FUTURE OF CONCRETE IN URBAN AND INFRASTRUCTURE DEVELOPMENT

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ABSTRACT. The existing infrastructure in a number of urban centres is either critically deficient or already crippled. This is an enormous challenge and could have a significant impact on future generations, if not solved in time and properly. The planet's resources are limited, which places an extraordinary constraint on how we go about living in the future. Climate change is a reality and no longer a fictional theme. Resources that were thought to exist in abundance a century ago are now becoming scarce. Unless we stop and take stock of where we are now, change, and adapt to the future demands, we will soon run out of opportunities that currently exist. The paper critically examines where we are today in terms of meeting the demands of our current and future societies. It reviews the contribution of concrete over the course of modern civilisation through the lens of infrastructure development. The paper aims to open discussion around the promotion and use of concrete for future urban and infrastructure development. The focus is on adopting some of the disruptive technologies of the fourth industrial revolution to potentially shape the world for many centuries to follow.

Keywords: Infrastructure development, Concrete, Sustainability, Resilience

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INTRODUCTION

The current world population of 7.6 billion is expected to increase by 50% by the end of this century, reaching 11.2 billion [1]. The growth of population is predicted to be concentrated in just nine countries, of which India tops the list that consists of several Asian and African countries, in addition to the USA. Of the 7.6 billion population, 55% currently live in urban areas, which is projected to increase to 68% by 2050 according to a new UN data set launched this year [2]. This means the overall population growth would add another 2.5 billion people to urban areas by 2050, with close to 90% of this increase taking place in Asia and Africa. This highlights that our basic needs such as access to low-cost shelter, clean water, sanitation, food, health services, and education are on the rise, while the availability of resources are on rapid decline.

The existing infrastructure in many urban centres is either critically lacking or already crippled. There is enormous pressure to solve infrastructure challenges on a global scale. This means engineers, environmentalists, scientists, and urban architects need to work together with politicians to solve the crisis.

This paper examines where we are today in terms meeting the demands of our current and future societies. It reviews the contribution of concrete over the course of modern civilisation through the lens of infrastructure development. The paper aims to promote discussion around the promotion and use of concrete for future urban and infrastructure development. The focus is on adopting some of the disruptive technologies of the fourth industrial revolution to potentially shape the world for many centuries to follow.

CONCRETE AS A BUILDING MATERIAL – THE STATUS QUO

Concrete is the second most consumed material after water and plays a very significant role in the built environment. It is said that twice as much concrete is used in construction around the world than the total of all other building materials, including wood, steel, plastic, and aluminium. An estimated 30 billion tonnes of concrete were consumed globally in 2006, compared to 2 billion tonnes in 1950 [3]. A fifteen fold increase in the consumption of concrete between 1950 and 2006, where the population increased by less than three times in that period. This is a clear indication that the consumption of concrete is increasing disproportionally to the population growth.

There could be several reasons for the disproportional increase of concrete's consumptions including (a) financial, social, and cultural demands of our societies have increased in multiple folds necessitating more infrastructure; and (b) concrete is now used readily and widely where it was not the case previously. Prestressed and factory-made precast concrete modules have directly competed with materials such as steel, and often preferred to other materials as we see now.

The Origins and Use of Concrete in Modern Civilization

The origins of concrete can be traced back to Romans for their extensive use of concrete including stones and mortar, more than 2,000 years ago. Although various forms of concrete existed until 19th century, it was Joseph Aspdin, an English brick layer by trade, paved the way for modern days concrete. Aspdin patented his product as "Portland Cement" as the hardened material resembled the Portland stones. Subsequently, his son continued the business of producing cement and supplying to the rest of the world. While concrete was initially used on its own, utilising its inherent compressive strength, soon reinforcements in the form of chains, rods, flats, and mesh made of iron were introduced to improve concrete's tensile strength. Reinforcements to concrete made it as a popular building material. The reinforced concrete was then called ferro-cement or "*béton armé"* (in French).

Early Use of Concrete in New Zealand

One of the early concrete construction in New Zealand is Coronation Bridge (Figure 1), named after the King George V's coronation in 1911. An arch bridge initially designed to carry horse carts and wagons, it was rejuvenated in 2008 to provide access between the adjacent carpark and street for pedestrians and cyclists.

