PART VII. DEVELOPMENTAL APPLICATIONS

CONCRETE TECHNOLOGY FOR THE FUTURE

CEMENT CONCRETE
& AGGREGATES AUSTRALIA

This section considers areas of concrete technology that will take both concrete as a material and concrete construction into the future. Concrete has evolved from the basic material developed in the 1800's, and if anything, the rate of expansion of concrete technology is increasing in line with (a) demands for improved performance, and (b) the growth of technology generally.

CONTENTS

1. INTRODUCTION

While the Romans were excellent exponents of concrete technology, and examples of their use of concrete persist to this day, the reality is that concrete technology did not develop continuously from that point, and in fact went into 'hibernation' until about the time of the Industrial Revolution. With the Industrial Revolution came the need for bigger, better and more durable buildings to support the investment required in new factories, as well as the need to provide reliable infrastructure for railways, shipping and other transport modes needed in this period of growth. Ease of construction and improved durability were two of the primary necessities. After a period of development in the late 1700's and early 1800's, 'Portland' cement and concrete as we now know it became a reality. Development of concrete technology has been 'non-stop' since then.

2. PIVOTAL DEVELOPMENTS IN CONCRETE TECHNOLOGY

There have been a few pivotal developments in concrete technology that have led to more wide-ranging applications of concrete and which have formed the basis for the expanded use of the material in a huge array of applications. Concrete technology has been supported by excellent research that has been carried out in many countries leading to an in-depth understanding of concrete performance. One of the advantages here has been the 'universal' nature of 'Portland' cement concrete. No matter where it is made in the world it is based on the same fundamental technology which has meant that effectively all research has been useful in increasing the understanding of the nature and performance of the material.

Two fundamental development areas that have made concrete into the high performing, versatile material that it is now are (a) use of steel reinforcing, and (b) admixture development.

2.1 STEEL REINFORCING

(The sub-section provides a brief development history of concrete reinforcing-prestressing and can be regarded as supplementary information for Part I, Part II-Section 6 and Part V-Section 11 of this Guide.)

While concrete is well known for its high compressive strength, it is also known as a brittle material of low ductility. Used alone, concrete would not have become the highly sophisticated and versatile building material that it is now. It is the combination of concrete and steel reinforcing, based on the inherent compatibility of the two materials that has expanded the range of uses of modern concrete.

Reinforced concrete was developed initially in France and England in the mid-1800's and used in some quite simple construction including making flower-pots and for domestic dwellings. In the late-1800's a German firm used reinforced concrete widely leading to an increased understanding of reinforced concrete applications. Then in the early-1900's, reinforced concrete started to gain traction in the USA with it being used in bridge construction, in an aesthetic application (a bell tower in San Francisco which survived the 1906 earthquake) and, in 1904 for the first 'skyscraper' – the 16-storey Ingalls Building in Cincinnati. This was followed quickly by a number of similar high-rise constructions in Los Angeles. It was the 1906 San Francisco earthquake and the need for more resilient buildings that increased interest in concrete construction due to its relatively high strength and the fire resistance of the material.

Today reinforced concrete, particularly through newer approaches to reinforcing (e.g. post-tensioned applications including bridges and floors in high-rise commercial structures), is widely used and has further extended the scope of structural applications of concrete.

It should be noted however, that steel embedded in concrete will lead, ultimately, to the destruction of that concrete after steel corrosion begins. Through either carbonation or ingress of chloride ions, embedded steel will ultimately corrode unless some electrochemical protection is applied to prevent or reverse any active corrosion. It is often stated that modern concrete is a lesser product than (say) Roman concrete, with the example of the Pantheon in Rome being given as a concrete structure that has lasted, in pristine condition, for 2,000 years. It is notable that this structure contains no steel (or metal) reinforcement.

2.2 CONCRETE ADMIXTURES

While very basic admixtures were used even by the Romans (e.g. blood as an air entraining admixture), it has been the development of modern concrete admixtures that began in about the 1930's and accelerated towards the year 2000, that has taken concrete into new paradigms. In their earliest versions, concrete admixtures were confined to simple air-entrainers, retarders, accelerators and water-reducers. Modern admixtures allow a huge range of concrete performance characteristics to be managed, including very high strength concrete of excellent workability that can be produced, pumped and placed; concrete that can be placed underwater; concrete that can be 'put to sleep' for up to 3 days and then 'woken up' and applied to a substrate achieving high strengths very quickly; concrete where the workability can be managed for extended periods in high temperature environments without unreasonably delaying setting time. Concrete admixtures can also now be 'tailored' to achieve certain performance outcomes using PCE technology (see Section 5 *'Admixtures'*).

