2nd R.N. Raikar International Conference and Banthia- Basheer International Symposium
on Advances in Science and Technology of Concrete, 18-19 December 2015, Mumbai, India

Geopolymer Cement Concrete - An Emerging Technology for the Delivery of Resilient Highway Infrastructure Solutions

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ABSTRACT

The 20th UK Annual Local Authority Road Maintenance survey has recently highlighted that, despite local authorities reporting an increase in overall maintenance expenditure, one in six roads in England and Wales are classed as being in poor condition. The estimated cost of rectifying this situation is £12 billion. As such, there has never been a more important time to identify resilient and cost effective planned/preventative highway maintenance solutions.

Geopolymer cement concrete is generally regarded as an attractive alternative to Portland cement owing to environmental and performance benefits. Reported in this paper are preliminary findings of research undertaken to further interrogate its potential as a high-performance repair material for specific road defects, such as potholes. Undertaken collaboratively with local geopolymer cement producer Banah UK Ltd., metakaolin/alkali silicate-based geopolymer cement was assessed in this capacity. As part of a mix optimisation investigation, reported are key fresh and mechanical material properties including setting time, compressive/flexural strength and impact resistance. Indicative in situ performance, based on findings from accelerated road testing, is also discussed. On-going research to investigate composite material behaviour and optimisation of key material properties, such as bond, modulus of elasticity and abrasion resistance, is additionally reported.

Keywords: Highways; Maintenance; Geopolymer cement concrete; Durability

INTRODUCTION

Alarmingly, one in six roads in England and Wales are currently classed as being in poor condition (Asphalt Industry Alliance, 2015). The estimated cost of rectifying this situation is £12 billion. In England and Wales alone, 2,670,350 potholes were repaired in 2014; an average of around 15,706 repairs per highway authority responsible. With an average reported cost of £57 per pothole, the associated repair bill equated to around £144.3 million. While a significant sum of money in its own right, this represents only a fraction of the total costs associated with related traffic and resource management, compensation claims and administration. The proportion of total budget spent on structural maintenance in 2014 was 58% in England and 52% in Wales. Similarly in North America, pavement patching is reported to represent one of the most extensive and expensive pavement maintenance activities undertaken by highway agencies at all levels (McDaniel et al., 2014). Furthermore, despite high levels of ongoing financial investment, typical service lives of various pavement preservation techniques is reported as being only 2-6 years (Wei and Tighe, 2004). As such, there has never been a more important time to identify resilient and cost effective planned/preventative highway maintenance solutions.
In terms of materials used for highway repair, a wide variety of conventional options exists for flexible and rigid pavements, including cold and hot asphaltic materials, cementitious materials and polymeric materials (McDaniel et al., 2015). In recent times, interest is growing in the application of novel geopolymer cements, which are generally regarded as attractive alternatives to Portland cement owing to considerable environmental and performance benefits. It is claimed (Davidovits, 2013), for instance, that geopolymer cement production can achieve up to 90% CO_2 emission reductions relative to Portland cement production. Improved properties reported for geopolymer cement concrete include dimensional stability (Wallah, 2010; Aurora Construction Materials, 2014), compressive/flexural strength and resistance to acids, sulphates (Shi, 2003; Ariffin et al., 2013; Glasby et al., 2014), fire and freezing-thawing cycles (Provis and van Deventer, 2009; Abdulkareem et al., 2014). Compressive and flexural strengths in the ranges 90-125 MPa (Banah, 2014; Ambily et al., 2014), for example, are reported.

Despite these promising findings, however, research into the application of geopolymer cement in highway infrastructure environments is limited. Initial trials into its use in light pavement applications have be trialled by an Australia-based geopolymer cement concrete manufacturer (Andrews-Phaedonos, 2014). In this work, in-service visual examinations of footpaths, precast walkways, and cycle lanes showed no signs of stress, cracking or other failure types, resulting in the material's inclusion within a regional road authority specification (VicRoads, 2013). While a study undertaken in Thailand (Hawa et al., 2013) reported the potential use of geopolymer cement concrete as a rapid road repair solution, the material was based on fly ash, palm ash and parawood ash which required heat curing at temperatures around 80°C. No durability testing was carried out as part of this work, with reported suitability based on compressive and bond strengths only.

Against this background, reported in this paper are preliminary findings of a research programme aimed at optimising geopolymer cement concrete's application, under ambient curing conditions, as a resilient highway infrastructure repair solution.

