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Case study

A survey on problems encountered in current concrete construction and the potential benefits of self-healing cementitious materials

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ABSTRACT

The annual costs for repair, maintenance and replacement of civil engineering infrastructure attracts significant expenditure in the UK. Anecdotal evidence suggests that a significant number of existing and new concrete structures suffer from repair and maintenance problems, but a lack of objective construction industry supported data concerning these problems makes it difficult to establish, with any certainty, the actual problems encountered in current concrete construction in the UK. To address this lack of data, a market research exercise was commissioned by the Materials for Life (M4L) EPSRC funded research project. The market research has shown that damage in the form of cracking in concrete structures was experienced by more clients, design team members and civil engineering contractors than any other problem. Structures requiring articulation and subject to dynamic loads such as bridges were noted as being the most vulnerable to damage, with this damage mostly occurring in the joints and half joints, bearings and the deck of such structures. The main consequential effects of damage in concrete structures were the need for the contractor to return for repairs as well as the need for regular monitoring. The current approaches taken to enhance a structure's longevity mainly involve the use of additional cementitious material to improve the barrier between the environment and the steel reinforcement. However, an alternative could be to use the self-healing cementitious materials that have been proposed by the M4L research team. Until now there has been insufficient evidence regarding how these materials may be deployed in the construction industry, and the applications to which they may be best suited in terms of added-value. The market research results show that highways and infrastructure generally and water retaining structures would benefit most from self-healing cementitious materials, with reduced maintenance costs over a structure's lifetime justifying a premium in the capital material cost. Reduced whole-life costs and fewer repair and maintenance interventions will have a significant influence on the economic, environmental and social impact of repair and maintenance events, which will be of benefit to the UK as a whole.

1. Introduction

Developed countries spend a large percentage of their infrastructure budgets on repairs, maintenance and the replacement of existing and new structures (35–45% in the UK [1], 50% in EU [2]), which points to significant inadequacies in past practice and current design and construction techniques. There is much anecdotal evidence that concrete structures have repair and maintenance problems, a fact that is supported by the high expenditure on maintenance. However, a lack of industry supported quantitative data means that it is difficult to establish, with any certainty, the most common problems encountered during the construction of today's

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concrete structures in the UK. When transport-related structures cease being serviceable there are large societal costs associated with delays and disruptions. Moreover, the cement and concrete industry have huge energy demands and produce large amounts of CO_2 [3]. As a result it is widely recognised that more efficient and durable cementitious materials are needed if the construction industry is to make its contribution to climate change targets [4]. Structures with more resilience may be achieved by pro-active management of damage by employing materials that have an ability to adapt, self-heal and respond to their exposure environment. Through the use of cementitious materials that have this ability, our concrete structures can evolve over their lifespan rather than being defined by individual events. Such structures, whilst having an increased capital cost would have significantly lower if not negligible maintenance costs over their life and therefore much reduced whole life costs.

In order to better understand the problems encountered during the construction of today's concrete structures in the UK and the degree to which concrete cracking/damage is a major problem, a piece of market research was commissioned by the Materials for Life (M4L) EPSRC funded research project [5]. The three main objectives of this market research were to identify:

(a) the nature of concrete damage and the structure types and elements vulnerable to damage;
(b) the consequential effects of concrete damage and maintenance; and
(c) the current approaches taken to address damage in concrete and their impact.

The market research survey was also used to explore the potential applications of self-healing cementitious materials and the benefits in their use, the findings of which will be used to inform future developments in this research area.