Admixture use forms the basis of many modern concrete applications.

3. CONCRETE TECHNOLOGIES FOR THE FUTURE

Like all other modern technologies, developments in concrete technology are increasing (a) as general science and engineering evolve, and (b) in response to increased performance requirements (to enhance both engineering and environmental performance) from industry and the community. In the following, several of the newest approaches to improving and expanding concrete applications are discussed.

3.2 SELF-COMPACTING CONCRETE (SCC) OR SUPER WORKABLE CONCRETE (SWC)

While SCC/SWC has been in use for some years, it is the range of applications and the likelihood that SCC/SWC will become the new ‘norm’ for many concrete applications that has it included in this review.

SCC/SWC is becoming more widely used as demand increases for very high strength concrete in both precast and pre-mix applications that (a) is stable with respect to segregation risk, (b) is able to be pumped in (very) high-rise structures, (c) is able to produce high quality off-form finishes, (d) is (more) easily placed in elements with highly congested reinforcement, and (e) reduces manpower requirements for placing and finishing.

As with any high-performance material being used in demanding applications, it is imperative that the use of SCC/SWC be trialled for any project for which it is being considered as there is a large range of performance properties able to be achieved with this product type and these need to be assessed against the needs for each potential project.

(For more information about SCC/SWC, refer to Part VI-Section 22 of this Guide.)

3.3 FIBRE REINFORCED CONCRETE (FRC)

FRC in its simplest forms has been used in the concrete industry for many years. However, the basic applications of steel or plastic fibres for control of cracking or improved tensile performance and abrasion resistance are now being extended by the use of specialised fibre and material types.

In the USA, a ‘bendable’ concrete has been developed. This is a relatively light-weight concrete that uses very fine silica sand in its formulation, as well as coated PVA fibres. When load is applied to a concrete element using this technology, the lubricated fibres allow the concrete to bend rather than break (i.e. they increase its ductility). This technology is useful in seismic areas and has been applied in high-rise buildings in Tokyo, Japan.

In related research, carbon nano-tubes (synthetic carbon ‘tubes’ of about 5-60 ɳm diameter and 5-30 µm length) have been added in low proportion to cementitious materials with resultant increases in compressive and tensile strengths and improved paste microstructure.

(For more information about fibre reinforced concrete, refer to Part I, Part II-Section 7 and Part V-Section 11 of this Guide.)

3.4 ULTRA-HIGH STRENGTH / ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

UHPC has been developed and applied in many countries, with the USA leading the way in many applications. With compressive strengths in the order of 200 MPa and tensile strengths in the order of 10 MPa, this type of concrete is being used in bridge construction (for girders and decks and seismic retrofits), in precast applications and in security/blast mitigation applications.

UHPC, by its very nature, is expected to have at least a 100-year design life and to be highly durable and relatively very resistant to penetration by chloride ions, to freeze-thaw attack and to carbonation and has very high abrasion resistance. These characteristics make it an ideal (albeit initially expensive) concrete material for use in bridges in regions where snow and ice are common, and salt-based materials are used for management of ice build-up.

UHPC is produced from a mixture of powdered cementitious materials (cement plus silica fume), other inert powders, super-plasticising admixtures, water (with a W/C ratio generally <0.2) and (steel, synthetic or natural) fibres. Mixing of the UHPC is a prolonged process, but given the fineness of the components, is fundamental to its success. Nanoparticles have also been used to further enhance the performance of UHPC.

3.4 POLYMER CONCRETE

Polymer concretes can (a) use thermoplastic polymers or thermo-setting resins as replacements for cement in a concrete mix, or (b) use polymeric materials in combination with cement as a binder in Polymer Cement Concrete or Polymer Modified Concrete.

When manufacturing polymer concrete with polymer only as the binder, the resin content is typically in the range of 10-20% by mass of the concrete – the actual proportion used depends on the nature and size of the aggregates and the concrete strength required. No water is used in these particular mixes. With the range of polymer types available and varying proportions of polymer that can be used when making Polymer Cement Concrete, a wide range of concrete performance properties is possible.

The use of polymeric binders has several effects, including (a) increased cost, (b) good compressive strength performance, (c) improved tensile strength performance, (d) low permeability and resistance to water penetration, (e) good adhesion to a range of other materials, (f) good freeze-thaw resistance and (g) lighter weight concrete that is readily compacted by vibration.

