USING DURABILITY TO ENHANCE CONCRETE SUSTAINABILITY

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INTRODUCTION

The sustainability of concrete buildings and infrastructure must be considered both in terms of its benefits to society and the environmental impact associated with its use in construction. Production of Portland cement (PC), in particular, is energy intensive and generates a significant amount of carbon dioxide. Cement is, however, only a relatively small component of concrete and overall the material is resource efficient and has moderate embodied energy and carbon dioxide footprint. Concrete is widely used due to its low cost, ease of use, good track record, versatility, local availability, thermal benefits, acoustic dampening, and durability.

Durability performance of construction materials is important, and concrete is often considered to be inherently durable due to its chemical and physical resistance to various environments and dimensional stability. Concrete structures are assumed to be largely maintenance-free and to provide long service lives. Figure 1 shows an 80-year-old concrete bridge in South Africa that is still providing good performance under severe weather conditions. This assumption is not true in all environments and service conditions unless special attention is given to ensuring a high level of durability performance.

With an understanding of concrete microstructure and potential deterioration mechanisms, it is possible to engineer almost any level of durability performance. Increasing the service life of buildings and infrastructure through improved durability has clear advantages in terms of optimizing resources and reducing waste, thus enhancing efficiency. Other advantages associated with improved durability that enhance the sustainability of concrete include improved structural performance, reduced labour, and improved understanding of concrete materials, which will assist in development of new technologies.

FIGURE 1. Kaaimans River Bridge in the Southern Cape region of South Africa.

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SUSTAINABILITY OF CONCRETE

Concrete has a long track record of contributing toward development of many aspects of modern civilization, with a history of over two thousand years. This implies that PC-based concrete is well understood, reliable, and likely to have predictable future performance.

Since most of the constituents of concrete are locally sourced, the material may be considered to be indigenous or "natural." Constructing with the material is usually done with local labour and helps support the community. A thriving local construction industry has been identified as a key indicator for a healthy economy in developing countries.

Concrete is widely used in construction since it is relatively cheap to produce. The low overall cost is mostly due to materials savings compared with alternatives but also due to the relative ease of production and construction of concrete. Less obvious benefits associated with concrete use include lower operating costs due to less maintenance and repair.

Many of the technical advantages of concrete are not immediately apparent when comparing different building materials. Technical benefits of concrete that are sometimes overlooked include thermal mass, acoustic dampening, fire resistance, drainage, and light reflectivity or albedo (Ashley 2008). Figure 2 shows how the thermal mass of concrete can be utilised in a building structure to moderate indoor temperatures and reduce overheating.

Production of Portland cement is generally assumed to generate 0.85 kg of carbon dioxide for every kg of cement (Atkinson 2009). Concrete is an alkaline material that contains considerable calcium hydroxide, which is a byproduct of cement hydration. Some carbon dioxide is recaptured by carbonation of concrete in service (reaction between carbon dioxide and calcium hydroxide that form calcium carbonate) but the process is usually quite slow since carbon dioxide diffuses slowly through dense concrete. Estimates vary on the amount of recarbonation that occurs in service but it is found to be about 0.20 kg per kg of cement (Dayaram 2008) for structural concrete. Crushing and recycling demolished concrete significantly increases recarbonation potential since the increased surface area allows increased chemical reaction between uncarbonated concrete and atmospheric carbon dioxide (Pade 2007).

Waste utilization has been standard practice within the concrete industry for some time. Waste oils and other combustible materials are used to fire cement kilns, recycled steel has traditionally been used for reinforcing steel, and supplementary cementitious materials (SCM) such as slag and fly ash have been used to reduce cement contents in concrete for more than fifty years, while simultaneously utilising waste streams from other industries.

Concrete is chemically inert and relatively impermeable, and this results in good air quality in build-

FIGURE 2. Computer Science Building at the University of Canterbury, Christchurch, New Zealand showing how concrete thermal mass is used to improve thermal efficiency.