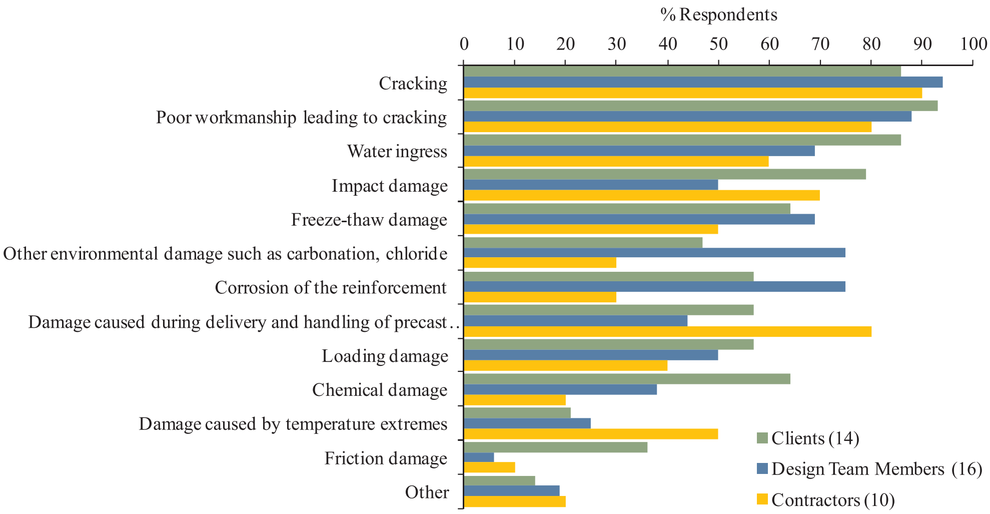
The market research was conducted by Lychgate Projects Ltd. [6] in 3 stages. The first stage included 5 in-depth semi-structured interviews with a main contractor, a concrete structures contractor, a repair contractor, a multi-disciplinary consultancy and a supplier of bulk cement. Stage 2 comprised three 20 min discussion groups with attendees at a CIRIA event in July 2016. In stage 3, a total of 40 structured interviews were conducted by phone with organisations involved in delivering infrastructure projects, including end clients (14 no.), civil engineers from large practices/design teams (16 no.) and civil engineering contractors (10 no.), henceforth referred to as the 'participants'. This paper presents a summary of the results of the stage 3 interviews. All interviews were conducted 'off the record' and thus the companies participating in the survey are not identified but the participants included a number of the largest UK contractors, consultants and client bodies.

2. Market research results

The market research results are presented according to the questions posed to the survey participants, as compiled in the original market survey report [6].

2.1. Damage in concrete structures

The market research indicated that the main problems experienced with concrete (both old and new construction) in projects on which the respondents had worked over the last 5 years (presented in Fig. 1) are as follows:



Other includes: Expansion due to ASR. Salt damage. Sulphate damage. Fire damage. Concrete specs have been higher than required which has caused cracking due to brittleness.

Fig. 1. The main causes of damage in concrete structures (according to participants).

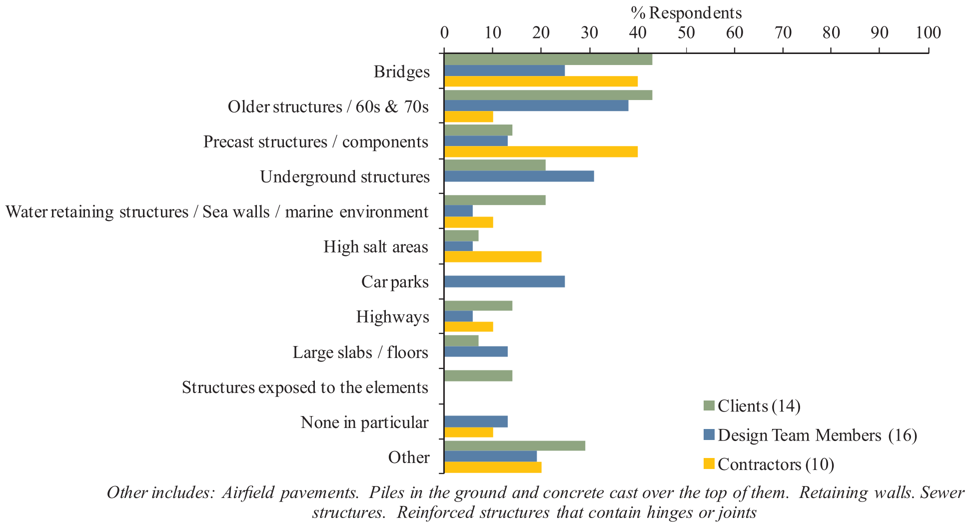


Fig. 2. Concrete structures vulnerable to damage.

(i) Cracking (including as a result of poor workmanship during execution), which was experienced by more clients, design team members and contractors than any other problem, and overall by an average of 90% of all respondents;
(ii) Water ingress (experienced by an average of 73% of all respondents);
(iii) Impact damage (experienced by an average of 65% of all respondents);
(iv) Damage caused by freeze-thaw conditions, and other environmental damage of which sulphates, salt/chlorides, carbonation and acid attack were the most common.

