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UPTAKE OF ADVANCED AND SUSTAINABLE ENGINEERING MATERIALS IN CIVIL INFRASTRUCTURE PROJECTS

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ABSTRACT: Advanced and sustainable engineering materials, such as engineered fibre composites, geoploymer cement, and recycled concrete have the potential to reduce demand on scarce resources, improve safety, reduce greenhouse gas emissions and contribute to positive initiatives in civil engineering design and construction in areas like foundations and structural members. For example, engineered fibre composites can replace other materials (such as timber), because of their high strength to weight ratio, light weight and ease of installation. They can also have positive impacts on sustainability. While advanced materials have several advantages, their take-up by industry, and in particular small and medium enterprise companies (SMEs), has in a number of cases been relatively slow. This is likely to be the result of a number of factors, such as relatively high cost, financial risk in using an unproven technology, lack of suitable design standards, an unproven life cycle, uncertainty over long-term sustainability issues, and possible changed building and construction methods. Advantages and disadvantages of the use of selected advanced and sustainable materials in civil engineering projects are investigated. A weighted scoring methodology for improved evaluation of their advantages and disadvantages, with a view to aiding decisions, is proposed.

Keywords: Advanced Materials; Sustainability; Innovation; Civil Engineering; Construction

1. INTRODUCTION

Advanced and sustainable engineering materials have the potential to make a positive contribution to civil engineering design, construction, operation and maintenance through reducing demand on scarce resources, improving safety and positively impacting on sustainability and resilience. While there have been a number of applications of these materials, their uptake at a more general level in civil engineering projects, and particular the small and medium enterprise (SME) building and construction sector, has tended to not been as rapid as it could.

A number of such materials have considerable promise in terms of innovation in engineering design, construction and asset management. Polymer composites, for example, are well-known for their use in manufacturing applications like aircraft. They have also had considerable use in non-critical structural applications such as bathrooms and vanities, cladding, decoration and finishing. It has been claimed that, in 1999, the construction sector was the world’s second largest consumer of polymer composites, with 35% of the global market [1]. More recently, they have also been used in a number of applications like walers in corrosive environments, fibre composite bridge girders as alternatives to timber girders, railway sleepers, and repair and replacement of timber piles [2]. These structural applications of advanced materials promise to provide considerable efficiencies to the construction process and contribute to sustainability through increased sustainability of scarce resources like old-growth timber. Other advanced and sustainable materials are similarly being successfully used in civil engineering applications.

The SME construction sector has been shown to be quite innovative in a number of areas, and in particular in the adoption of proven products and improved processes [3]. At the same time, there appears to be some reserve with respect to the development of less well-known or less well proven technologies. Price, for example, driven by the competitive tendering process, was found to be the main factor in a Welsh study on the adoption of pozzolans as substitutes for cement [4].

The decision-making process with respect to the adoption of new innovations (including new materials) is likely to be the result of a balance of barriers and enablers to adoption of innovations. Other factors, such as knowledge of the innovation, client requirements and legislative factors are also likely to impact on the decision to use advanced and sustainable materials.

This paper explores some of the issues, barriers and enablers with respect to this decision, discusses research with respect to innovation in small builders that illustrates the innovation process, and proposes a weighted scoring methodology for aiding the decision making process.

2. EXAMPLES OF ADVANCED MATERIALS

The materials selected for the discussion in this paper are engineered fibre composites, cement (pozzolanic substitutes for cement and geopolymer based cement) and concrete using recycled materials. These materials have been selected because of their potential impact on civil engineering developments.

One definition of composite materials is that they combine and maintain two or more distinct phases to produce a material superior to either of the base materials [5]. Polymer composites combine polymer resin (for example, polyester, vinyl and epoxy) with fillers and reinforcing fibres (such as glass, aramid and carbon) used as the primary means of carrying load, while the polymer resin protects the fibres and binds them into a cohesive structural unit, commonly called fibre composites [6]. As previously discussed, they have a wide range of applications in civil engineering and building, particularly in corrosive environments or as replacements for more traditional materials.