TABLE 1. Durability characteristics of concrete constituents.

Component of concrete	Characteristic	Enhancement for durability
Hardened cement paste	Low permeability, high pH, high compressive strength	Low water/cement ratio, SCM and moist curing
Pore structure	Capillary porosity allows ingress of fluids and ions	Mix design and good construction practice
Aggregates	High strength and stiffness, relatively inert and stable	Optimize grading and control particle shape
Reinforcing	Tensile strength, passivated by high pH of concrete	Dense cover concrete and adequate cover depth

ings with less volatile organic compounds, mould, and moisture (Nielsen 2006). Concrete produces virtually no volatile organic compounds compared with many building products such as glues and epoxies. The high fire resistance and absence of toxic chemicals within concrete is a further health advantage.

The relatively inert and stable nature of concrete makes the material durable in most environments. Reinforced concrete has the added benefit of natural synergies between steel and concrete in terms of corrosion protection and thermal movement (Hansson 1995). Concrete durability is not always guaranteed, however, with many cases of premature failure occurring, mostly when concrete is exposed to extreme conditions such as are found in marine or industrial enviroments.

DURABILITY OF CONCRETE

Concrete is a complex composite material that is exposed to a wide range of environmental and service conditions and this means that deterioration mechanisms interact dynamically with material and structural influences. Deterioration of concrete begins almost immediately after casting as the hardened properties are affected by construction practice and environmental factors. In the hardened state, concrete may be affected by a variety of internal and external mechanisms causing physical and chemical damage.

Concrete is inherently durable and suffers little deterioration in moderate environments and normal service conditions. Environmental exposure conditions have a pronounced influence on the durability of building materials, with dry conditions being relatively benign. When exposed to more severe service conditions, deterioration of concrete can occur through a variety of different mechanisms, which may be quite complex. Some of the more common forms of deterioration include corrosion of reinforcement, alkali silica reaction, chemical attack by acids and sulphates, and physical attack due to abrasion, freeze-thaw, and fire. Table 1 gives the inherent durability characteristics of the various constituents of concrete.

In many countries it is now acknowledged that PC concrete cannot guarantee durability in all environments, and there has been widespread occurrence of material deterioration (Phair 2006). Various material deficiencies have been suggested for this lack of performance, but fundamentally these problems are associated with a lack of appreciation of the microstructural limitations of concrete and the physical and chemical processes causing deterioration.

Enhancing the durability performance of concrete is achieved by modifying the microstructure both physically and chemically. Many forms of deterioration involve ingress of aggressive agents from the exterior and are best controlled by improving the resistance to transport of fluids and ions into concrete. Internal forms of deterioration such as alkali silica reaction are well understood, and control of this deleterious reaction is done by careful material selection and correct construction practice. Table 2 shows the main forms of deterioration that occur in concrete structures and how these deleterious effects can be mitigated.

IMPROVED SERVICE LIFE

Buildings are generally designed for service lives of 30–50 years with the expectation that minimal maintenance will be required for concrete elements. Concrete bridges have greater service life requirements of

TABLE 2. Mitigating concrete deterioration in order of sustainable approaches.

Deterioration	Option 1	Option 2	Option 3
Corrosion of rebar	Improved cover resistance using SCM	Increasing cover depth of reinforcing	Increasing cement content of concrete
Alkali silica reaction	Use of SCM such as fly ash and slag	Use non-reactive aggregates	Use low alkali cements
Physical attack and abrasion	Correct concrete strength and curing	Good finishing of concrete surface	Surface hardeners and penetrants
Sewer pipe corrosion	Chemically resistant cements	Calcareous aggregates	Sacrificial outer layer of concrete

typically 100 years or more. However, many buildings, and in infrastructure in particular, do not achieve these objectives and further resources are required in terms of maintenance and repair.

