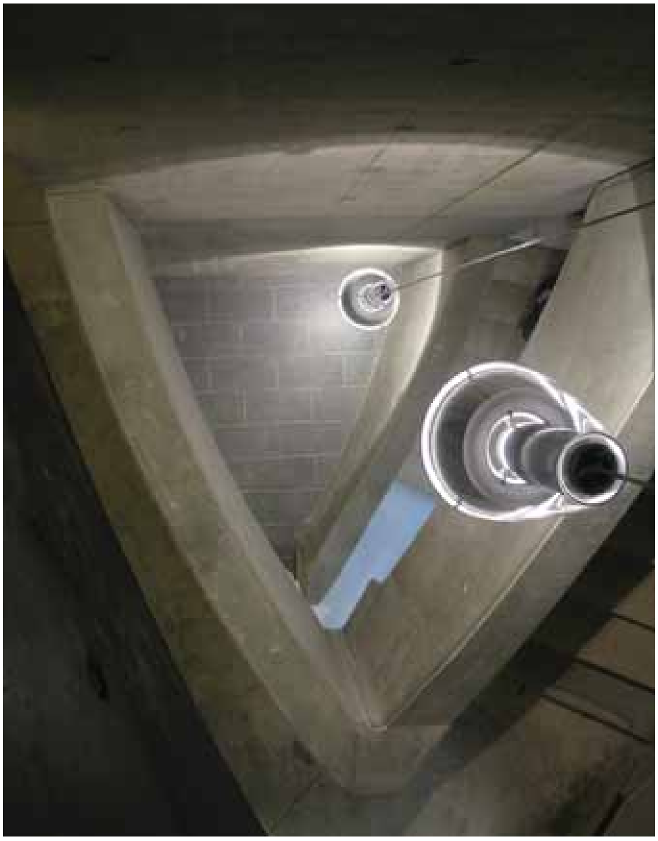
Mechanical and electrical services design

The cellular design of the building allows for different control regimes for temperature and humidity to accommodate the different types of material that are being stored – from plant specimens to rare books and illustrations – and each archive has a separate control system in the form of a closed control unit.

The building is air-conditioned using a ground source heat pump system linked to open loop boreholes in the grounds of the building, which provide a source for heating and cooling throughout the year. A key requirement of the project was that the archive rooms should have a high degree of thermal mass to provide stability and control and to minimise peak loads during the occasional periods when the herbarium or library archive rooms are heavily used.

The use of concrete allowed us to minimise the size of the air-conditioning systems, which control both temperature and humidity, as the thermal mass absorbs fluctuations in heat gain and prevents the temperature from swinging too rapidly as loads are imposed or removed. The hygroscopic (water absorbing) nature of the material also helps to attenuate fluctuations in humidity, once the initial construction moisture has been released.





Above
Lift shaft, balustrade beam and half-landings of the drum stair before the precast treads were fixed

Above
Looking down one of the voids of the drum stair

Right
View through an archive vault to one of the study pods on the east elevation

Further, the high thermal mass allowed us to incorporate less redundancy into the plant and equipment than would otherwise have been required. It is envisaged that, in a situation where an individual climate control unit within an archive store malfunctioned, the store area would be isolated for access temporarily by restricting entry and the lighting turned off to minimise heat gains. In this situation the high levels of insulation and the high thermal mass of the store will maintain adequate conditions within the structure for a period of one or two days while the equipment is repaired.

This characteristic of concrete, its ability to absorb heat gains, although not immediately appearing to be 'sustainable', is therefore very much a key factor in allowing us to reduce the size of the plant, the operating hours of the plant and the duplication of systems, and allows us to use considerably fewer resources in both the construction and the operation of the building.

By any definition, a building that does more with less is more sustainable than an alternative solution. There is clearly some penalty to be paid for the embodied CO_2 in the concrete itself; however, it was felt that the combination of the environmental benefits and the benefits in terms of fire suppression and security for this very important archive, and from the reduction in resources and energy use, more than compensated for the decision to use concrete throughout the building.