EXPERIMENTAL INVESTIGATION

Geopolymer cement used

While numerous alternative inorganic polymer and alkali-activated cement types are currently being researched and developed internationally, the focus of this study is the application of geopolymer cement based on calcined clay; a technology reported (British Cement Association, 2009; McLeod, 2005) to show the greatest potential for realistic development and commercialisation. Having experienced successive historic volcanic episodes, multiple sources of ferruginous kaolinitic clay exist in Northern Ireland. These usually occur in deposits ranging from 10-20 m in depth, many of which have been exposed at existing quarry sites. Despite its relatively high iron oxide content, this material has been found to offer a good precursor for geopolymeric binders (Davidovits, 2011). Indeed in recent years, a local company, Banah UK Ltd, has undertaken research into the potential exploitation of this material for commercial-scale production of geopolymer cement (McIntosh and Soutsos, 2014). The manufacturing process established involves initial calcination of the kaolinitic clay to dehydroxylate the main mineral component. The resultant powder (relative density 2.89), is then activated using a silicate solution of an alkali metal (57% by mass solids) formulated to enable dissolution of aluminosilicates and supply additional soluble silica to form a binder matrix with a defined Si to Al ratio (McIntosh and Soutsos, 2014). The resultant two-part (powder and activator) system (banahCEM) was employed throughout this research.

Mixture proportions

Research undertaken on behalf of South Carolina DOT (Rangaraju and Pattnaik, 2008) identified a range of key material properties and values influencing the compatibility of parent pavement structures and subsequent repairs. Key properties reported included modulus of elasticity, flexural/tensile strength, porosity and dimensional stability. Against this background, and representing the initial stages of a more comprehensive body of work aimed at optimising and predicting performance, nine geopolymer cement concrete mixtures were initially considered to assess effects of powder, activator and water contents on performance. As shown in Table 1, ranges considered for each of these variables were 450-550, 300-400 and 50-60 kg/m^3 respectively and for each mix, one variable was changed while the other two remained at the middle content level. Fine aggregate contents were adjusted in each case to maintain constant volume. Given a lack of harmonised standards, mixing was carried out in accordance with guidance provided by Banah UK (2011), which involved using a motorised table-top mixer to blend the powder and alkaline activator initially followed by addition of fine aggregate.

Specimen preparation and testing

Material characterisation

To help identity factors potentially impacting ultimate performance, materials were initially characterised using Fourier transform infrared spectroscopy (FT-IR) and scanning electron microscopy (SEM). FT-IR spectra were recorded using a Thermo-Nicolet FT-IR, Nexus model 470 operated over a 4000–500 cm^{-1} frequency range in attenuated total reflectance (ATR) mode. Analysis was undertaken of both reacted geopolymer cement and the unreacted powder component powder used in its manufacture. Each sample was ground to a fine powder using a pestle and mortar to ensure homogeneity before FT-IR recording. In terms of SEM, low vacuum Hitachi S3200N equipment operated at 25kV was used to analyse geopolymer cement concrete samples.

Table 1. Geopolymer mortar mixture proportions

Mix no.	Mixture proportions (kg/m³)				Activator/ powder ratio	Water/ powder ratio
	banahCEM powder	banahCEM activator	Sand	Water		
Effect of activator content						
1	500	300	1545	55	0.60	0.11
2	500	350	1495	55	0.70	0.11
3	500	400	1445	55	0.80	0.11
Effect of binder content						
4	450	350	1545	55	0.78	0.12
5	500	350	1495	55	0.70	0.11
6	550	350	1445	55	0.64	0.10
Effect of water content						
7	500	350	1500	50	0.70	0.10
8	500	350	1495	55	0.70	0.11
9	500	350	1490	60	0.70	0.12

Compressive and flexural strength

For each of the nine mixes considered, 7- and 28-day compressive and 28-day flexural strength was measured. Both 50 mm cube and 40x40x160 mm prism specimens were cast in steel moulds and wrapped in polythene sheet to retain moisture and stored at ambient temperature for 24 hours. Specimens were then de- moulded and stored at the same ambient temperature until testing was carried out in accordance with BS EN 1015-11: 1999 (British Standards Institute, 1999i).

Fresh properties

In this limited study, only the optimum mix in terms of compressive/flexural strength was further assessed for setting time and flow to ensure compliance with typical pavement repair material requirements. Testing was carried out according to BS EN 196-3: 2005 (British Standards Institute, 1999ii) and BS EN 1015-3: 1999 (British Standards Institute, 1999iii) respectively.