Also of particular interest was the response given by 80% of contractors who highlighted that one of the main sources of damage to concrete results from the handling and loading of precast elements. It is standard practice to amend the concrete design or mix specification to address the types of problems highlighted in Fig. 1, particularly cracking, water ingress, chemical and other environmental damage. Of these, preventing water ingress was considered the most challenging issue to resolve by 43% of respondents, followed by cracking, as mentioned by 23% of respondents.

Whilst the problems in Fig. 1 were reported to be experienced at all stages throughout the life of a concrete structure, contractors in particular, highlighted problems with early age cracking (< 3 days), whereas clients and design team members emphasised problems with longer-term cracking (> 5 years).

2.2. Concrete structures vulnerable to damage

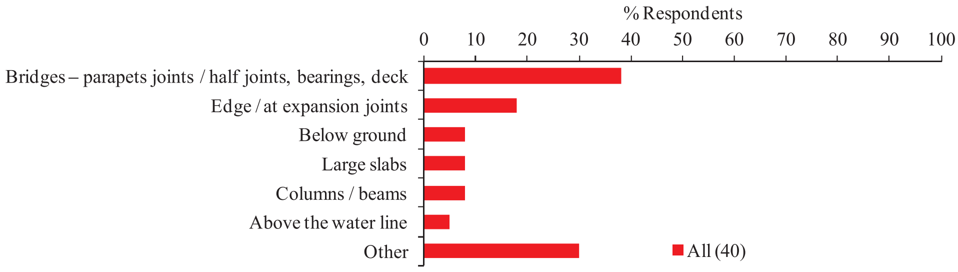
The participants were asked to identify (unprompted) the types of structure or elements within a structure that are particularly vulnerable to damage. As summarised in Fig. 2, bridges, regardless of age, were reported to be particularly vulnerable and were described as a structure type that frequently required maintenance. Older structures, such as those constructed in the 1960s and 1970s, were also vulnerable to damage, perhaps due to shortcomings in design codes and workmanship at the time of design and construction. Underground structures were likewise thought to be particularly vulnerable, although interestingly not amongst the contractor respondents. Their response may have been influenced by the fact that damage is often hidden in buried structures. Other structure types considered to be vulnerable to damage included car parks, tunnels, other underground structures and water retaining structures.

2.3. Concrete elements vulnerable to damage

In addition to identifying concrete structures vulnerable to damage, participants were also asked to highlight particular concrete elements that were susceptible to damage. Most damage occurring within bridge structures was reported to concern the joints and half joints, bearings and the deck, as highlighted by 38% of all respondents in Fig. 3. Damage and deterioration in all vulnerable elements was mainly attributed to water ingress and impact damage. The edges of structures and zones around expansion joints were also reported to be particularly vulnerable.

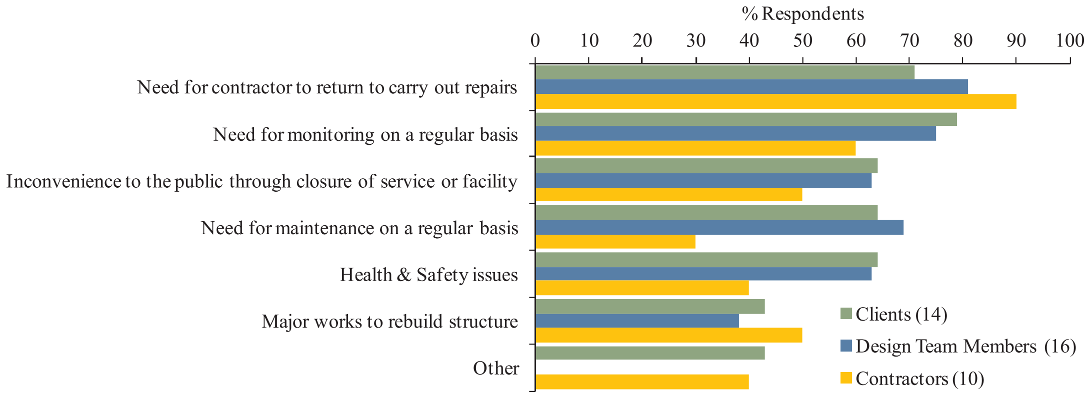
2.4. The consequential effects of concrete damage and maintenance

The consequential effects of damage in concrete structures, as presented in Fig. 4, are many and they have far-reaching implications. The need for the contractor to return for repairs was the consequence most reported, as well as the need for regular



Other includes: Service ducts (railway). Stair units. Retaining walls. Concrete used as a fire protection. Retaining walls. Head walls of tunnels. Areas of high pollution. Airports in the Middle East or other severe environments. Hinges, half joints. Structures directly above the track (tube tunnels).