With increasing demands for high durability performance for some concrete applications and some reduction in cost of polymer materials, there is an increasing interest in ‘polymer concrete’ in specialised applications like sewerage systems, in concrete repair and for the construction of smooth concrete surfacing.

3.5 PERVIOUS CONCRETE

Pervious or permeable concrete allows water to run through it rather than run over it as would be the case in conventional slab or pavement applications (**Figure 24.1**). With conventional concrete use in open-space environments (e.g. car parks at shopping centres, council paths and airports) there can be significant run-off and potential flooding issues associated with any reasonable rainfall event. With pervious or absorbent concrete, the water can run through the concrete and be directed to flood control systems located beneath the concrete. This has both functional and environmental advantages.

Figures 24.1 – A Permeable Paver Demonstration, Austin’s Ferry, Tasmania, Australia[24.1]

Pervious or absorbent concrete is effectively a no-fines concrete where the sand is omitted from the mix design. This creates a coarse aggregate mix where the paste adheres to the coarse aggregate and binds it together, while leaving voids between the coarse aggregate particles that allow water to easily penetrate the concrete. Typically, a single-sized aggregate is used – usually either 20 mm, 14 mm or 10 mm – and no aggregate material <5 mm or flaky or elongated aggregate should be present in the mix. Final strength is dependent on the cement content and water/cement ratio. Increasing the paste volume (water + cement) will reduce the permeability. Water demand can be very tricky and too much water can affect placing and final performance characteristics. There is no workability test as such for this concrete. The concrete should not be subjected to compaction, except possibly rodding around the edges of formwork or penetrations and specialised rollers where placing pavement. The concrete should be placed quite quickly as it has a tendency to dry out easily. Effective curing of the exposed surfaces of this product generally requires barriers such as covering in plastic film.

While this type of concrete is suited to the purpose intended (for example, as in **Figure 24.2**), and for the particular environments indicated, concerns have been raised about the general performance and durability of pervious/absorbent concrete. This has limited its applications by some specifying authorities and in some geographical regions. There is concern, for example, about the freeze-thaw resistance of this type of concrete. In temperate and tropical regions this does not create an issue, but in cooler climates it would be a problem.

Figure 24.2 – Porous Concrete Pavement in the Middle Strip of Two Parallel Concrete Pavements[24.2]

3.6 SELF-HEALING CONCRETE

One of the realities regarding concrete is that it can crack for a variety of reasons. Generally, this is anticipated in the design phase for a new structure and accommodations are made to ensure that any cracking does not unduly influence the life or performance of the structure.

Recently, self-healing concretes have been developed. These concrete products will react to water ingress into the concrete from any crack that has formed by initiating a reaction that forms a product that will seal the crack(s) (see **Figure 24.3**). This type of reaction can be by one of several mechanisms.

In a more conventional approach, the concrete mix can contain either (a) 'hydro-gels' or (b) capsules of polymeric materials that break when and where the concrete cracks. In both cases, the hydro-gel or the polymeric material from the capsule reacts with the water that has entered the concrete and swells, thus sealing the crack.

In a less conventional approach, the concrete as manufactured contains a type of bacteria that, when it comes into contact with air and water, reacts with lime (from cement hydration) to form limestone (or calcite) that can seal the crack.

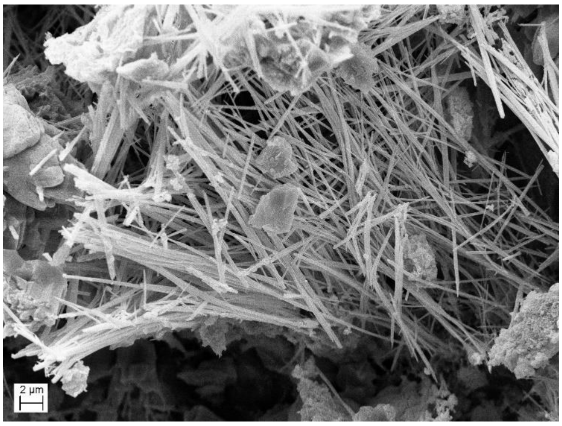

Figure 24.3 – A SEMI Image showing the Formation of a Crack Bridging for Self-healing in Concrete[24.3]

It should be noted that these approaches to 'healing' cracks cannot be retro-fitted and the materials – polymers or bacteria – need to be included in the original concrete mix.