Figure 1 Coronation Bridge, Henderson, New Zealand (opened for public in 1912)

The next advancement in concrete took place when prestressing of steel reinforcement was invented and applied to improve its versatility. Prestressed concrete can span longer and economically compared to steel options. It gave structural engineers and architects to push boundaries of materials further. One of the pioneering application of prestressing (in post-tensioning) in New Zealand bridges was the old Newmarket viaduct (Figure 2).

It was constructed in mid-1960s by the balanced cantilever method, the first bridge to use this technique in New Zealand. Unfortunately, the initial design overlooked the differential thermal stresses, which were not well understood at that time. This and a few other problems meant the viaduct had to be strengthened with additional external post-tensioning not long after opening in 1966 [4]. In 2015, a new viaduct replaced the old one to add extra traffic lanes and provide seismic resilience to Auckland's Southern Motorway.

Figure 2 Old Newmarket viaduct on the Southern Motorway, Auckland, New Zealand

Concrete in Modern Infrastructure Development

Availability of raw materials in abundance combined with the low cost, especially in the developing countries, has a great influence on the use of concrete for both major infrastructures and residential development. It is used heavily for constructing buildings of all types, including hospitals, airports, sea ports, tunnels, and power stations. It is commonly viewed as an effective material yielding relatively low, whole-of-life costs, not only at construction, but during operation of these assets over their 100-year design life.

Steel reinforcements and prestressing strands used for strengthening concrete are susceptible to environmental effects. However, there has been progress in mitigating most of these durability issues, to delay major interventions during the life of the assets.

In developed countries, concrete has been heavily used for significant infrastructures. The reasons for its widespread use include economies, politics, and industrial conditions, to name a few. For example, in New Zealand, the industrial action from the Boilermakers' Union in 1970s and 80s disrupted big infrastructure projects such as BNZ Centre in Wellington and Mangere Bridge in Auckland over a decade or more. This was a catalyst to tip the balance for the use of concrete as the preferred material for a long time to come.

Some of the iconic structures constructed out of concrete in the last century have transformed the landscape forever and brought locals and tourists to the place to marvel at these master pieces. The Sydney Opera House, Australia opened in 1973 (Figure 3) and the Bahai House of Worship (Figure 4), also known as Lotus Temple, New Delhi, India are two examples of such iconic structures.

Figure 3 Sydney Opera House, Australia

Figure 4 Bahai Temple, New Delhi, India

While both structures demanded complex structural analysis and design, there was a common thread in these two projects. There was incredible collaboration between the client, stakeholders, architects, engineers, and contractors to achieve the best for the project. The Opera House suffered from the consequence of the original architect resigning mid-way through, but it was fortunate to see another architect stepping up to complete the project, although ended up costing four times more than the initial estimate.

The tallest tower “Burj Khalifa” in Dubai (Figure 5) is an exemplar of a building at extreme heights. At 828m high, it is the tallest structure in the world since it was completed in 2010. The primary structure is made of concrete while the pinnacle is steel. Both concrete and steel were utilised to their advantages in this project. One of the major innovation is the use of high-performance concrete for the core and walls, providing concrete the necessary plasticity to be pumped higher than it has ever done before [5]. Both the flow and strength of concrete were improved by using a combination of microsilica fume, pulverised fly ash, and ground granulated blast furnace slag.

TOM DULAT/GETTY IMAGES

Figure 5 Burj Khalifa, Dubai - the world's tallest structure

The engineering and architecture are inseparable in this structure and the collaboration between the two professional disciplines were instrumental in developing a design that could be constructed successfully.

Concrete in Modern Urban Development

The contribution of concrete in our urban sprawl and development has been on the increase for a long time. The skyscapes of all major cities are now visibly dominated by high-rise towers and land transport infrastructure primarily constructed with concrete. It is clearly evident that concrete has lent itself to create the character of many cities and contributed to the modern architecture post WWII.

A good example is Chandigarh, the capital city of northern Indian States of Punjab and Haryana. The city was planned and designed in 1950s by the Swiss architect, Le Corbusier using concrete as the main construction material. His choice of concrete was influenced by the availability of material at a reasonable cost in a poor country not long after the independence from the imperialism and the traumatic partition.