Doubling the service life of a structure from 50 to 100 years does not require a significant increase in construction resources. In many cases the extra requirement involves only a slight adjustment in concrete resistance or cover depth to embedded reinforcement. The cover concrete that surrounds reinforcing steel provides protection from environmental agents such as moisture and salt that cause corrosion. The time to corrosion of reinforcement is compared in table 3 for marine structures built with different concrete types (Mackechnie 2001).

Concrete bridges are routinely designed for lives of 100 years using durability prediction models.

TABLE 3. Time to corrosion (years) of reinforcing steel in 50 MPa marine concrete.

PC (%)	SCM (%)	40 mm cover	60 mm cover
100	0	5	9
92	8 silica fume	7	50
70	30 fly ash	8	>100
50	50 slag	13	>100

An example of a project with such a service life is the new Tauranga Bridge in New Zealand shown in Figure 3. Concrete used in the bridge deck was a ternary blend of Portland cement, microsilica, and fly ash that was shown to have high chloride resistance and hence excellent protection from steel corrosion.

FIGURE 3. New Tauranga Bridge in New Zealand built over the harbour using an incrementally launched bridge deck system (Fletcher Construction).

The advantage of long service life without the disruption of maintenance or repairs is beginning to be appreciated. The Tinsley Viaduct in England required strengthening due to increased axial loads, and projected congestion costs during closure for reconstruction were estimated to be almost five times higher than construction of a new bridge (Long 2008). Much of the existing world's infrastructure simply cannot be taken out of service or replaced, and durability performance is becoming a critically important component of sustainable development.

GREATER WASTE UTILIZATION

Utilization of waste or recycled material is an obvious way of encouraging more sustainable concrete production, but this is sometimes limited by technical constraints. Incorporating waste in concrete is unlikely to be successful if there are limited technical benefits or worse if there is any risk of deleterious reactions. The durability implications of using commonly used waste materials are shown in table 4 (Ansari 2000).

On the other hand, SCM such as fly ash, slag, and silica fume are industrial wastes that improve many concrete properties, most notably durability. The microstructure of concrete is enhanced when these binders are used, by improved pore refinement, particle packing, and improvement of the aggregate-paste interfacial zone. In many countries, the cost of SCM is cheaper than Portland cement making the durable option cheaper both in terms of life cycle costs as well as construction costs.

TABLE 4. Effect of waste materials on concrete durability.

Waste material	Durability considerations for use in concrete
Recycled concrete	More variable, possible contamination, increased shrinkage
Crushed glass	Potential for ASR expansion, reduces strength and workability
Crumb rubber	Low stiffness and poor bond to hardened cement paste
Latex paint	Increases air content of concrete, reduces permeability
Plastic	Very low strength and stiffness, poor fire resistance

Specifying a high level of durability performance will almost by default lead to increased use of SCMs since these materials densify the microstructure of concrete. Specifying a service life of 100 years for a reinforced concrete structure in the marine environment might be best achieved with concrete where 30–50% of the cement is replaced with fly ash or slag. In New Zealand, the concrete design standard recommends that blended cement must be used in marine applications, making use of recycled or low carbon materials such as fly ash, microsilica, or slag mandatory (New Zealand Standards 2006).

IMPROVED STRUCTURAL PERFORMANCE

Enhancing the durability performance of concrete will produce associated benefits to the material such as improved structural capacity or reduced deformations in service. It is therefore possible to produce lighter and more stable structures while simultaneously improving the service life of the structure. Buildings can then be engineered in such a way that performance can be optimized rather than being designed using more conservative deemed-to-satisfy principles.