Pavement wear and skidding resistance

The optimum mix in terms of compressive/flexural strength was additionally assessed for its resistance to simulated wear when applied as a pothole repair material. To achieve this, a pothole was simulated in a 275x275x40 mm asphalt sample by removing material using a hammer and chisel to form a roughly circular defect with rough, sloped sides and approximate volume of 0.00104 m³. This defect was designed to satisfy reported minimum dimensions of potholes as defined by over 60% of local authorities in England and Wales (Asphalt Industry Alliance, 2015).

The defect was then filled with geopolymer cement concrete to the same level as the original slab surface. Compaction was achieved initially by hand using a steel tamping rod, followed by 20 seconds of compaction using a vibrating table. Excess mortar was removed using a hand trowel and no further surface texturing was applied. The repaired slab was then covered with a polythene sheet to retain moisture. After 24 hours at 20±2 °C, the polythene sheet was removed and the specimen was stored at this temperature, uncovered, for a further 6 days before the wearing test was carried out. Air curing was selected, as this method is likely to reflect in-situ curing applications for pothole repair material. The simulated wear test was carried out using an accelerated road test machine in accordance with Appendix H of TRL Report 176 (1997). This test involves a pair of loaded (5±0.2 kN), standard pneumatic-tyred car wheels revolving so as to repeatedly pass over the surfacing of a series of 275x275x40 mm specimens in a turning action. As well as revolving, the loaded wheels move 160±25 mm laterally across the specimens in a cycle taking 1-10 minutes. Undertaken at an ambient temperature of 20±2 °C to replicate slow-speed, high friction traffic loading, specimens in this study were exposed to 2,000 wheel-passes (1,000 revolutions) at a rate of 10 revolutions per minute.

Skid resistance values (SRV) of the repaired pothole were also assessed before and after application of the wearing test according to RRL Road Note 27 (1969). This test involved pre-saturating samples and determining the angle through which a slider attached to a pendulum rose coming into contact with tests surfaces. Losses of texture depth and skid resistance values were then calculated as:

$$Loss = 100\ x\ \frac{(Initial\ value - final\ value)}{Initial\ value}\ \%$$

RESULTS AND DISCUSSION

Material characterisation

Previous research has identified FT-IR analysis as a proven technique for characterising geopolymeric materials (Khale and Chaudhary, 2007; Rees et al., 2007). For both the unreacted and reacted geopolymer cement samples, and associated with Si-O-Si or Si-O-Al asymmetric stretching vibrations (Khale and Chaudhary, 2007), the most prominent feature identified was an intensive absorbance peak recorded between wavelengths of 1250 and 800 cm^{-1}. In comparison to the unreacted powder sample where this peak occurred at 1036 cm^{-1}, absorbance of increased intensity at 980 cm^{-1} was recorded for the reacted cement sample. This clearly indicated the formation of geopolymeric gel, a trend reinforced by the presence of an additional absorbance signal at 780 cm^{-1} for the geopolymer cement powder Khale and Chaudhary, 2007).

Shown in Figure 1 are SEM micrographs at differing resolutions of samples made with plain geopolymer cement concrete (Figure 1, a-c) and basalt micro fibre-reinforced polymer cement concrete (Figure 1, d-f). While not a focus of this paper, the basalt micro fibre-reinforced specimens (added at a rate of 2% by mass of geopolymer cement powder) form part of an ongoing study to investigate geopolymer cement concrete-based composites. Clearly, the images shown in Figure 1 indicate a very dense microstructure for both samples, albeit with limited micro cracking. Positively, Figures 1 (e) and (f) indicate that the basalt micro fibres deflect crack growth, hence toughening the material. Importantly in terms of long term structural and durability performance, the bond of geopolymer cement paste around aggregate and fibre surfaces is homogeneous, with no evidence of a defined, low quality transition zone.

Compressive and Flexural Strength

Mean 7- and 28-day compressive and flexural strength results for each mix are reported in Table 2 and presented graphically in Figures 2-4. Clearly from Table 2, the nine different mixes considered produced a range of 7- and 28-day compressive (54-69 and 54-77 MPa respectively) and 28-day flexural (1.7-3.1 MPa) strength values.

Across the range of values measured, 28-day flexural strengths were on average 3.9% of corresponding compressive values; a relationship typical of conventional cement-based materials containing fine aggregate only. As expected, and encouraging in terms of potential future performance predictions based on compressive strength, a relatively well-defined (R^2=0.68) relationship was noted between flexure and compression as shown in Figure 2. Positively, the upper range of flexural strengths measured exceeded the minimum laboratory-based value of 2.4 MPa proposed for selecting rapid-setting patch materials (McDaniel et al., 2014).