Fig. 3. Concrete elements susceptible to damage.

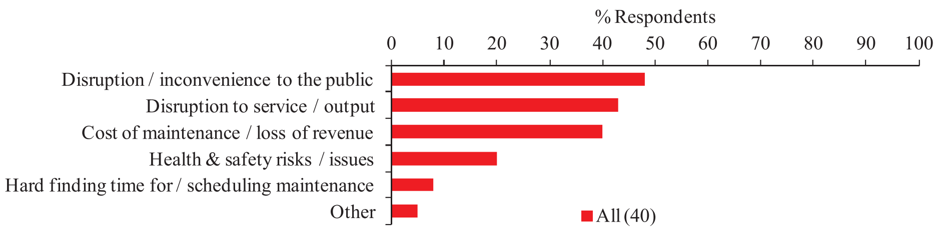


Other includes: Litigation or the implications of litigation. Having to pay for work if they are out of their guarantee phase. Delay to progress on the live construction site. Reputational issues. Real risk or danger to the public due to failure. Most issues appear within a minimum of 10 to 12 years, long after the 3 year original contract has expired. Financial constraints.

Fig. 4. The consequences of problems with concrete.

monitoring. Both of these activities have significant economic impact. Other issues raised by over half the respondents included inconvenience caused to the public through service disruption (experienced by over 60% of respondents), the need for regular maintenance, and Health and Safety issues concerned with repair and maintenance activities. 43% of all respondents had experience of major works to rebuild an older concrete structure, which has social, economic and environmental impacts.

The main consequential effects of maintenance are disruption to the public or to the provision of a service, and the associated financial cost, as highlighted in Fig. 5. Whilst the nature of the disruption was not explored in any greater depth in the market research, the result from 48% of the respondents does serve to highlight the importance of considering the social effects associated with the performance of the nation's infrastructure. Responses under the "other" category included increased pollution due to stationary or slow vehicles and the disruption of the integrity of the structure due to too many maintenance patch-ups.



Other includes: Increased pollution due to stationary or slow vehicles. Too many maintenance patch-ups could disrupt the integrity of the structure.

Fig. 5. The consequential effects of maintenance.

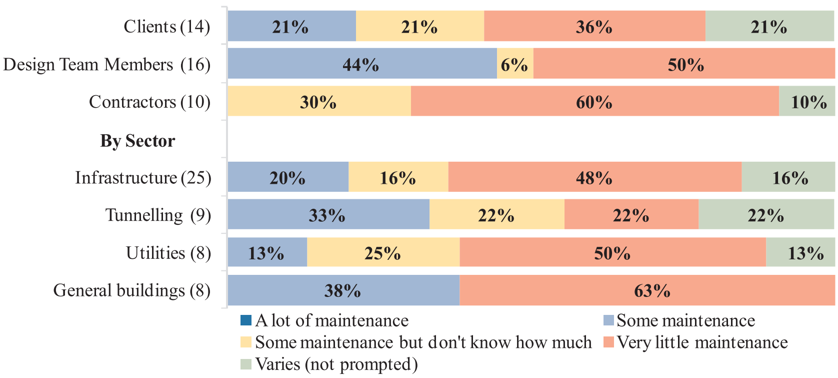


Fig. 6. Expected degree of maintenance required for concrete on respondents' projects.

2.5. Anticipated maintenance requirements for concrete on current design projects

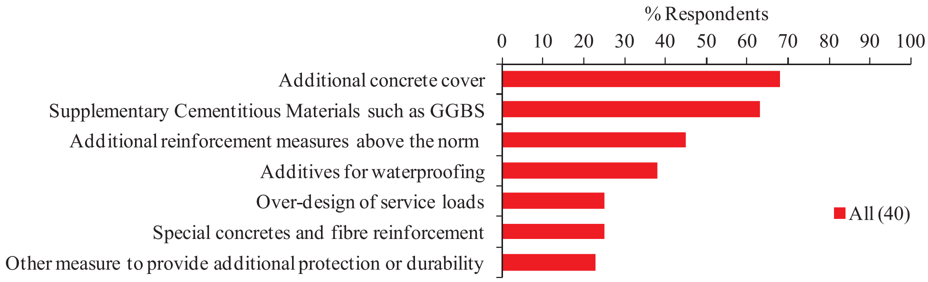
Respondents were asked to consider what degree of maintenance over the anticipated life of the structure they felt would be required for concrete being designed and used on their projects, the results of which are presented by participant group and sector in Fig. 6.