It has been claimed that in North America alone 10 billion tonnes of concrete are produced each year. This concrete has a definite impact on the environment. Strategies to meet the environmental challenge include the use of supplementary cementitious materials (such as fly ash and granulated blast furnace slag), use of recycled materials in place of natural resources, improved durability, improved mechanical and other properties (for example, doubling the strength of concrete in compression members to reduce the required amount of material) and reuse of wash water. There are both advantages and disadvantages with these processes. For example, while cement made with fly ash utilizes a waste material and is useful for mass structures because it has a delayed and different reaction from Portland cement, its relatively slow rate of strength development makes it unsuitable for applications requiring high early strength. The variation in the properties of fly ash between different electric power plants also raises an issue with respect to quality control. Recycled aggregate generally has lower densities than the original material used because of the cement mortar that remains attached to the original particles, and larger water absorption than virgin aggregate. The aggregate also varies in quality. Concrete made with recycled aggregate tend to have lower strength that concrete made with virgin aggregate. It is expected, however, that a shifting public attitude towards global warming is likely to increase the use of concrete containing recycled materials [7].

A geopolymer may be described as “the inorganic aluminosilicate polymeric gel resulting from the reaction of amorphous aluminosilicates with alkali hydroxide and silicate solutions.” The material may have various names, including geopolymer cement (or concrete). It has been used on concrete of up to 70 MPa in strength, and can attain satisfactory high early strength if the temperature is above 20 degrees Celsius. Concrete made with this material as binder is claimed to have higher tensile and flexural strength, and lower drying shrinkage, relative to concrete made with Portland cement. It has been used in a range of applications like pavements, a retaining wall, water tanks, a boat ramp and precast bridge decks [8].

Carbon dioxide emissions from concrete made with this material have been compared that made from Portland cement. One such study, on a one cubic metre sample used in a Melbourne, Australia, bridge, reported that when obtaining raw materials, concrete manufacturing, and construction (transport and onsite placement) were taken into account that the carbon dioxide emission from the concrete made with geopolymer cement was 9% less than that from equivalent concrete made with Portland cement [9].

In summary, while there are a number of advantages with advanced and sustainable materials, there are also some disadvantages with them from the point of view of the product (material) itself. The following sections develop this discussion further.

3. THE INNOVATION ADOPTION PROCESS

The uptake of advanced and sustainable materials and their associated processes can be described by the concept of innovation, which can be defined as the development of an idea, practice, or object that is perceived as new by an individual or other unit of adoption. According to Rogers [10], the generation of innovations has the steps of recognizing a problem or need, research (basic and applied), development, commercialization, diffusion and adoption and the consequences (changes that occur to an individual or a social system as a result of adoption or rejection of an innovation). In the adoption process, the potential user of the innovation makes a decision, the stages of which are gaining knowledge of the innovation, forming an attitude about it (persuasion), making a decision whether to accept or reject it, implementation of the new idea, and confirmation of this decision. All steps in the decision process involve communication.

The decision process is when an organization decides to adopt or not adopt a new product or process. There are rewards for early adopters of a process. There are also negative risks, such as potential financial loss. The materials discussed in the previous section would tend to be mainly in the research or development phases of the innovation process. Thus, any adopter of one of these materials would be considered to be an early user of it.

The Queensland Department of Transport and

Main Roads have further identified that in order to achieve the successful development of a product, it is necessary for all members of the interdisciplinary team to have a common and shared understanding of the material and service life conditions. In their consideration of engineered fibre composites, the major participants are the fibre composite designers, manufacturers, installers, infrastructure owners and academia [11]. There should be a shared understanding and clear lines of communication between these parties for successful adoption of the product.

4. ENABLERS IN MATERIAL UPTAKE

The process of forming an attitude about an innovation, which is the focus of the persuasion stage of the decision process, will require an assessment of items like relative advantages, compatibility, complexity, trialibility and observability [12]. The assessment of these factors will require evaluation of the advantages and other enablers of the adoption of these materials, and of the disadvantages and other barriers to this adoption or uptake.

From the point of view of enablers of innovation in the Australian construction industry, a national survey of 383 construction industry firms [13] identified a number of drivers for innovation in the firms surveyed, which included efficiency, productivity improvements and customer needs. Better performing firms adopted a number of advanced practices, and invested in research and development.

Profit, market and legal related factors [14], and knowledge, along with its organization and dissemination [15], have also been identified as aids to innovation. A United Kingdom study found that in small construction firms, owners have the power to ensure rapid decision-making and thus facilitate rapid innovation, and that the process of innovation was behavioral and cyclical in nature [16].