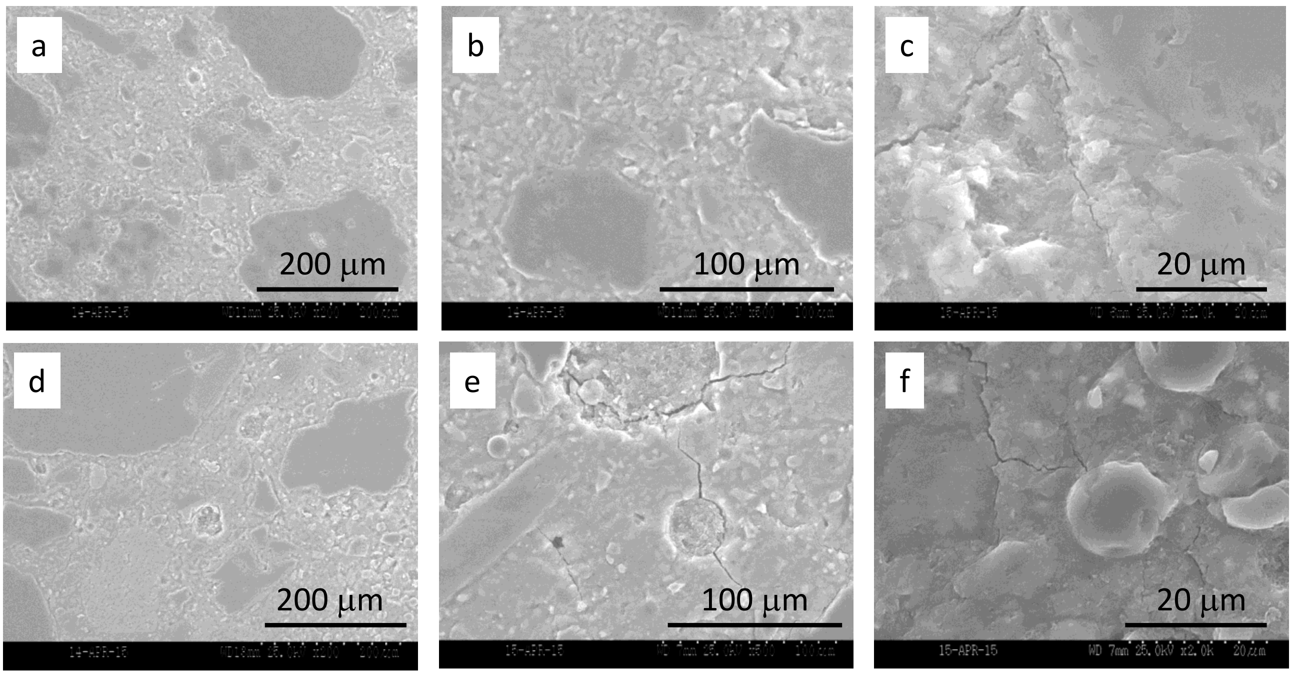

Figure 1. SEM micrographs of basalt fibre (a-c) and plain geopolymer cement concrete (d-f)

Table 2. Mean compressive and flexural strength results

Mix no.	Compressive strength (MPa)		Flexural strength (MPa)
	7-day	**28-day**	**28-day**
1	59	62	2.7
2	66	67	2.4
3	61	59	2.7
4	54	54	2.7
5	66	67	1.7
6	69	77	2.3
7	69	76	3.1
8	66	67	2.7
9	58	58	2.4