3.7 SELF-CURING CONCRETE

There is no real debate about the importance of curing concrete to ensure that the best strength and durability performance is obtained from a given concrete mix. There is also no debate that, in many cases, curing is ignored in most concrete construction projects.

Another concern in modern concretes, with respect to ensuring expected strength and durability performance is achieved, is that (a) the prevalence of low water/cement ratios (say <0.35) and (b) the use of silica fume in high-performance concretes, increase the risk of self-desiccation of the concrete which can lead to increased autogenous shrinkage. In these situations, a process which allows the concrete to be 'self-curing' is advantageous. For low W/C ratio mixes, it is also the case that the application of external water curing is likely to be a less effective curing method because of the low porosity and permeability of the resulting concrete.

In the process of self-curing, either (a) water is added to the concrete from internal sources (e.g. saturated porous aggregates), or (b) water is retained within the concrete by using chemicals that prevent or limit water loss by evaporation.

The use of saturated, lightweight aggregates allows the exchange of water between the aggregate particles and the 'cement paste' in both the plastic and hardened states of concrete. It is the exchange in the hardened state that promotes ongoing curing. These aggregates may be natural or synthetic and examples include scoria and expanded shales. In some cases, the outer surface of the aggregate material has some pozzolanic characteristics and this further contributes to strength improvement when using these special aggregates.

The chemicals added to the mix to promote internal curing include polyethylene glycols of various molecular weights and other polymeric materials. These compounds form hydrogen bonds with water molecules in the 'cement paste' which lead to a reduction in water vapour pressure and reduced evaporation rates – leaving more water in the paste for ongoing hydration reactions as indicated by increased compressive strength in concrete using these particular additives.

3.8 TRANSLUCENT CONCRETE

Concrete is typically a solid mass and provides a rigid barrier to heat and sound transmission, and of course, to light transmission. Or at least that was the case until recently.

There have been two approaches used to making concrete translucent (**Figure 24.4**) – that is, allowing a degree of light penetration through the 'solid' concrete.

In one form of translucent concrete, optical fibres are included in the concrete mix and these are able to align to a sufficient degree to allow some light to be passed through the concrete – sufficient to allow an object on one side of the (say) wall to be seen in outline from the other side.

In another version, translucent fabric is cast layer by layer in the concrete. The final product shows no detriment to strength or durability performance but allows a degree of visibility of forms and even colours to be passed through the concrete structure. The fibres in the fabric are very fine and the proportion of fabric to concrete is low which accounts for the minimal impact on the physical performance of the concrete.

Figure 24.4 – Translucent Concrete Booth at Expo Bau 2011 in Munich, Germany[24.4]

In a similar development, a cement that can emit light has been developed. It would appear that the cement/concrete contains a phosphorescent chemical that absorbs light during the daylight hours and then emits light once the sun goes down. The suggestion is that it would be useful for paths and on bridge surfaces to improve user safety in these situations.

3.9 GRAPHIC CONCRETE

Graphic concrete involves the creation of complex images on the surface of concrete, particularly for precast wall applications (**Figures 24.5** and **24.6**). The primary use is in architectural finishes and the creation of murals for a variety of purposes. There are a couple of different methods for producing these types of surfaces.

In one system, the precise application of retarders to the surface of concrete form liners is used to create contrasting surface finishes – most particularly between 'smooth' concrete surfaces and exposed fine aggregate surfaces.

For more information see: www.graphicconcrete.com

Figure 24.5 – Artwork created on Concrete Walls of Hämeenlinna Provincial Archive, Finland[24.5]

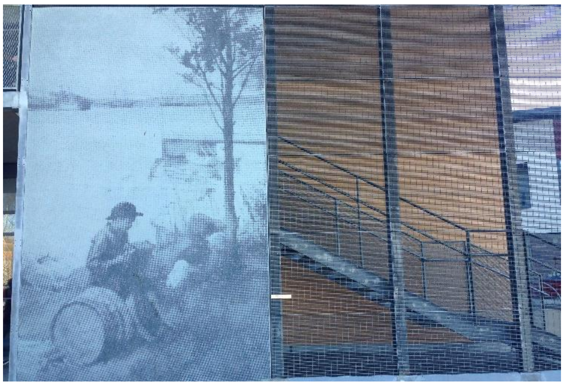

Figure 24.6 – Artwork created on a Precast Concrete Wall[24.6]

In another system, thermochromatic pigments are combined in a concrete mix and, along with the use of wire heating technology and microprocessor control, changing images and colour-changing patterns can be manipulated in the surface of the concrete element. For more information see: www.chromastone.com

3.10 3-D CONCRETE PRINTING

Perhaps one of the most exciting and useful developments in concrete technology is the potential use of 3-D printing to create useful concrete structures like housing and bridges, and in reality, any other type or style of structure that can be produced by this process.

