Research Repository UCD

Title	Expansive fracture agent behaviour for concrete cracking
Authors(s)	Laefer, Debra F., Ambrozevitch-Cooper, Huynh, Minh-Phuoc, Midgette, J., Ceribasi, Seyit, Wortman, John
Publication date	2010-06
Publication information	Laefer, Debra F., Ambrozevitch-Cooper, Minh-Phuoc Huynh, J. Midgette, Seyit Ceribasi, and John Wortman. "Expansive Fracture Agent Behaviour for Concrete Cracking" 62, no. 6 (June, 2010).
Publisher	Institution of Civil Engineers/Thomas Telford Publishing
Item record/more information	http://hdl.handle.net/10197/3441
Publisher's version (DOI)	10.1680/macr.2010.62.6.443

Expansive fracture agent behaviour for concrete cracking

D. F. Laefer*, N. Ambrozevitch-Cooper†, M. P. Huynh*, J. Midgette‡, S. Ceribasi*
and J. Wortman§

University College Dublin; Malpass and Associates

Increasing concerns regarding litigation and terrorism provide a strong dual motivation to decrease high explosives usage in the construction industry. This paper provides parameter considerations and initial guidelines for the application of expansive fracture agents, typically used for concrete and soft rock removal. This approach may be especially appropriate near environmentally and historically sensitive sites. Thirty-three unreinforced blocks (approximately a cubic metre each) of varying strengths, composed of sand, cement, and fly ash, were tested under various temperature environments, with differing expansive agents, confinement levels and post-cracking treatments. Cracking characteristics such as crack initiation and crack expansion were analysed. Although the performance of expansive cement was dependent on a highly complex set of variable interactions, higher ambient temperatures, higher agent mixture temperatures and chemical configuration designed for colder temperatures decreased the time to first crack and hastened the extent of cracking. Conversely, higher strength material required more time to first crack, as well as an extended time to achieve a 25·4 mm wide crack. Manual interference with the normal material volume expansion slowed the cracking process but did not truncate it, while the manufacturer's recommendation to introduce water post-cracking actually reduced and slowed the extent of cracking.

Notation

D   borehole diameter
k   scalar ($k = L/D$)
L   distance between holes

Introduction

Increased prohibitions against blasting in urban areas warrant a more rigorous assessment of rock and debris removal methods. This experimental study was designed to investigate usage optimisation of rock and existing concrete foundation removal using soundless chemical demolition agents (SCDAs), also known as chemical expansive agents. This class of products was designed to remove in situ material without the noise and vibrations traditionally associated with blasting and percussive removal techniques.

Although using SCDAs for complete replacement of traditional explosives is cost prohibitive (Table 1), these products offer distinct advantages over dynamite and ammonium nitrate for specific projects. Explosives usage can require a large resource commitment extending beyond the construction application (including surety bonds, permits, explosives training, certifications and multiple years of record keeping of all material receipt, removal, use, disposal, misfires, loss and theft, as well as any accidents) (SBCCI, 2001). Notification of law enforcement, fire department and local emergency planning committees, plus possible supervision from code officials is also required. Additionally, strict construction and maintenance guidelines of storage containers for all explosives and detonators are mandated. The substantial stand-off distances required for explosives storage and use can be prohibitive in congested areas (Table 2) (SBCCI, 2001; Sickler, 1992). Furthermore, many communities have simply banned explosives usage within city limits.

* School of Architecture, Landscape, and Civil Engineering (SALCE), University College Dublin (UCD), Newstead, Room G25, Belfield, Dublin 4, Ireland
† 12144 Meadow Post Lane, Charlotte, NC 28269–8725, USA
‡ Malpass and Associates, Greenville, NC 27858, USA
§ P.O. Box 54, Ceasar, NC 28020, USA

Table 1. *Cost comparison of rock removal methods*

Agent	Dollars per 0·76 m^3 of rock	Source
Dynamite	<2	www.get-a-quote.net (2009)
Air hammer	24·55	www.get-a-quote.net (2009)
SCDA*	41·80	www.bluecirclesoutherncement.com.au (2009)

* The cost of SCDA is just the material.

Table 2. *Excerpts from American table of distances for storage of explosives (data from Sickler (1992))*

		Distances: feet					
Quantity of explosive materials		Inhabited buildings		Public highways with less than 3000 vehicles/day		Public highways with 3000+ vehicles/day	
Pounds over	Pounds not over	Barricaded	Unbarricaded	Barricaded	Unbarricaded	Barricaded	Unbarricaded
0	5	70	140	30	60	51	102
20	30	125	250	50	100	93	186
75	100	190	380	75	150	139	278
150	200	235	470	95	190	175	350
1000	1200	425	850	165	330	318	636
6000	7000	770	1540	245	490	573	1146
25 000	30 000	1130	2000	340	680	933	1866
75 000	80 000	1695	2000	510	1020	1293	2000
150 000	160 000	1935	2000	580	1160	1629	2000

Background

Soundless chemical demolition agents are typically reserved for use around sensitive structures, where blasting or percussive methods risk damaging utilities, roads and nearby buildings. When compared to traditional explosives, non-blasting options may offer a relatively high level of safety but at a higher cost.