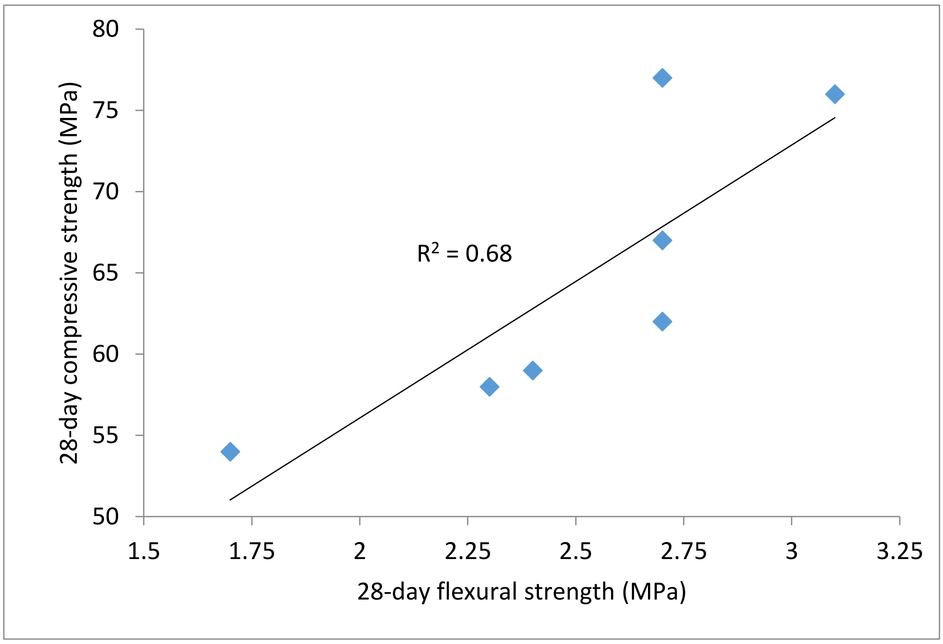

Figure 2. Relationship between 28-day compressive and flexural strength

In terms of compressive strength development with time, a more inconsistent pattern was observed. From Figure 3, for instance, it is clear that 7 to 28 day strength increases (in the range 2-12%) were noted for the majority of mixes. Mixes 4 and 9, on the other hand, exhibited no strength increase, while mix 3 exhibited a minor strength loss (-3%). An explanation for this observation may be that one element of the material proportions for each of these mixes was at the limits of those considered. For mixes 3, 4 and 9 this was maximum activator content (400 kg/m^3), minimum binder content (450 kg/m^3) and maximum water content (60 kg/m^3) respectively, suggesting a negative impact of these outer limits. This conclusion is further analysed in Figure 4.

Effect of activator content

Figure 4(a) demonstrates a non-linear relationship between compressive strength development and BanahCEM activator/powder ratio for mixes 1-3. While based on a relatively limited data set, Figure 4(a) suggests that an optimum activator/powder ratio in the region of 0.70 exists. Indeed, as the activator/powder ratio increased from 0.70 to 0.80, a reduction in 28-day strength from 67 (mix 2) to 59 MPa (mix 3) was noted. As mentioned above for mix 3, this value of 28-day strength was additionally linked to a minor reduction in strength between 7 and 28 days.

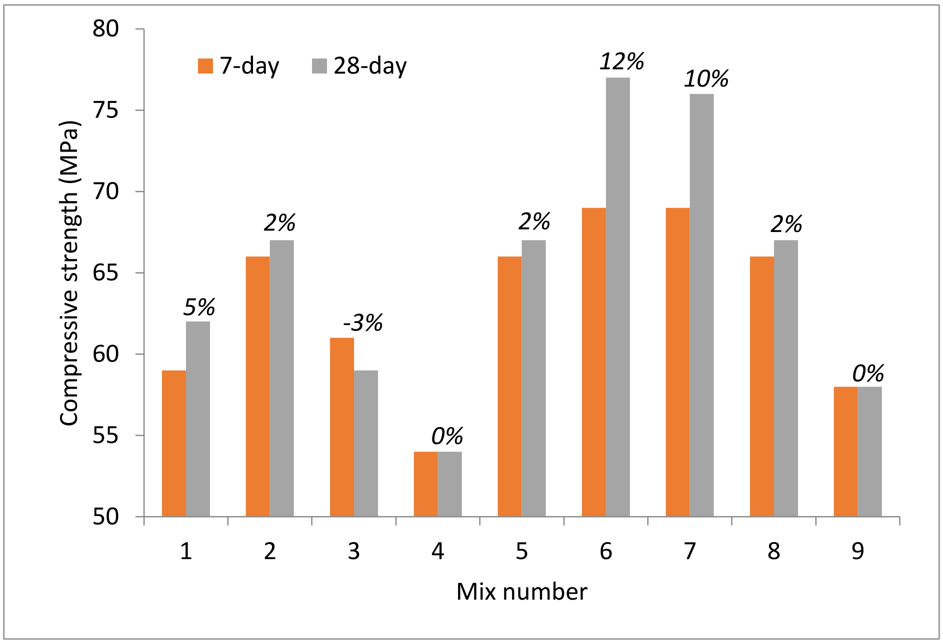

Figure 3. Comparison of 7- and 28-day compressive strength values

Effect of binder content

Compressive strength data for mixes 4-6 is plotted in Figure 4(b), which as predicted, shows a significant (R^2=0.99) relationship between strength and geopolymer binder content. With constant activator and water contents of 350 and 55 kg/m^3 respectively, as powder contents increased from 450-550 kg/m^3 (corresponding to an activator/powder ratio range of 0.78-0.64), 28-strength values increased significantly from 54 to 77 MPa. Relative to activator content, therefore, this finding clearly confirms a dominant influence of geopolymer binder content in terms of ultimate compressive strength.