A further potential driver of innovation for organizations undertaking civil engineering projects is the growing requirement for sustainable construction practices, including energy efficiency and resilience of buildings to extreme weather events [17]. Sustainability may come at an economic cost [18], which requires consideration.

Other enablers in the uptake of advanced and sustainable materials may include superior performance, improved client and community acceptance of modern energy efficient materials, and ease of construction and installation (such as with the relatively light fibre composite materials).

5. ISSUES IN MATERIAL UPTAKE

While there are a number of factors that facilitate the uptake of advanced and sustainable materials in civil engineering, a number of issues and barriers to this uptake have also been identified.

For example, the Queensland Department of Transport and Main Roads has identified a number of areas in which there are deficiencies between engineered fibre composites and other products such as concrete and steel. One of these areas is the lack of an Australian standard for this product. While there was a draft standard developed, it did not progress because of a lack of industry interest. Fragmentation and the use of Intellectual Property as a tool to closely guard information but also limit transparency surrounding manufacturing limits the openness of information published in papers. Ultimately, the lack of standards poses a professional indemnity risk for designers.

Other issues identified by the Department include uncertainty about the material properties with changes in temperature, and deficiencies in manufacturing and installation specifications, knowledge of design life and asset management procedures. The risk of brittle collapse is also an issue that remains unresolved. The Department is mitigating these risks by working with academics, undertaking trial installation of fibre composite replacement girders and undertaking structural health monitoring. It is also developing its own specifications [19].

While these processes might be useful for larger organizations, it is unlikely that the SME sector would have the financial strength to support the extensive development and testing required. There are also likely to be other barriers to the adoption of new materials by industry, and particularly its SME sector. For example, the Australian construction industry has been considered fragmented, adversarial and having low profit margins, low-bid tendering, inequitable risk sharing, small firm size, a lack of investment in technology, a cyclical nature, a large proportion of very small firms and a limited history of business deliverables from researchers [20]. The small firm size tends to be an international trend [21]. It has also been found that cost-related factors are significant barriers to innovation, as are market-related factors and lack of skilled staff [22]. In summary, if the construction industry is to benefit from innovation, it has to change from an adversarial and blame culture to a sharing one [23].

Other negative factors that may have a bearing on the decision process to use advanced and sustainable materials in civil engineering projects, and in particular by SME firms, are likely to include the high cost of adopting and using these materials and the risks (particularly financial risks) of the new innovation not being successful.

6. RESEARCH - INNOVATION IN BUILDERS

In order to better understand the innovation process in the SME engineering and construction sector, the author undertook research in 2006 into innovation in the small firm residential building sector in South-East Queensland, Australia [24]. One hundred small residential builders constructing housing up to $A750,000 in value were contacted, with 20 agreeing to a structured interview.

A qualitative methodology incorporating a semi-structured interview process was used. The objectives of the interview questions were to explore the extent of innovation in the firms selected, provide an understanding of how they developed or adopted innovations, assess the value of innovations to the firm and determine their readiness to adapt to changes in their operating environment.

Seven of the firms interviewed had four or fewer staff, 11 had five to 19 staff, and two had just over 19 staff. Of these firms 18 were primarily engaged in construction, and the other two in renovation and maintenance. Eleven of the firms undertook design as well as construction. All were involved in private sector residential work.

There were 50 examples of innovation in these firms. Of these innovations, 25 were associated with the development of a new or improved product. The majority of other innovations were associated with the development of a new or improved process. Eleven of the innovations were related to new or improved materials. Advanced materials like engineered fibre composites were however not listed by the builders.

Interviewees were also asked to select a particular innovation and discuss in depth why they developed or used it. The reasons given for their development ranged from an interest in a particular aspect of improvement (for example, sustainability) to the specific business objective of improving productivity and/or efficiency.

A majority of the firms stated that the innovation was profitable, with none reporting a decrease in profits. Most firms did not feel that they had gained a competitive advantage by using the innovation, and there was uncertainty that using the selected innovation had reduced risk. However, all firms indicated that they would use the innovation again. This was a positive sign that the innovation had been of benefit to the firm.

Responses to questions about sustainability related innovations were varied, and included the positive responses that sustainable practices were good for business, made firms competitive and were a point of difference. Negative responses included the cost availability (of suitable materials), that some firms would only undertake sustainable practices if required and that tight margins were a barrier to adopting sustainable practices.