The basis of 3-D printing is the interaction of robotics (and other mechanical systems) and concrete technology to produce structures without any (or with very little) manual intervention. Arguably, any design that can be converted into a computer file and loaded into a computer-controlled robot can be created – provided the concrete-related issues can be controlled. To date there has been huge interest in this technology from the military, from space agencies and from commercial companies to try to implement the technology in their respective areas.

*(**NOTE**: 3-D printing has been widely and successfully used in other applications, particularly in creating medical prostheses, and its applications in these 'soft' applications are growing. Concrete, having a finite plastic life and being required to create high strength/durability structures, provides some different and interesting challenges.)*

3-D printing involves the creation of walls and elements using layering of 'concrete' that eventually grow into the final structure (**Figure 24.7**). Complexities that are being grappled with include the use of coarse aggregate materials to provide strength; the bonding between successive layers in the structure and the means by which reinforcing might be used to provide improved strength performance.

Figure 24.7 – Robotics and 3-DPrinting, Extrusion-based Techqniue[24.7]

To date, 3-D printing has been used to create housing, public buildings, bridges and various structures that might be described as architectural or art-based (see **Figures 24.8** to **24.11**). This variety of structures is indicative of (a) the versatility of the process and (b) the wide-scale potential for use across the world, with a pertinent example being for the production of cheap but durable homes for people in poor countries or where some weather (or similar) event has caused widespread destruction.

If the amount of research on 3-D printing of concrete is any indicator, this technology will be at the forefront of concrete technology development for many years to come.

3-D printing does not follow the 'conventional' construction technology described in Part V of this Guide (i.e. handling and placing, compaction, finishing, curing, control of surface finish and control of cracking etc.). As the name implies, 3-D printing, also called 'additive manufacturing' or 'additive layered depositing', in general, is constructed by 'joining materials to make objects from 3-D model data, usually layer upon layer' (The American Society for Testing and Materials – ASTM). From this initial concept, 3-D printing has been developed into two major co-existing trends for concrete production, namely Extrusion-Based Techniques and Powder-Based Techniques:

- ***The extrusion-based techniques***, also called 'continuous extrusion' and 'fused deposition modelling', relies on the consecutive extrusion and deposition of a (semi-liquid) paste/mortar/concrete mixture in a layer-upon-layer manner. The mixture is proportioned and mixed in advance, then is stored in a reservoir before being pumped to a printing head/nozzle (**Figure 24.7**).

  An appropriate mix design to facilitate the extrusion-based techniques focuses on balancing two important yet somewhat contradicting requirements. On one hand, the mix must ensure sufficient workability, pump-ability without segregation; which reflects similar characteristics to self-compacting concrete (see 3.1). For this reason, a careful selection of aggregate sizes and shapes, along with other ingredients, must be conducted in relation to the chosen size and type of the printing nozzle. On the other hand, in the absence of formwork, the mix must ensure the stability (i.e. without heavy distortion) of extruded layers once they are placed. This is crucially important as each layer carries not only its self-weight but soon after it is placed, it will also support the 'dead loads' imposed by subsequent layers. This requirement normally necessitates a mix design with a fast setting capacity and a high rate of strength gain. Equally importantly, without formwork protection, moisture loss and its effects on hydration and strength gain (discussed in Section 15), as well as other durability issues, need to be properly addressed.
- ***The powder-based techniques***, also called 'binder jetting' or 'granular binding fabrication', sinter numerous layers of loose base powder by selectively depositing a specialised liquid (also known as 'ink') on each layer. The ink acts as a binding agent which also activates chemical reactions in the base powder. The final element is then dug out of the powder mass either by vibration or air blow. Although there is no practical limitation, the techniques have mostly been employed for small to medium scale structures with complicated compositions (**Figures 24.10** and **24.11**).