There was the general expectation by the majority of respondents that, with current concrete design approaches, 'some or little' maintenance should only be required. The spread of results in Fig. 6 for the different respondent groups reflects the nature of those groups; for example, clients manage a vast range of assets with different maintenance regimes and interventions, which led to this participant group having the most uniform distribution of answers for the different degrees of maintenance. The majority of respondents in the general buildings sector tended to be of the opinion that very little maintenance should be expected, which is perhaps not surprising given the enclosed nature of building structures and hence limited impact of external factors on the structural concrete frame. In contrast, the responses given by the tunnelling sector revealed the greatest uncertainty, which may be attributed to unforeseen ground conditions, uncertainty in ground-structure interactions and challenges associated with handling and placing precast units. It is perhaps reassuring to note that no respondent expected 'a lot of maintenance'. This would suggest that the measures employed by the most recent design codes of practice and material standards to ensure a minimum level of structural durability and longevity may be adequate, but it would seem that whilst those interviewed hold this optimistic view, in practice these expectations are not realised, as evidenced by the responses given to the questions discussed in sections 2.1 to 2.4.

2.6. Current approaches taken to address shortcomings in concrete

Varying measures are taken by industry to address concrete's main shortcoming, its propensity to crack, which in turn facilitates water ingress and the promotion of further deterioration processes. These measures are summarised in Fig. 7.

More than 60% of all participants reported knowledge of the provision of additional concrete cover (in response to client specifications and in the design of high-value assets) and the use of supplementary cementitious materials (SCMs), both aimed at improving the barrier between external environmental actions and steel reinforcement. Additional reinforcement measures primarily involved the use of stainless steel and epoxy coated reinforcement in zones susceptible to corrosion damage (soffits, edge beams, diaphragm walls, joints and structures). Durability and deterioration modelling was also mentioned under the 'other measures' category. This represents a movement towards a service-life based design approach that extends beyond the current prescriptive



Other includes: Steam curing (precast elements). Cathodic protection. Corrosion inhibitors. Separate waterproofing coat over the original concrete coat, also a coating to prevent salt ingress. Viscosity agents. Stainless steel reinforcement. Chemical treatments. Durability and deterioration modelling.

Fig. 7. Current measures taken to address shortcomings in concrete.

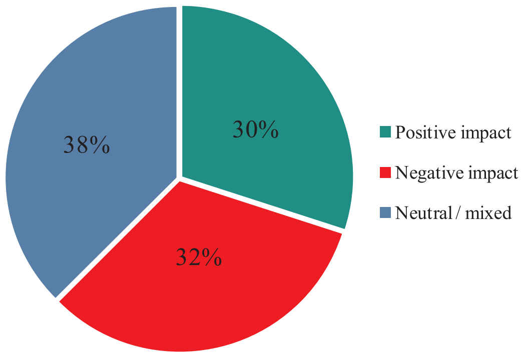


Fig. 8. Perceived impact of current approaches taken to address shortcomings of concrete.

methods used to achieve minimal durability design in concrete (limiting values on mix constituents e.g. max. w/c, min. cement content (BS EN 206:2013)).

2.7. Impact of current approaches taken to address shortcomings in concrete

The impact of the current approaches, identified in Fig. 8, was found to vary amongst participants. One third of the respondents described the downside of current protection measures such as the cost of maintenance, disruption due to maintenance closures and the cost and environmental impact of the extra concrete used. On the other hand, almost a further third of the respondents felt that the measures they take are positive and provide whole-life cost savings, a longer design life and a reduced carbon footprint (e.g. through use of supplementary cementitious materials and fewer maintenance vehicles on the road). Over a third of all respondents had no or mixed concerns about the impact of current approaches taken to achieve durable concrete. Their responses, however, were mainly associated with the cost of achieving durability, particularly noting that such measures usually result in higher initial material costs, whilst the lifetime cost of the structure is generally lower than for a structure where no allowance has been made to enhance durability.