While not all of the firms reported problems in implementing the selected innovation, they expressed concerns with respect to the availability of suitable trades people. Cost (which also impacts on client expectations) and the need for legislation to keep up with industry advances were also cited as issues in this regard.

In summary, the SME builders, while generally supportive of innovations that utilized new or improved materials, had a number of reservations in areas like profitability and risk, and had concerns in areas like cost and availability of suitable materials.

7. PROCESS FOR ASSESSING UPTAKE

The above discussion has shown that while industry is interested in adopting innovative materials and processes, there are a number of factors that both encourage and discourage their use. A weighted scoring process has been proposed to aid the adoption decision process. This process focuses on the persuasion stage of that decision process, and in particular on the relative advantage of the innovation.

The stages in this process are to a) adopt a scoring system that enables factors expressed in different units of measurement to be included in the evaluation on an equivalent basis; b) weight the factors with respect to each other; and c) calculate a total weighted score combining the weights and the scores of individual factor values.

In order to provide an approach that permits a mix of quantitative and qualitative variables to be combined in the same analysis on an equivalent basis, each variable in the evaluation is assigned a score on the same rating scale. For quantitative variables, the score would be assigned on the basis of calculation, based on a formula that related the scores to actual variable values. Qualitative variables would be assigned a utility value derived from a risk profile based on the indifference point between various combinations of worst and best expected outcomes, given the probabilities of receiving each [25]. Stakeholder views would aid this process.

While there are a number of options for assigning the weights for each factor being assessed, one approach is the rational management process of Kepner and Tregoe [26]. This approach formulates a goal statement and considers the objectives supporting this goal by dividing them into musts (which are not negotiable) and wants. The wants are then grouped into related variables, and the groups are ranked using pair wise comparison or other techniques. Benefit and cost may be may be considered separately from the analysis, or else assigned a score and included in the analysis.

The final step is to calculate a total weighted score by summing the individual weighted scores, as follows:

$$T = \sum_{i=1}^{n} WiSi$$

Where:
T = Total Weighted Score
Wi = Weight for factor i
Si = Score for factor i

This process is illustrated for engineered fibre composites, in which the alternatives of "adopt" and "not adopt" in the replacement of a timber bridge girder are compared. For simplicity, the analysis uses the selected factors of material, design life, ease of construction, availability of standards, ability to trial and sustainability. A scale of 0 to 10 is used to assign scores, which are multiplied by weights assigned to each factor and summed for each case, as shown in Table 1. In this table, "ease of construction" has been shown as "ease of building", "availability of standards" has been shown as "available standards", and "sustainability" as "sustain." The abbreviation "Tot." has also been used in the header rows for "Total."

Table 1 Example Weighted Scoring Calculation for Adoption Decision - Fibre Composite

Factor	Weight	Adopt		Not adopt	
Scores		Item	Tot.	Item	Tot.
Material	0.25	8	2	2	0.5
Design life	0.15	6	0.9	4	0.6
Ease of Building	0.15	7	1.05	5	0.75
Available Standards	0.3	2	0.6	10	3
Sustain	0.15	6	0.9	2	0.3
TOTAL	1.00		5.45		5.15

On the basis of the result in Table 1, the decision would be to probably adopt the material, subject to consideration of other factors like benefit and cost.

8. CONCLUSION

This paper has focused on the uptake of advanced and sustainable materials in civil infrastructure projects, with particular emphasis on their adoption by small and medium enterprise companies. It has overviewed the topic, discussed examples of advanced and sustainable materials, outlined the innovation process, discussed factors which aid (enablers) and prevent (barriers) with respect to uptake of these materials in civil engineering projects, discussed previous research into a similar area and outlined a possible approach to the adoption decision process.

It is concluded that as demonstrated in the research into innovation by small builders the industry is quite interested in adopting new materials and methods of design and construction, there are still reservations that prevent the complete uptake of advanced and sustainable materials in civil engineering projects. While advances in methods and the requirements of sustainable development may facilitate this process, there is a strong requirement for appropriate standards to be developed, increased trials of these materials in applications, and extensive communication to the industry about the benefit of using advanced and sustainable materials in their businesses.

9. REFERENCES

[1] Humphreys, MF, "The Use of Polymer Composites in Construction", in Proc. 2003 International Conference on Smart and Sustainable Built Environment, November, 2003, Brisbane, Australia.