Le Corbusier’s buildings are bold, striking, and used concrete to facilitate function while protecting from the environment, especially providing characteristic sun breakers (brisesoleil). Figures 6 and 7 show the Assembly Hall in the Capitol Complex in Chandigarh and Tower of Shadows.

Figure 6 Assembly building, Chandigarh, India

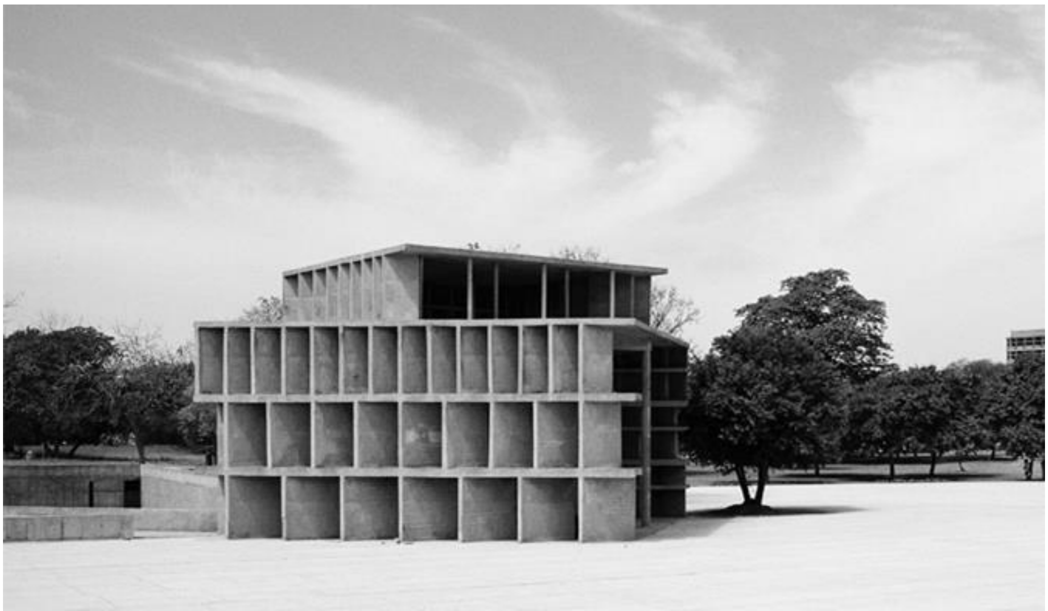

Figure 7 Tower of Shadows, Chandigarh, India

Where developed cities require enhancements to the existing infrastructure, there have been development underground to prevent disruptions to the overland flow and use. This was the case in Auckland, New Zealand, when the city's authorities decided to improve the public transport in a concerted effort to mitigate congestion and improve the integrated transport in Auckland. The city's old railway station, built in 1930s, was located approximately 1.5km from the city centre and was quite inconvenient for commuters. The new transport interchange brought the station back to the site where it was 70 years ago, but this time it is underground to maximise land use above and to minimise conflict with ground-level circulation [6].

The underground station (Figure 8 shows the construction) has been formed by a watertight reinforced concrete box structure, 11.5m deep and approximately 45m wide. Both 1,200mm and 900mm secant pile walls of 20 – 24m deep are used in the western end of the box where it lies in a valley, whereas the eastern end walls are *in-situ* reinforced concrete between 600 – 750mm thick founded on bedrock.

Figure 8 Britomart Station (Eastern end), Auckland under construction in 2002

Concrete was the primary material of choice for forming the underground station's retaining walls, roof, and base slab with water proofing membranes to protect any water ingress. The station's base is 11m below the sea level and only 200m away from the foreshore. The site was also the former sea bed. Concrete designed for crack-control at serviceability loads was the principal defence against the water penetration. The construction joints were formed with hydrophilic waterbars and additional hydrophilic material on the outside. The station box has also been tanked with a bentonite waterproofing membrane as a second line of defence under water penetration.

CHALLENGES AND OPPORTUNITIES OF CONCRETE

The continuing increase of concrete as a construction material inevitably poses a challenge towards sustainable development. The limited resources of our planet forces us to be mindful of our consumption of natural resources. At the same time, the emissions of manufacturing products, travel, farming, and other activities of our lives increasing the CO_2 emissions has contributed to global warming.