Effect of water content

For mixes 7-9, which possessed constant powder and activator contents of 500 and 350 kg/m^3 respectively, the influence of water content is plotted Figure 4(c). As with conventional concrete, a significant inverse relationship (R^2=1.0) existed between strength and water content. As water contents increased from 50-60 kg/m^3 (corresponding to a water/powder ratio range of 0.10-0.12), 28-strength values decreased significantly from 76 to 58 MPa.

Optimising performance

The mix design influences discussed above are further analysed in Figure 5, which provides plots of 28-day compressive versus both activator/powder and water/powder ratios for all nine mixes considered. Clearly from this plot, the influence of water/powder ratio dominated (R^2=0.87) that of activator/powder ratio (R^2=0.25) across the mixes considered. This is perhaps surprising, but suggests that provided sufficient activator is present in the system to promote dissolution of Al and Si and supply additional soluble silica, ultimate performance, as is the case with conventional concrete, is driven by water/powder ratio. In the current study, optimum performance in term of 28-day compressive strength was achieved by mixes 6 and 7 (77 and 76 MPa respectively). While these mixes had differing activator/powder ratios (0.64 and 0.70 respectively), both were prepared with the minimum water/powder ratio considered (0.10).

Fresh Properties

Based on the optimisation process described above, mix 6 was selected for further testing in relation to key fresh properties. Mean initial and final setting times recorded for mix 6 were 100 and 150 minutes respectively. While suitable for standard mortar applications, it is recognised that accelerated setting times are typical of road repair materials. Indeed, the minimum recommended laboratory-based strength requirement of 20 MPa for rapid-setting patch materials is required after only 2 hours (McDaniel et al., 2014). While research into the performance of rapid-set geopolymer cement concrete is on-going as part of the current study, this falls outside the scope of this paper.

The mean mortar flow recorded for mix 6 was 143 mm, representing a 69.9% increase from the lower diameter of the test mould. Falling within a flow range of 140-200 mm and, therefore, classed as plastic mortar (British Standards Institution, 2007), this indicated an adequate level of workability for progressing to the next stage of research.