[2] Aravinthan, T, "Fibre Composites in Civil Infrastructure – Research to Reality in Australia", in Manalo, A and Kee-Jeung Hong (eds.) Research to Reality: Promoting Fibre Composites in Civil Infrastructure, February 2014, pp. 2-7.

[3] Thorpe, D, Ryan, N., Charles, M., 'Innovation and small residential builders: an Australian study', Construction Innovation, Vol. 9, No. 2, 2009, pp. 184-200.

[4] O'Farrell, M and Miller, CJM, "The barriers to new technology diffusion in the construction industry of South Wales", in Current Issues in Small Construction Enterprise Development, Welsh Enterprise Institute Monograph No. 4, ed. Miller, CJM. Packham, GA and Thomas, B, Pontypridd: University of Glamorgan Business School, 2002, pp.123–137.

[5] Humphreys, MF, op. cit.

[6] Humphreys, MF, op. cit.
[7] Meyer, C, “Recycled Materials in Concrete”, in Mindness, M (ed.), Developments in the Formulation and Reinforcement of Concrete, Cambridge, England: Woodhead Publishing Limited, 2008, pp. 208-230.
[8] Aldred, J and Day, J, “Is Geopolymer Concrete a Suitable Alternative to Traditional Concrete?” in 37th Conference on our World in Concrete & Structures”, Singapore, August 2012.
[9] Turner, LK and Collins, FG, “Carbon Dioxide Equivalent ($CO_{2\text{-}e}$) Emissions: A Comparison between geopolymer and OPC Cement Concrete”, Construction and Building Materials, Vol. 43, 2013, pp. 125-130.
[10] Rogers, EM, “Diffusion of Innovations”, 5th ed., New York: Free Press, 2003, pp. 12, 136-168.
[11] Pritchard, R, “an Infrastructure Owners Perspective of Fibre Composites”, in Manalo, A and Kee-Jeung Hong (eds.) Research to Reality: Promoting Fibre Composites in Civil Infrastructure, February 2014, pp. 30-34.
[12] Rogers, EM, 2003, op. cit., p. 170.
[13] Manley, K, Allan, D, Blayse, A, Coillet, M, Hardie, M, Hough, R, MacKenzie-Smith, S, May-Taylor, W, McFallan, S, Miller, M, Swainston, M, Taylor, G, “BRITE Innovation Survey”, Brisbane: Cooperative Research Centre for Construction Innovation, 2005.
[14] Australian Bureau of Statistics, “Innovation in Australian Business 2003”, ABS Catalogue No, 8158.0. Canberra: AGPS, 2005.
[15] Egbu, CO, “Managing Knowledge and Intellectual Capital for Improved Organizational Innovations in the Construction Industry: an Examination of Critical Success Factors”, Engineering, Construction and Architectural Management, Vol. 11, No. 5, 2004, pp. 301-315.
[16] Sexton, M, and Barrett, P, “Appropriate Innovation in Small Construction Firms”, Construction Management and Economics, Vol. 27, No. 6, 2003, pp. 623-633.
[17] Australian Building Codes Board, “Discussion Paper - Resilience of Buildings to Extreme Weather Events”, Canberra: AGPS, April 2014.
[18] Meyer, C, “The Economics of Recycling in the US Construction Industry”, in Chun, Claisse, Naik and Ganjian (eds), Sustainable Construction Materials and Technologies, London: Taylor and Francis Group, 2007.
[19] Pritchard, R, op.cit.
[20] Hampson, KD and Brandon, P, “Construction 2020: A Vision for Australia’s Property and Construction Industry”, Brisbane: Cooperative Research Centre for Construction Innovation, 2004.
[21] European Commission, “Constrinnonet – Promoting Innovation in Construction Industry SMEs Project Final Report”, Constrinnonet Project Consortium, 2004.
[22] Australian Bureau of Statistics, op. cit.
[23] Egbu, CO, op. cit.
[24] Thorpe, D, Ryan, N., Charles, M.,2009, op. cit.
[25] Hamburg, M, "Statistical Analysis for Decision Making", NY: Harcourt, Brace and World, pp. 631-644.
[26] Kepner, CH and Tregoe, BB, "The New Rational Manager", Princeton, NJ: Kepner-Tregoe Inc.

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