The UN’s 2030 Agenda for Sustainable Development [7] made in 2015 provides a shared blueprint for peace and prosperity for people and planet, now and into the future. Of the 17 goals within the Agenda for Sustainable Development, there are many that would be influenced by infrastructure building and urban development. There is greater responsibilities for us to now focus on sustainable development of our infrastructure and urban regeneration.

Constituent Materials of Concrete and Their Effects

Because concrete has been used in vast quantities in our construction industry, the resulting Carbon footprint is also remarkable. It is reported that currently concrete material is contributing to 5% of the world’s total CO_2 emissions. This is mainly due to cement, the key ingredient used in concrete.

Production of cement involves high temperatures (up to 1,500^o Celsius) to initiate the breakdown of limestone ($CaCO_3$), the main material of cement, which results in Calcium Oxide (CaO) and CO_2. Both the energy required to produce cement and the resulting CO_2 emissions as part of the reaction process, cause the concrete’s high carbon footprint.

The vast amount of natural resources such as limestone and clay used in producing cement and aggregates used in the concrete mix will not be available forever. Additionally, fresh water requirement for concrete mixes is challenging in certain parts of the world.

Strategies Aiming to Making Concrete a Sustainable Material

A number of strategies and techniques have been developed over the years to make concrete a more sustainable construction material, starting with reducing the use of cement by increasing the supplementary cementitious material. By increasing the use of supplementary materials such as fly ash and slag, which are by-products of burning coal and smelting of metal ores respectively, have a significant impact on achieving the sustainable goals on both counts: using the waste material of another process and reducing the carbon footprint of concrete.

Another strategy is the use of recycled construction and demolition waste in the production of concrete mix. The Cement Sustainability Initiative [4] has been looking at recycling of concrete as a component for new construction such as road works aggregates and aggregates in new concrete mix. While the use of recycled aggregates reduces the wastes going into our environment such as landfills and reduces the use of new natural resources, it does not have a tangible effect on reducing the CO_2 emissions.

Improving the strength and durability of concrete would require reduced quantities of materials including cement, and reduce replacement efforts. The emerging fields of nano-engineered concrete with the use of graphene dispersions is a good example in terms of improving the concrete’s compressive and flexural strength by 145% and 80% respectively [8]. It is also reported that a decrease of nearly 400% in water permeability compared to the standard concrete has been achieved in these experiments.

Given the shortage of potable water in many countries there have been a push for the use of alternative sources of water for the production of concrete. In Australia, the water authorities are increasing the supply of recycled water as “greywater” for domestic use and as “reclaimed water” for agricultural and industrial needs [9]. It has been made possible to reuse higher proportion of wash water as well as combined wash water and slurries from concrete production operation, an ambitious move towards making concrete industry becoming zero-discharge facilities.

There are National and International Standards providing guidance and information related to mandatory limits on impurities in water for making concrete and performance criteria for the recycled water use in concrete.

FUTURE OF CONCRETE FOR RESILIENT AND SUSTAINABLE SOCIETIES

Fourth Industrial Revolution (4IR)

The Fourth Industrial Revolution refers to the significant and unprecedented advancement in technology that is already disrupting all aspects of our societies. As Professor Klaus Schwab, founder of the World Economic Forum, stated in *Foreign Affairs* (2015):

> *“We stand on the brink of a technological revolution that will fundamentally alter the way we live, work, and relate to one another. In its scale, scope, and complexity, the transformation will be unlike anything humankind has experienced before. We do not yet know just how it will unfold, but one thing is clear: the response to it must be integrated and comprehensive, involving all stakeholders of the global polity, from the public and private sectors to academia and civil society.”*

The first and second industrial revolutions made use of steam and electric power respectively to mechanise production. The third industrial revolution utilised electronics and computers to automate production. Now, the Fourth Industrial Revolution blends technologies from the digital, physical, and biological realms to enable entirely new systems and business models. The possibility of machines augmenting humans for better outcomes is already here, with respect to the use of robotics in manufacturing industry.