Highly engineered concrete materials not only increase the mechanical properties but have a dense, crack resistant matrix that encourages high levels of durability. Examples of some recent innovations include:

- Reactive powder concrete with extremely high strength (Sakai 2005)
- High ductility engineered cementitious composites (Lepech 2006)
- Lightweight concrete with enhanced structural performance (Kayali 2008)
- Photocatalytic cement for self-cleaning concrete surfaces (Giannantonio 2009)

BETTER CONSTRUCTION

The durability performance of concrete is influenced by construction practice on-site, particularly compaction and curing. Increasingly these construction practices are difficult to control since supervision of construction has reduced significantly in recent decades. New technologies such as self-compacting concrete (SCC) are able to produce durable concrete while requiring reduced labour on-site. The high

FIGURE 4. SCC allows more rapid and efficient precast concrete construction since no consolidation using vibration is required after casting.

durability of SCC mixes is due to increased binder contents, use of SCM, reduction in entrapped air, good aggregate-paste bond, and excellent packing of particles (De Schutter 2007). The advantage of SCC in concrete construction is shown in Figure 4.

Fibre reinforced concrete has also had a significant impact in reducing labour on construction sites. Industrial floors are increasingly being built with steel fibres that reduce the need for welded mesh reinforcing and allow for easy placing on-site. Durability of fibre reinforced concrete is generally improved since fibres are able to control crack widths and limit ingress of harmful agents from the exterior.

New classes of “bio-inspired” fibres that are recyclable and biodegradable are being used in concrete (Banthia 2008). Examples of technologies used to reduce labour in construction and maintenance of concrete structures are shown in table 5.

CREATING DURABLE GREEN CONCRETE SOLUTIONS

Concrete has a long tradition of incorporating waste materials to reduce use of virgin aggregates and cement. Unfortunately incorporation of these recycled materials often compromises the durability potential of concrete. This means that either a lower durability outcome must be accepted or more cementitious material is required to compensate. Using more cement in a concrete mix containing recycled concrete aggregates, for instance, rather defeats the purpose and other solutions need to be devised.

Using a more comprehensive approach, significant improvements have been made toward achieving concrete with a high recycled component that is also durable. Synergies are sometimes possible between recycled materials in concrete such that the performance can be achieved without increasing the environmental footprint. Some examples of durable, green solutions for concrete include:

TABLE 5. Technologies that reduce construction and maintenance labour.

Technology	Construction benefit	Material benefit
Self-compacting concrete	No compaction, easy placing of concrete	Denser microstructure and refined interfacial zone
Fibre reinforced concrete	No fixing of reinforcing steel, easy placing of floors	Controls cracking to fine widths, 3D network
Controlled permeability formwork	No moist curing/protection of concrete surfaces	More durable concrete cover layer
Self-cleaning concrete	Less maintenance of façade and exposed surfaces	Dense surface with reduced absorption and growth

- Improving the bonding between paste and crumb rubber using magnesia cements.
- Reducing shrinkage of recycled aggregate concrete using fly ash and slag additions.
- Using SCM to prevent ASR expansion of concrete containing waste glass.

BETTER MICROSTRUCTURAL UNDERSTANDING

Durability studies have enhanced our understanding of the material science of these complex multiphase materials and will be critical in assessing future generations of concrete. Currently, the durability potential of Portland cement concrete is often assessed using empirical tests that have been shown to be reliable predictors of long-term performance. Pressure to develop low carbon dioxide cements and increase the amount of waste materials in concrete will require a good understanding of materials, microstructure, and deterioration mechanisms. Reliance on simple empirical indicators of durability will not be possible with new materials and technologies, and a more scientific approach will be required (Scrivener 2008).

There are many instances of alternative or new materials showing variable performance when assessed with standard empirical tests that were developed for traditional concrete. Examples of recent findings with concrete materials that fall into this category include:

- Inorganic polymer concretes showing high levels of chloride resistance when assessed in the laboratory despite being relatively porous and permeable (Mackechnie 2009).
- Waste glass aggregate testing for alkali silica reaction showing misleading accelerated properties compared with long-term test results (Zhu 2009).
- Sewer pipe corrosion assessment of calcium aluminate based concrete where mineral acid testing poorly estimated the resistance to bacteriogenic corrosion conditions (Scrivener 2008).