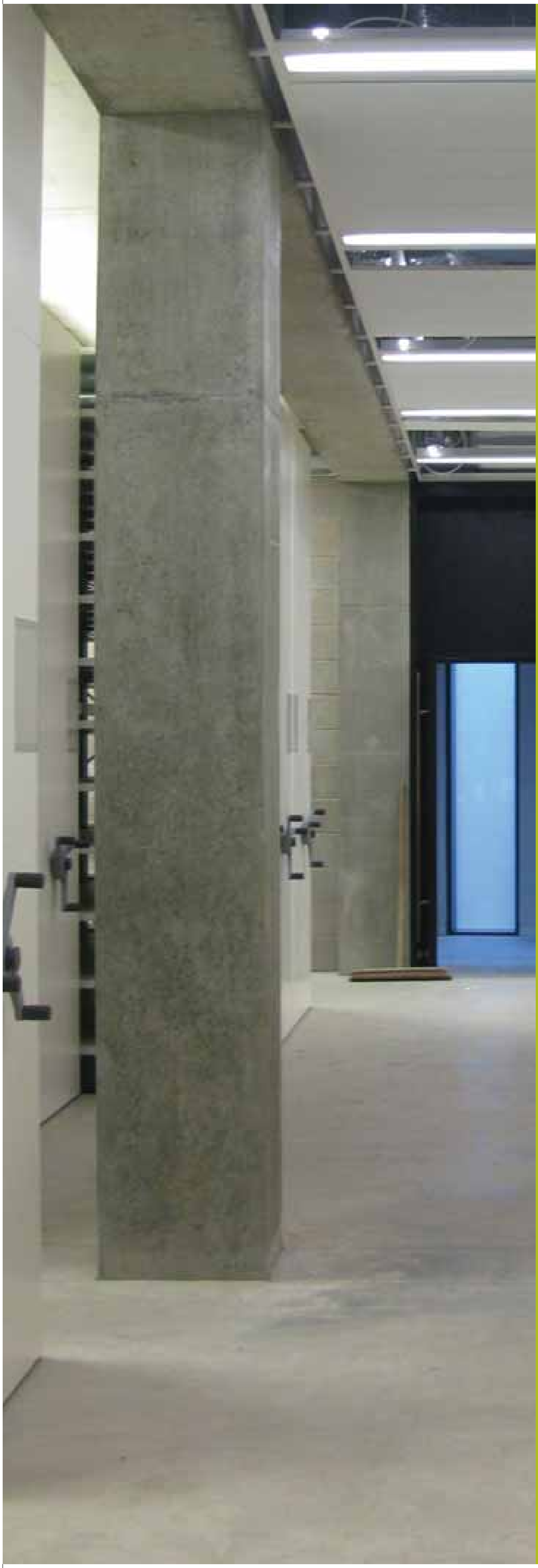
Sustainability issues

The building design achieves a 23 per cent improvement on the target emissions rates based on the 2006 Building Regulations Part L, which has lower targets than the 2002 Part L which was current at the time of design. This result was due partly to the client's BREEAM rating targets to improve U-values by 15 per cent, and partly to the use of the ground source cooling installation. Edward Cullinan Architects' design of the building fabric allowed the U-value improvement to range between 10 and 50 per cent improvement, depending on which element was considered; the drum roof, the insulated rendered soffits and the timber rainscreen cladding scored the best improvements.

Airtightness

To comply with Building Regulations, the 'On-Site Whole Building Air Tightness Test' to CIBSE TM 23 needs to achieve a minimum of 10 m^3/h per m^2 at a test pressure of 50 Pa. However, to achieve the client's BREEAM targets, this figure needed to be improved by 25 per cent. Attention to designing the detail between the cladding materials and the junctions with the roof, soffits and floor focused on an airtight construction. The details are bespoke, so achieving good results in the post-construction airtightness test also relied on the contractor's ability to build the details well.

The on-site tests achieved 5.07 m^3/h per m^2, which is a 50 per cent improvement on Building Regulations and a 25 per cent improvement on the design's target figure.



Energy data

Gross and treated floor area	5,000 m^2
Predicted annual CO$_2$ emissions	*kg CO$_2$/m^2/yr*
Space and water heating	3.12
Regulated electrical usage	8.85
Total	11.97*

* Does not include non-regulated energy usage (see notes on page 256)

Our services consultant, Atelier Ten, carried out as-built calculations and the building is consuming 15 per cent less energy annually than our aim. The target annual CO$_2$ emission was 14.10 kg/m^2; however, the building is achieving 11.95 kg/m^2.

Description of heating and cooling provision
Improving the U-values over and above Building Regulations, using the concrete's thermal mass, orientating the rooflight to the north, and orientating the windows using careful solar studies and by providing fixed ***brise soleil*** to the south-facing glazing, have passively contributed to reducing energy consumption and CO$_2$ emissions.