The 4IR has introduced disruptive technologies that can change the way we manufacture, construct, and make things. These disruptive technologies include artificial intelligence (AI), autonomous vehicles, drones, internet of things, advanced materials, 3D printing, and bio-technology. While the challenges to the humanity have given more problems to solve, some of these disruptive technologies have offered hope and opportunities for life-changing solutions.

The focus here is to review some of the ways our concrete industry can tap into the unknown potential to become the material of choice.

Innovative Use of Raw Materials

One of the biggest problems in the sustainable development of concrete is cement. As mentioned earlier, cement production involves significant energy and the release of CO_2. The reduction in the use of cement in concrete by additives and other cement substituting materials is one way of minimising the effect. Even if the use of cement is only halved, there is greater benefit to the environmental challenges.

The next natural question then would be whether cement can be fully replaced with another renewable resources or less impactful material, and would that still be effective as cement added concrete? Do we have any alternative cement substituting material that could fully replace cement? If we do not use cement at all in concrete, as cement is currently produced and used, would that mixture can be equivalent or better than our modern day concrete?

While it is still early days to make any conclusive comments, it is encouraging that nano-engineered materials have been currently trialled to improve concrete's performance. The use of graphene to both improve performance of concrete while reducing the cement quantity and concrete required is a progress that would continue to grow with more nano-materials emerging to trial different mixes of concrete.

Robots and 3D Printing

Construction methods for concrete infrastructure development has evolved over the times together with material development. The combination of AI (robots) with 3D printing is a fascinating concept for advancing our ability to build fast and may be cost effective with good quality control. It has already been trialled at small scale structures at the Nanyang Technological University, Singapore, to study the viability. If this takes off in the next decade or so it would revolutionise our construction industry. Concrete needs to be able to flow through nozzles and additionally able to bond with adjacent units/casts.

Self-healing Concrete

While self-healing seems an intuitive method of curing ailments, applying this to concrete to heal its woes is an exciting opportunity. Various studies and laboratory tests have confirmed that adding certain bacteria to the concrete mix had the ability to close the micro-cracks when formed and improved the water tightness of the concrete.

The research and development work undertaken at Delft University, Netherlands, has found what they call "bioconcrete", which consists of a form of bacteria that converts nutrients into limestone [9]. Their focus was to study the self-healing potential of various materials including concrete. The mix is made with specially selected types of bacteria found in nature, together with a calcium based nutrient, and nitrogen and phosphorous to the other ingredients of the concrete mix. These self-healing particles stay dormant until a crack initiates and water seeps through, and only then these bacteria start to germinate. It also prevents corrosion of the reinforcement by reducing the oxygen as the bacteria would have consumed the available oxygen in the water for its reaction to complete.

While promising, this advancement is still its development stage and the cost is currently prohibitive.

Maintaining and Upgrading the Existing Infrastructure

There are a large number of existing infrastructure assets that have either reached or are nearing 'end of life'. Often, some of these require increased structural capacity for the increasing demands. These assets require significant intervention to extend their lives, or demand replacement. It is important to keep in mind that we cannot and should not simply replace all the existing infrastructure at end of life, but rather find ways of extending their service beyond the original design life and improving the capacity of the structure, if that proves the economical and practical solution.

There are many examples where concrete structures, including bridges, have been extensively modified and strengthened to cater for the improved capacity. One of the examples include the Esmonde Road underpass in Auckland, New Zealand, which goes over the Auckland's Northern Motorway [10]. This had to undergo significant upgrade as a part of the Northern Busway Project in 2006-08. The purpose of this project was to improve the public transport beyond north of the Auckland Harbour Bridge.

The original underpass was built in 1960s when the motorway was constructed in Auckland. The underpass is a continuous bridge of four spans, supported by three intermediate piers and abutments at each end. It is a three-cell reinforced concrete box girder of depth 1.1m. The middle pier and the other two piers are located in the median and shoulders of the motorway carriageway respectively (Figure 9).