ENSURING DURABILITY

Modern design and construction practice of concrete structures has led to improvements such as the use of more consistent quality cement, higher allowable stresses, faster concrete casting and setting times, and greater variety of binder types and admixtures. Whilst these advances have improved concrete productivity, they have sometimes made concrete less durable and more sensitive to abuse that has contributed to premature deterioration.

The increasing number of concrete structures exhibiting unacceptable levels of deterioration has resulted in more stringent construction specifications. Unfortunately, the durability performance of concrete structures has not always shown a corresponding improvement, despite the use of these specifications (Bentur 2008). This appears to be due to a lack of understanding of what is required to ensure durability as well as inadequate means of enforcing or guaranteeing compliance (Alexander 1997).

Most durability specifications for concrete are prescriptive or recipe-type specifications, setting limits on water/cement ratios, cement contents, cover to reinforcement, etc. Prescriptive specifications have been criticized for being inflexible, inefficient, and are often difficult to check during construction (except for cover depth). Since performance criteria are not specified, it is difficult to ensure satisfactory durability is achieved during construction except by inferring durability performance from compressive strength, which is a tenuous relationship in many circumstances.

Performance-based specifications are increasingly being used to ensure durability of concrete structures. Depending on the type of structure, its location and service requirements, critical material properties such as permeability or chloride resistance can be identified and performance specification devised that unambiguously measure the resistance of the concrete. These can be used to optimize project mixes and control concrete production during construction (Alexander 2001). Table 6 shows typical durability performance tests used in concrete construction.

Advantages of performance-based specifications include the following:

- Concrete is more efficient since materials and processing can be optimized.
- Durability potential can be predicted at construction allowing early remedial work.
- Durability performance is enhanced since this is implicit rather than inferred.
- Reduces the inherent conservatism in larger infrastructure projects.

TABLE 6. Durability performance tests for concrete.

Performance requirement	Measured parameter	Intended benefits
Chloride resistance	Diffusivity, conductivity	Protection of reinforcement with a dense cover concrete
Carbonation resistance	Gas permeability	Protection of reinforcement with an impermeable concrete
Water absorption	Sorptivity	Improve curing efficiency and near surface properties
Pore structure quality	Porosity	Improve mix designs and control compaction and curing

New concrete structures are expected to provide extremely long service, with 100 year life being commonly specified (see figure 5). Performance-based specifications for durability are essential in these cases, being used to optimise concrete mix designs, provide site quality control, and provide assurance of long-term performance.

CONCLUSIONS

Durability is a fundamental but often ignored property when assessing the sustainability of construction materials. Concrete is frequently described as being inherently durable despite some evidence to the contrary, especially when considering the performance of concrete infrastructure. Enhancing the microstructure of concrete is possible and does not necessarily involve an increase in Portland cement. The use of industrial wastes such as fly ash, slag, and silica fume has been shown to dramatically improve the durability performance of concrete structures, particularly when dealing with the most pernicious forms of deterioration such as chloride-induced corrosion of reinforcing steel and alkali silica reaction of aggregate.

A new approach is required to solve durability problems in concrete structures, such that environmental, service, and material aspects are integrated to produce appropriate performance specifications. The benefits of this approach to sustainability include longer service life for structures, better waste utilization, improved overall performance, and reduced labour on-site. Better use of resources is also possible when suppliers and contractors have more flexibility in choosing the most appropriate materials and construction techniques.

Improved micro-structural understanding of concrete durability will be vital to managing the rapid evolution of concrete materials in the future. Portland cement is fairly uniformly produced and consistent around the world, but the diversity of new binders is growing in response to environmental pressures. These new cementitious materials must be carefully characterized so that durability performance can be predicted. Designers will be reluctant to adopt new materials until the durability performance can be confidently predicted and guaranteed in service.

FIGURE 5. New concrete bridge for the Gautrain railway system in South Africa designed for a service life of 100 years.