Figure 24.8 – 3-D Printed House, Extrusion-based Technique[24.8]

Figure 24.9 – 3-D Printed Bridge, Extrusion-based Technqiue[24.9]

Figure 24.10 – 3-D Printed Bridge, Powder-based Technique[24.10]

Figure 24.11 – 3-D Sculpture, Powder-based Technique[24.11]

4. SUMMARY

Concrete (as we know it) has had a life of about 200 years and although concrete technology is often seen as static and boring, the reality is that concrete has been developing and evolving as a material throughout its 200-year life. Modern concrete technology and the types of structures that are achievable would not have been contemplated 50 or even 30 years ago – such is the speed of development of the technology. This section has described some of the important advances of recent times and some of the (potential) improvements that will be made in the field of concrete technology over the next few years. It is likely however, that this section will be redundant much sooner than we might expect – such is the rate of change.

Of importance to the rate of change is the growing scope of concrete applications. The potential use of concrete by military and space agencies will likely see very high rates of change in the potential applications and the nature of the material as more challenging requirements are created by these new end-users. For those who don't think concrete is boring – these are exciting times!

End Notes:

[24.1] Photo adopted from *'A permeable paver demonstration, Austin's Ferry, Tasmania, Australia',* by JJ Harrison, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license, https://commons.wikimedia.org/wiki/File:Permeable_paver_demonstration.jpg

[24.2] Photo adopted from Aaron Volkening, licensed under Creative Commons Attribution 2.0 Generic (CC BY 2.0), https://www.flickr.com/photos/87297882@N03/8071001110/in/photostream/

[24.3] Photo adopted from *'Concrete Crack Bridge for Self-Healing'*, by Department of Engineering, University of Cambridge, licensed under Creative Commons Attribution 2.0 Generic (CC BY 2.0), https://www.flickr.com/photos/cambridgeuniversity-engineering/14272521260

[24.4] Photo adopted from *'LUCEM Translucent Concrete booth at Expo Bau 2011'*, by Luxgineer, licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license, https://commons.wikimedia.org/wiki/File:LUCEM_Translucent_Concrete.jpg

[24.5] Photo adopted from *'Hämeenlinnan maakunta-arkisto'*, by Kansallisarkisto, licensed under the Creative Commons Attribution 2.0 Generic license, https://commons.wikimedia.org/wiki/File:H%C3%A4meenlinnan_maakunta-arkisto.jpg

[24.6] Original art by Albert Edelfelt, photo by Zuissii, Public Domain license, https://commons.wikimedia.org/wiki/File:AETeos.jpg

[24.7] Screenshot adopted from *'Optimising 3D Concrete Printing'*, by 3TU.Bouw, licensed under Creative Commons Attribution-NoDerivs 3.0 Unported (CC BY-ND 3.0), https://vimeo.com/204877955

[24.8] Photo adopted from Marine Corps Systems Command, Public Domain license, https://www.marcorsyscom.marines.mil/Photos/igphoto/2001957675/

24.9 Photo adopted from *'This is a detail of the first ever 3D printed bridge in the world'*, by Marczoutendijk, licensed under Creative Commons Attribution-Share Alike 4.0 International license, https://commons.wikimedia.org/wiki/File:Detail_of_3D_printed_concrete_bicycle_bridge_in_Gemert_(NL).jpg

24.10 Photo adopted from *'The first structure of this type in the world'*, by Institute for advance architecture of Catalonia, licensed under the Creative Commons Attribution-Share Alike 4.0 International license, https://commons.wikimedia.org/wiki/File:3D_Printed_bridge.jpg

24.11 Photo adopted from *'A 3D printed sculpture made with D-Shape technology'*, by D-Shape, licensed under the Creative Commons Attribution-Share Alike 4.0 International license, https://commons.wikimedia.org/wiki/File:Radiolaria_d-shape.jpg

CCAA OFFICES

NATIONAL OFFICE (NSW)
Level 10
163 -175 O'Riordan Street
Mascot NSW 2020

POSTAL ADDRESS
PO Box 124
Mascot NSW 1460
Telephone: (02) 9667 8300

QUEENSLAND
Level 14, 300 Ann Street,
Brisbane QLD 4000
Telephone: (07) 3227 5200

VICTORIA
Suite 910/1 Queens Road
Melbourne VIC 3004
Telephone: (03) 9825 0200

WESTERN AUSTRALIA
45 Ventnor Avenue
West Perth WA 6005
Telephone: (08) 9389 4452

SOUTH AUSTRALIA
Level 30, Westpac House
91 King William Street
Adelaide SA 5000
Telephone: (02) 9667 8300

TASMANIA
PO Box 1441
Lindisfarne TAS 7015
Telephone: (03) 6491 2529

ONLINE DETAILS
www.ccaa.com.au
Email: info@ccaa.com.au