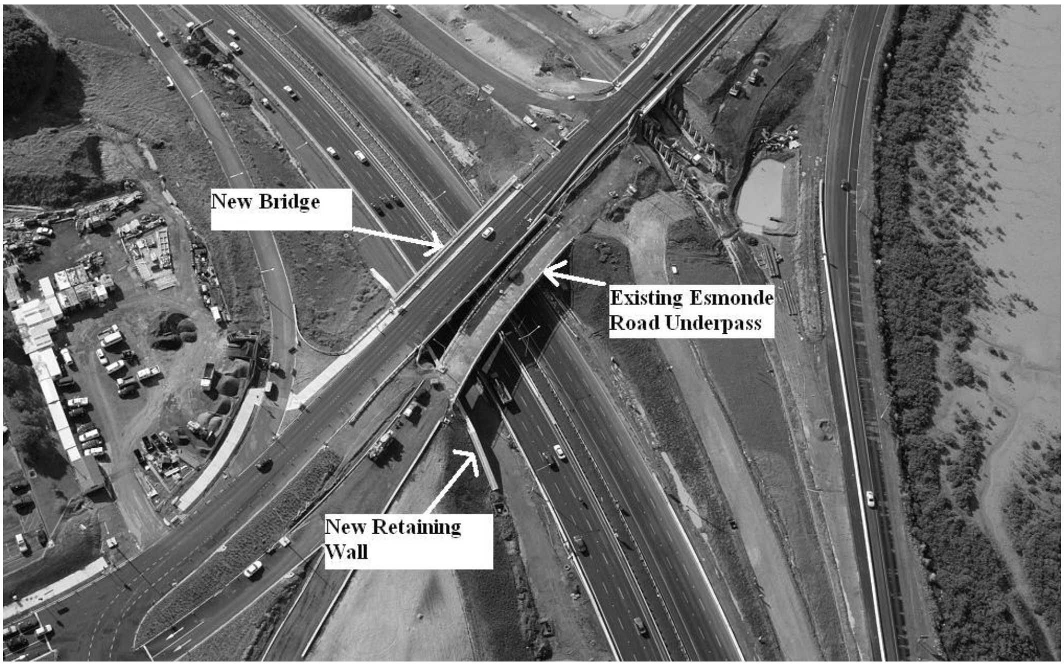

Figure 9 Modifications and Strengthening to the Esmonde Road Underpass

As part of the works, the deck of the underpass needed to be widened by up to 1.5m and raised by a maximum of 500mm to accommodate the modifications required at the motorway interchange. Retaining and strengthening the existing underpass was compared with constructing a new bridge, however constructing a replacement was found to be uneconomical and proved difficult without significantly disrupting the motorway. Therefore, it was decided to modify and strengthen the underpass. Strengthening included Carbon FRP sheets bonded to the reinforced concrete box girder webs that were deficient in shear and wrapping of the concrete pier columns to enhance confinement and ductility to provide improved seismic resistance. Additionally, the upgrade to the underpass allowed improved seismic resilience to the main motorway in Auckland.

Structural Health Monitoring

Monitoring our built infrastructure during operations and after significant natural disasters is fundamental for providing efficient infrastructure. With the available technology, new structures can be instrumented for relatively low cost these days. The ability to detect damages or deterioration in advance and act upon them is critical and unavoidable for the efficient use of funds and limited resources.

CONCLUDING COMMENTS

Concrete as a construction material has been around more than 2,000 years. The last century has seen an unprecedented development of concrete, significantly improving its performance--which has made concrete the second most consumed material in the world after water.

For it to continue to maintain its place in the urban and infrastructure development in the future, it is imperative that we make concrete a more sustainable material. This means the cement used in the concrete mix which has a high carbon footprint, needs either to be reduced or be completely replaced by substitutes. Recent innovations in nano-engineered materials have potential for improving the concrete’s strength and durability characteristics, while requiring reduced quantities of concrete.

While the ingredients and material properties of the concrete mix have been improved and made sustainable, it is also important that the construction methods should embrace the disruptive and emerging technologies to be sustainable.

When urban centres become dense and infrastructure needs grow continuously, there is the challenge of limited availability of space. More high-rises and underground structures would unlock the potential regeneration of space to cater for the ever-growing population.

It may have caused some controversy, but the proposed “sunken” stadium at the Auckland waterfront is a paradigm shift in our way of thinking when we set out to solve infrastructure challenges. It is fair to say that the next decade will see a rapid and broad development of new materials and improvements to concrete and other conventional construction materials, to meet the new frontiers of humankind and answer the need for sustainability and environmental protection.

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