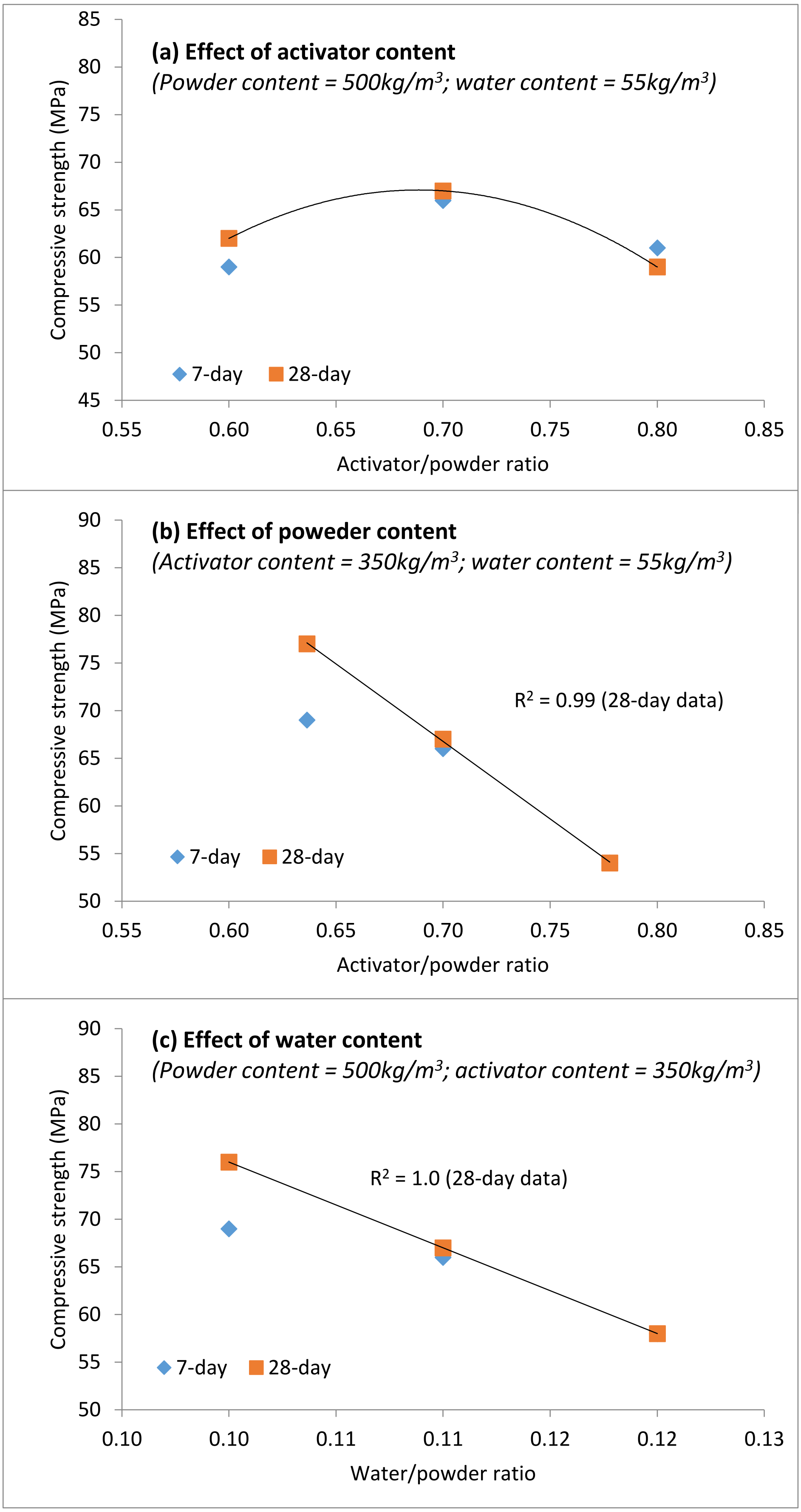

Figure 4. Influence of mix design parameters on compressive strength

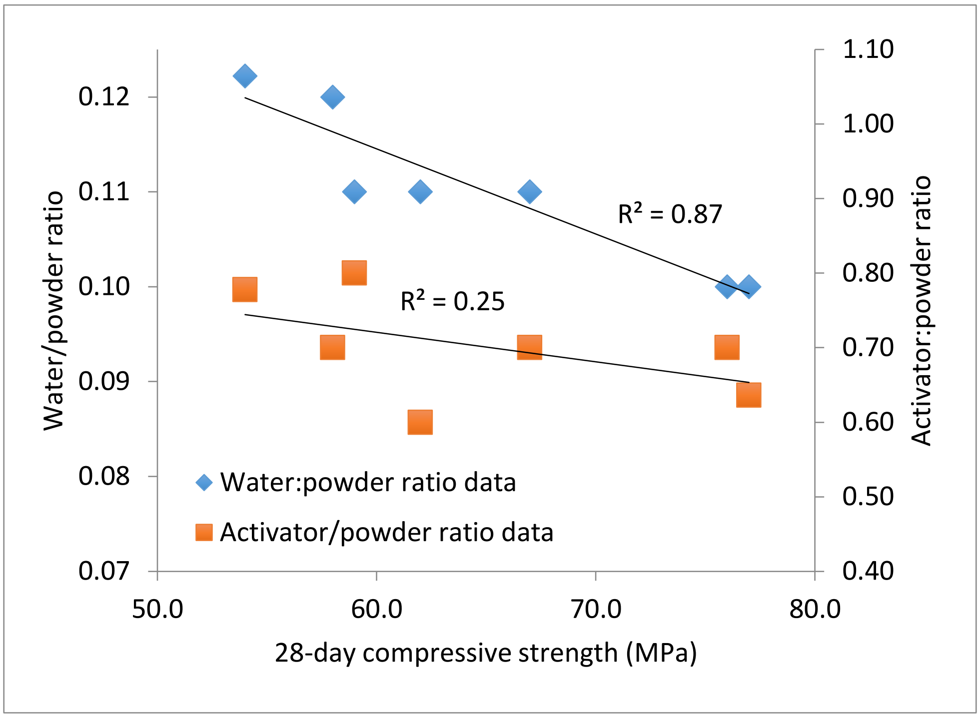

Figure 5. Influence of mix design summary

Pothole Repair Performance

In terms of pavement wear, both visual inspections and measurements of texture depth were recorded before and after exposure to 2,000 accelerated wheel passes (see Figure 6). While performance issues were predicted due to strength and stiffness incompatibilities between the parent asphalt and geopolymer repair, no visual surface cracking, delamination, de-bonding or deterioration was noted. This finding may, in part, have been influenced by the relatively small-scale nature of the test specimen and the high stiffness of the steel mould used. Equally, no measurable decrease in surface texture was noted (equating to a classification of E; excellent, no discernible fault (TRL, 1997)), although some minor shining of the pothole surface was noted. While the 2,000 wheel exposure level reported is only 20% of the maximum recommended for this test (100,000 passes), the early indication from this testing regime was that geopolymer cement concrete potentially offers a durable and compatible pavement repair material.