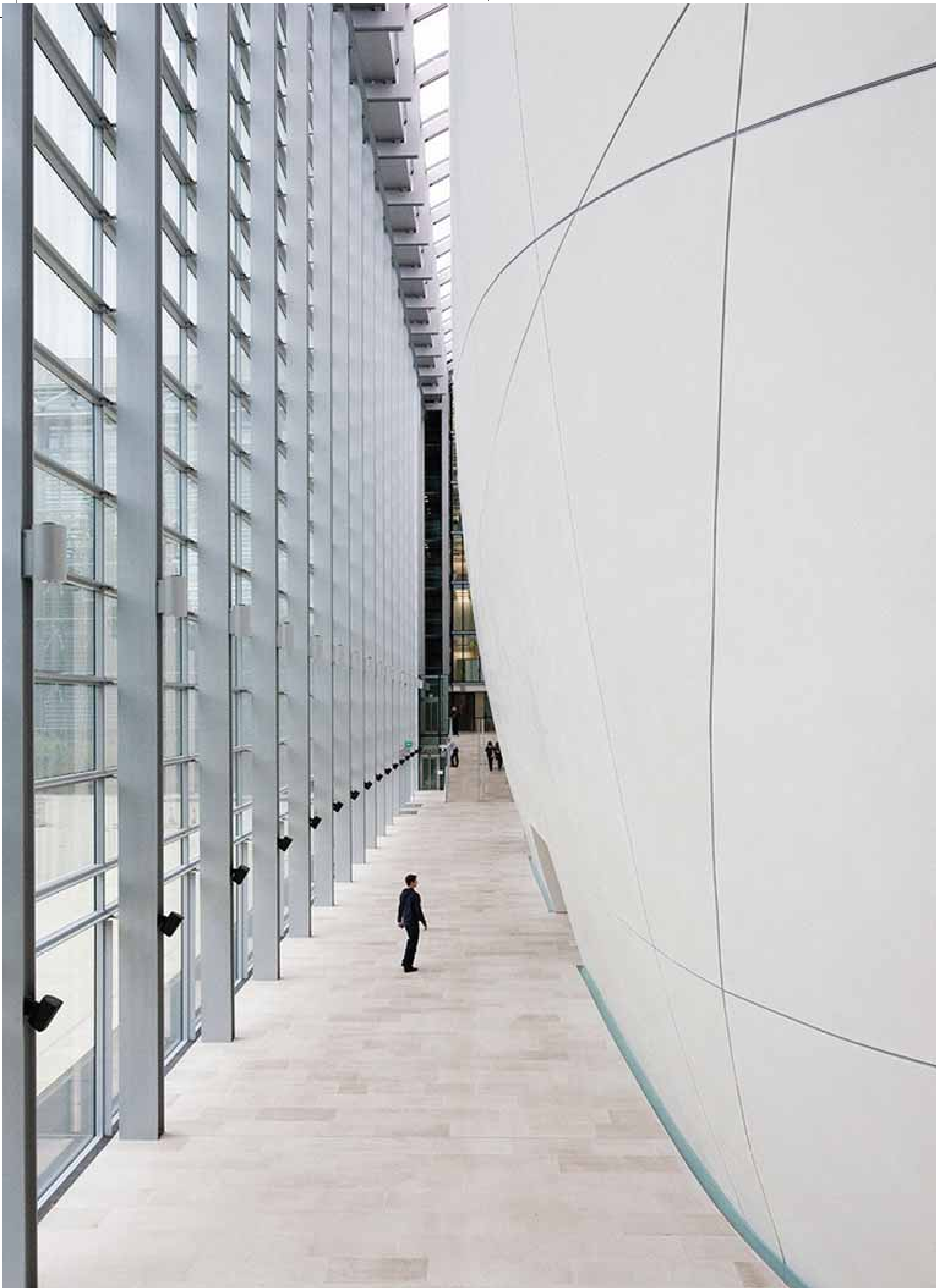
Providing night-time cooling and natural ventilation to the ground floor and third floor spaces, where pest control is not as high a priority as it is for other areas in the brief, are among the active measures to reduce energy consumption. The heating and cooling is provided by GSHPs and both air-handling units are fitted with a thermal wheel for heat recovery, and the unit controlling humidity is also fitted with a moisture-recovery wheel (or entropy wheel). These features have also actively contributed to reducing energy consumption and CO$_2$ emissions.

Project team

Client	Royal Botanic Gardens, Kew
Structural engineer	Buro Happold
Service engineer	Atelier Ten
Quantity surveyor	Fanshawes
Landscape architect	Chris Blandford Associates
Concrete consultant	David Bennett
Main contractor	Willmott Dixon
Concrete subcontractor	Toureen Mangan

Building data

New wing	5 floors
Dimensions	width 14 m, length 45 m
Year completed	2009



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