2.8. Summary of results

Despite the approaches taken during the design and construction of the nation’s infrastructure, it is apparent that the deterioration of concrete structures in the UK is an ongoing and concerning problem. The economic impact of maintenance and repair is significant and whilst the associated social and environmental impacts are less well-understood, it appears that they are still considered highly important by the construction industry. The advent of self-healing cementitious materials has the potential to enhance the economic, environmental and social sustainability of civil engineering infrastructure and address problems associated with its deterioration. In order to assess the views of the participants on self-healing cementitious materials, the survey continued by exploring the state of knowledge and perceived potential of these materials in the construction industry. The results of this part of the survey, along with some discussion on the findings, are presented in the following section of this paper.

3. Applications and appeal of self-healing concrete

The development of innovative, biomimetic (mimicking the behaviour of natural living systems), self-healing cementitious materials has engaged the global research community across a wide range of engineering and scientific disciplines and has the potential to transform the manner in which concrete structures are designed and constructed. Self-healing in cementitious materials can either be natural (autogenic) or engineered (autonomic) [7]. Novel self-healing technologies that form the basis of the work considered herein, include the use of calcite precipitating bacteria, microcapsules and vascular networks containing healing agents and shape memory materials acting to restrict crack widths. A summary of these technologies is provided in Table 1.

Despite the interest in self-healing cementitious materials there has been insufficient evidence regarding how they may be deployed in the construction industry and the applications to which they may be best suited in terms of added-value. When presented with the information in Table 1, the respondents independently suggested that the main anticipated applications for self-healing concrete were considered to be:

(i) highways and infrastructure generally,
(ii) water retaining structures,
(iii) tunnels and bridges.

The main justification for these applications was a reduction in maintenance and prevention of water ingress. When prompted with a list generated during the first stage of the market research, the main perceived applications, were bridges, marine/water

Table 1
Summary of self-healing technologies.

Technology	Scale	Form of technology	Healing action	Construction requirements
Microcapsules	Nano/Micro	Microcapsules randomly distributed throughout the cementitious matrix.	Microcapsule is ruptured via propagation of a crack. Release of healing agent into crack plane.	Inclusion of microcapsules as a standard component of the concrete mix.
Bacteria	Micro/Meso	Bacterial spores and nutrient sources randomly distributed throughout the cementitious matrix.	Exposure of spores to water and nutrient source in favourable conditions (i.e. on crack surface). Bacteria deposit calcium carbonate on crack surface.	Inclusion of bacterial spores and nutrients as a standard component of the concrete mix.
Flow networks	All	Small diameter hollow network formed in cementitious matrix. Tubes filled with healing agent. Potential for pressurisation of system.	Cracks in concrete will rupture the flow network allowing the release of healing agent into the crack plane. Network allows for repeated damage/healing events.	Placement of network in concrete prior to casting and removal of network forming tubes 24 h after casting.
Shape Memory Polymers	Meso/Macro	Strands of PET* in tendon format anchored in the matrix. Similar in nature to post-tensioning strands. Heat activation via an electric current. PET shrinkage causes post tensioning effect.	Cracks are closed to a level in which either natural autogenic healing can occur, or one of the other healing technologies directed at nano/micro scale healing.	Placement in concrete moulds similar to a post-tensioning system.

* PET: Polyethylene terephthalate.