REFERENCES

Alexander, M.G. 1997. "*An indexing approach to achieving durability in concrete structures.*" FIP Symposium, Johannesburg, CSSA.

Alexander, M.G., J.R. Mackechnie, and Y. Ballim. 2001. Guide to the use of durability indexes for achieving durability in concrete structures. *Research Monograph No. 2*. University of Cape Town.

Ansari, F. 2000. "*Recycled materials in Portland cement concrete.*" FHWA Report NJ-2000-03.

Ashley, E. and L. Lemay. 2008. "Concrete's contribution to sustainable development." *Journal of Green Building*, vol. 3, no. 4, pp 37–49.

Atkinson, C., A. Yates, and M. Wyatt. 2009. *Sustainability in the built environment*. London. BRE Global.

Banthia, N. 2008. "*Fiber reinforced concrete for sustainable and intelligent infrastructure.*" Proc. of First Int. Conf. on Microstructure Related Durability of Cementitious Composites. Rilem, Nanjing.

Bentur, A. and D. Mitchell. 2008. "Material performance lessons." *Cement and Concrete Research*, vol. 38, pp. 259–272.

Dayaram, K., G. Slaughter, M. Rynne, R. Gaimster, and L. McSaveney. 2008. "Uptake of carbon dioxide in New Zealand concrete: preliminary findings." *Proc of NZCS Conf. TR40.* Wellington.

De Schutter, G. 2008. "Final report of RILEM TC 205-DSC: durability of self-compacting concrete*" Materials and Structures*, vol. 41, pp 225–233.

D.J. Giannantonio, J.C. Kurth, K.E. Kurtis, and P.A. Sobecky. 2009. 'Effect of concrete properties and nutrients on fungal colonization and fouling." *International Biodeterioration and Biodegradation*, vol. 63, pp. 252–259.

Hansson, C.M. 1995. Concrete: The advanced industrial material of the 21st century. *Metallurgical and Materials Transactions,* vol. 26A, pp. 1321–1330.

Kayali, O. 2008. "Fly ash lightweight aggregates in high performance concrete." *Construction and Building Materials*, vol. 22, pp 2393–2399.

Lepech, M.D. and V.C. Li. 2006. "Long term durability performance of engineered cementitious composites." *Restoration of Buildings and Monuments*, vol. 12, no. 2, pp. 119–132.

Long, A.E., R.K. Venables, and J.D. Ferguson. 2008. Sustainable bridge construction through innovative advances. *Bridge Engineering*, vol. 161, no. 4.

Mackechnie, J.R. 2001. Predictions of reinforced concrete durability in the marine environment. *Research Monograph No. 1*. University of Cape Town.

Mackechnie, J.R. 2009. *"Durability of ambient and thermally cured inorganic polymer concrete made with Australasian or South African material."* Unpublished report, University of Canterbury.

New Zealand Standards, NZS 3101–Concrete structures standard. Wellington.

Nielsen, C.V. and M. Glavind. 2006. "Danish experience with a decade of green concrete." *Advanced Concrete Technology.* JCI, vol. 5, no. 1, pp. 3–12.

Pade, C. and M. Guimaraes. 2007. "The CO_2 uptake of concrete in a 100 year perspective." *Cement and Concrete Research*, vol. 37, no. 9, pp. 1348–1356.

Phair, J.W. 2006. "Green chemistry for sustainable cement production and use." *Green chemistry*, vol. 8, pp763–780.

Sakai, K. 2005. "Environmental design for concrete structures." *Advanced Concrete Technology*, JCI, vol. 3, no. 1, pp. 17–28.

Scrivener, K. 2008. "*Importance of microstructural understanding for durable and sustainable concrete.*" Proc. of Second Conf. ICCRRR, Cape Town.

Zhu, H., W. Chen, W. Zhou, and E.A. Byars. 2009. "Expansion behaviour of glass aggregates in different testing for alkali-silica reactivity." *Materials and Structures*, vol. 42, pp. 485–494.