Similar to the findings for pavement wear, no discernible reduction in skid performance was measured before and after trafficking, with an average skid-resistance value (SRV) of 41 recorded in both instances. While this is a positive result, it should be noted that this value fails to meet the minimum requirement for use on a public road (Category C - minimum SRV value of 45) according to RRL Road Note 27 (Road Research Laboratory, 1969). Minimum SRV levels recommended for motorways/trunk roads (category B) and difficult sites such as roundabouts/bends (category A) are 55 and 65 respectively. As such, further work is ongoing, via the use of surface texturing and aggregate selection, to improve initial SRV levels of geopolymer cement concretes. This work is in line with the recommended minimum texture depth of 0.65mm for category A and B roads (Road Research Laboratory, 1969).

SUMMARY AND CONCLUSIONS

The investigation reported in this paper focussed on characterisation of geopolymer cement and its application in nine mixes concrete mixes designed to optimise mix design in terms of powder/cement and powder/water ratios. Tested for each mix were 7 and 28 day compressive, and 28 day flexural, strengths. The optimum mix in this regard was selected for further workability testing and subjected to simulated wearing in a road repair application. A skid-resistance value for the geopolymer surface was additionally recorded. Based on the results reported, the following general conclusions may be drawn:

1. An ability to mix and cure geopolymer cement concrete in ambient conditions has been confirmed, enabling future in-situ applications to be considered.
2. For the mix designs considered, compressive and flexural strength values at 28 days ranged from 54-77 and 1.7-3.1 MPa respectively. This range of mechanical properties was considered appropriate in terms of future application in highway repair scenarios.

Figure 6. Simulated pot hole before and after repair with geopolymer cement concrete

3. The mechanical properties of geopolymer cement concrete are affected by both activator/powder and powder/water ratios. Optimum performance in this study was achieved by mix 6, prepared with activator/powder and water/powder ratios of 0.64 and 0.10 respectively.
4. For the optimum mix assessed, the initial and final setting times recorded in this study (100 and 150 minutes respectively) were too slow for the material to be considered as a 'rapid setting' solution. However, material flow indicated an appropriate level of workability for in-situ repair applications.
5. After exposure to simulated traffic wear in Ulster University's accelerated road test machine, the potential durability performance of geopolymer cement concretes in road pavement application appears to be excellent. Minimal surface wear was measured and no surface cracking or other surface deformation was apparent during a visual examination of the material after test completion.
6. While skid-resistance of the geopolymer cement concrete repair considered was deemed unsatisfactory for general road applications, reductions in performance after exposure to simulated traffic wear were minimal.
7. The overarching conclusion from this investigation was that geopolymer cement concretes exhibit considerable potential for application in road pavement applications.

Clearly in its infancy as a research programme, further work is merited to develop a market for geopolymer cement concrete applications in the highway environment. Indeed, based on the conclusions reported in this paper, three main areas of future development have been identified.

Firstly, further optimisation of geopolymer cement concrete mix design is required. In addition to considering powder/activator/water ratios, impacts of aggregate type and content will also be critical, particularly regarding wear and skid resistance performance. Given that pavement repairs are carried out on a wide range of parent structure types, also merited is optimisation in terms of properties such as stiffness and bond. As such, composite behaviour will be analysed using a variety of fibre and alternative aggregate types. Secondly, the exploration of geopolymer cement concrete mixes which enable setting time reductions, without compromising other fresh and mechanical properties, is required to offer a practical rapid road repair material alternative. As mentioned previously, attainment of desired properties, such as compressive/flexural strength, within a 2-hour window is the norm. Finally, while geopolymer cement concrete durability appears of high quality, further research is required into asphalt-geopolymer mortar bond and surface texturing techniques to ensure acceptable long-term skid-resistance properties. High impact for the study will be assured by engaging local road authorities and stakeholders in on-going research to additionally explore full-scale pavement trials and development of related design and specification documentation.

ACKNOWLEDGEMENTS

Financial and technical support provided for this research from the Department for Employment and Learning, Northern Ireland and Banah UK Ltd. is gratefully acknowledged.

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