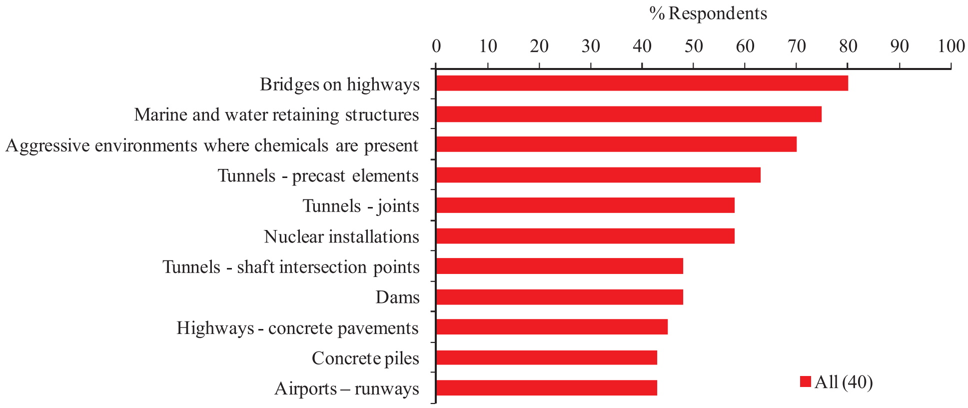


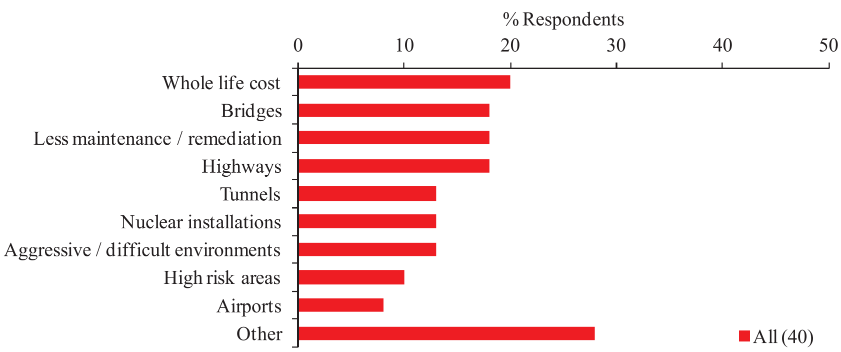
Fig. 9. Applications/Structures for which self-healing concrete could have particular appeal.

retaining structures, in aggressive environments, tunnels (precast elements and joints in particular) and nuclear installations. The responses, mentioned by more than 40% in each instance, can be seen in Fig. 9. Respondents were also asked to freely comment on any particular application or elements of structures which would suit self-healing cementitious materials. A wide range of suggestions, including some repetition from the prompted list, were given by the respondents. Joints and linings for tunnels were the most mentioned applications, which were specifically identified by one third of clients and one quarter of design team members. Other applications included difficult to access areas, the Nuclear industry, water retaining structures and airports.

It has always been acknowledged by the M4L research team that any addition/change to the concrete mix is likely to increase the cost of the final concrete product. Nevertheless, there may be instances in which this higher material cost may be offset by the reduction in the whole-life cost of the structure. The increase in material cost is estimated to be approximately 20%, with a negligible increase in the associated concrete installation costs. A recent study [8] has demonstrated that a minimum of two healing cycles are needed to justify the use of self-healing cementitious materials as opposed to traditional reinforced concrete when considering the performance of a bridge deck in a whole-life cost analysis. Moreover, the material is developed to ensure that there are no detrimental effects to the properties of concrete that make it such a versatile and suitable material for construction. With this in mind, respondents were firstly asked where its use would be of most value. As can be seen in Fig. 10, the unprompted answers were a mixture of application-based and benefits-based responses. Interestingly, the most common answer was whole-life cost, which supports the move to more economically and environmentally sustainable civil engineering infrastructure. This was of particular concern to client bodies (29% of them) who finance infrastructure projects and hence who bear the burden of costs associated with the deterioration of their infrastructure throughout its service-life. Drawing on their experience of design and involvement in repair and maintenance projects, design team members saw value in using self-healing concrete in highways (25% respondents), aggressive/difficult environments (25% respondents) and tunnels (19% respondents). Recognising the value of self-healing concrete in addressing some of the challenges resulting from concrete placement and curing, the top three responses for contractor respondents were less maintenance/remediation (30%), highways (30%) and nuclear installations (30%).

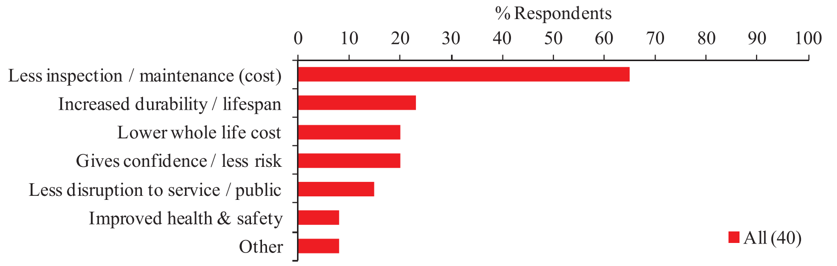
The second question posed to the respondents required them to consider what would be the main benefit in order to justify paying a premium for the material, the results of which are shown in Fig. 11.

The main benefits that justify a premium are reduced maintenance (and associated costs), mentioned by two thirds of all respondents, three times as many as the next categories, which were increased durability, reduced whole life costs and giving confidence/reducing risk. Responses by respondent type again were generally in agreement with the distribution of the full respondent



Other includes: If it will give a better means of predictive modelling of pavements. Storm tanks. Lift pits. Equipment room. Precast manholes. Sea defences. Floors for warehouses and factory. Swimming pool. Service reservoirs, spillways.

Fig. 10. Applications of self-healing concrete which hold most value to justify the increase in material cost.



Other includes: Designers will buy into better performance, all stakeholders will buy into better sustainability. Reduce waterproofing.

Fig. 11. The main benefit of self-healing concrete to justify paying a premium for the material.

group.

The appeal of self-healing concrete was considered by the respondents with respect to the benefits that it can offer over conventional concrete, as shown in Table 2. The greatest appeal of the novel self-healing technologies (described previously) is in the healing of cracks, the main benefit identified by each of the respondent groups interviewed. The reduced use and cost of additional concrete cover, additives and reinforcement also holds appeal.

Having a material which detects changes in the environment was of interest to around half of the respondents, although was not perceived to be particularly beneficial in and of itself. However, the authors consider the ability to combine this self-sensing technology with self-actuating technologies to represent a major step towards mimicking the intelligent structures found in nature.

The consequential benefits of using self-healing concrete were expected to be the reduction of maintenance costs (95% respondents) and reduced impact on the public of maintenance closures (90% respondents). When asked to rank the top three benefits in order, reduced maintenance costs hold the most appeal to end clients and their design teams.

From the general discussions with each of the respondents at the end of the market research interview, it is clear that there are still a number of challenges to overcome in the different self-healing technologies before they are market-ready. The acceptance and adoption of self-healing concrete by the construction industry is therefore undoubtedly one of the biggest challenges faced by the M4L research team. The interest and willingness of industry to participate in the market research and the keenness to remain informed of the research, as it develops, nevertheless serves to highlight the importance with which it views innovation. Whilst predominantly seen as a concrete that heals cracks, there are indeed far wider benefits of using self-healing cementitious materials, including the potential for resource efficiency via reductions in element cross–sectional areas and steel reinforcement volumes. Moreover, it has been demonstrated that there is an appetite for a range of new cementitious materials that have enhanced sensing abilities, in-built immunity to particular forms of damage, improved self-healing capabilities and superior actuation properties that can really enhance the resilience of the nation's infrastructure.

4. Conclusions

Representatives from client bodies, design team members and contractors have all helped to capture a picture of the current state of the UK's infrastructure. They have also highlighted the main challenges faced in building new, and maintaining existing, infrastructure. Concrete structures and elements most susceptible to deterioration have been highlighted and the consequences of dealing with this deterioration identified. The current approaches taken to enhance a structure's longevity mainly involve the use of supplementary cementitious material to improve the barrier between the environment and the reinforcement. The market research results have demonstrated that self-healing concrete may enable us to address some of the main concerns facing civil engineering infrastructure, and in doing so yield structures with reduced whole-life costs and fewer repair and maintenance events as a consequence of its enhanced durability. The latter will have a significant influence on the economic, environmental and social impact of repair and maintenance events, which will be of benefit to the UK as a whole.

Table 2
Distribution of responses for the benefits that hold appeal and hold the greatest appeal.

	Clients (14)		Design Team Members (16)		Contractors (10)	
Benefit	Appeals	Greatest appeal	Appeals	Greatest appeal	Appeals	Greatest appeal
Self-healing of cracks	100%	43%	75%	56%	90%	70%
Reduce use and cost of over-design, additives, excess concrete cover and reinforcement	64%	14%	64%	38%	60%	20%
Seal, limit porosity and prevent further absorption	79%	29%	56%	13%	80%	10%
Self-diagnose the nature of any degradation	50%	21%	63%	0%	50%	0%
Provide a concrete which is less brittle and more ductile	50%	7%	56%	6%	50%	0%
Ability to detect changes in materials and the environment	50%	7%	50%	0%	30%	0%

Acknowledgement

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