Soundless chemical demolition agents are fine-grained powders the consistency and colour of Portland cement (Table 3). When mixed with water of appropriate temperature and quantity, the SCDA forms a slurry that can be poured into pre-drilled holes. The mixture hydrates to 150°C and nearly triples in volume over several hours, during which pressure is generated from within the SCDA-filled hole by the formation and development of ettringite crystals (Taylor, 1997). When the expansive pressure exceeds the tensile capacity of the rock or concrete, cracking of the in situ material occurs. After the chemical reaction is complete, the SCDA resolidifies to a low-strength material that easily disintegrates. Because SCDAs do not generate substantial noise, vibration, fly-rock, dust or gas, they can be desirable as alternatives to conventional demolition, when protection of nearby structures or population is a concern. Yet, without technically based usage guidelines, true safety and economic feasibility of such products cannot be well established.

Traditional blasting agent quantities are based on the homogeneity, strength, density, rate of energy propagation and elasticity of the material being fractured, as

Table 3. *Product information*

SCDA mix	Mix A	Mix B
Product name	BRISTAR^{TM} 100	BRISTAR^{TM} 150
Recommended temperature range: °C (°F)	21–35 (69–96)	10–20 (50–68)
Recommended water content: litres	1·5–1·7	1·5–1·7
Water content selected: litres	1·5	1·6
Water temperature: °C (°F)	15 (59)	15 (59)
Chemical components*	Silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) ferric oxide (Fe_2O_3), calcium oxide (CaO) magnesium oxide (MgO), sulfur trioxide (SO_3) sulfonated melanine or naphthalene–sulfonic acid polymer with formaldehyde, sodium salt	

* The difference between mix A and mix B results from the proprietary ratio of the chemical components.

well as borehole spacing, depth and size. For SCDAs water temperature, mixture content and ambient temperature are additional factors (Blue Circle Southern Cement, 2009; Hinze and Nelson, 1996). At the current time, limited published research on parametric performance of SCDAs has explored material properties, construction practices and temperature variations.

Material properties

Gomez and Mura (1984) proposed $L = Dk$ for determination of hole spacing for various material strengths, where L is the distance between holes, D is the hole diameter and k is an in situ material property, where $k < 10$ for hard rock, $8 < k < 12$ for medium rock, $12 < k < 18$ for soft rock and concrete, and $5 < k < 10$ for prestressed concrete. The research of Gambatese (2003) on concrete yielded dissimilar results ($4 < k < 10$) suggesting half the allowable distance between holes proposed by Gomez and Mura (1984). However, Gambatese's conservative findings may have been an outgrowth of conducting small-scale work without compensatory material scaling.

Construction practices

In the studies by Dowding and Labuz (1982; 1983) of SCDA in steel cylinders and rock in laboratory and field tests, they found that pressure was independent of borehole diameter but heavily influenced demolition time, which was also a function of the quantity of SCDA introduced. Also, low ratios of boreholes to surface area maximised the amount of fractured material per kilogram of SCDA, but delayed the time of first cracking. Furthermore, an increase in time to first crack was observed for larger burdens (i.e. distance to free edge).

In the study by Gambatese (2003) on $152\cdot4 \times 152\cdot4 \times 76\cdot2$ mm specimens, hole depth, size, spacing and angle were shown to control cracking. For more specific installation guidelines, Hinze and Brown (1994) investigated borehole sizing and concluded that, at a specific temperature and water content, borehole sizing did not significantly affect the maximum achievable expansive pressure attained after 24 h of testing. What was left unanswered was the potential impact of a non-variable expansion pressure on material removal characteristics and whether there is a corollary for minimally achieved expansive pressures.

Furthermore, Hinze and Brown (1994) showed that although borehole diameter did not change maximum expansive pressures, water content did. Within the manufacturer's recommended water content (30–34% by weight), a 4% increase decreased expansive pressures by 25%. In a later study (Hinze and Nelson, 1996), a $2\cdot3$% water content reduction (to $27\cdot7$%) increased expansive pressure $19\cdot8$% over that attained with the recommended 30% water content. With only $27\cdot7$%, a superplasticiser offset workability losses of the drier mix. Thus, 30–34% water content appears as a work-

ability recommendation, as opposed to one to maximise hydration. Performance with common concrete additives, to adjust workability, has also been investigated but with conflicting results (Haneda *et al.*, 1994; Mehta and Lesnikoff, 1973; Polivka, 1973). As such, water may not be a straight-forward issue. The manufacturer recommends spraying water on the in situ material after initial cracking to speed cracking and increase crack width (Blue Circle Southern Cement, 2009). This suggests the possibility of a secondary hydration effect, a parameter hitherto not explored. Temperature, however, has been a topic of investigation.

Temperature variations

Tests at ambient temperatures within and beyond the manufacturer's suggested range (20–35°C) showed ambient temperature more strongly influenced maximum expansive pressure than borehole size or water content (Figure 1) (Hinze and Brown, 1994). Increasing ambient temperature from 20 to 30°C approximately doubled the expansive pressure, and raising ambient temperature another 50% to 45°C generated a further 50% pressure increase (Hinze and Brown, 1994); field and safety considerations may preclude such high ambient temperatures being utilised in practice, and these results must be considered as relative values not usage guidelines, because of the unusually high level of confinement provided by the 25–50 mm diameter steel tubes used for testing and the potentially detrimental impact of the hydration heat on the strain gauges.

Test set-up and methodology

Objectives

Research presented herein was intended to provide further insight into optimising concrete and soft rock removal with SCDAs, although testing was restricted to unreinforced concrete blocks, thus further applicability has yet to be verified. Crack formation and expansion were compared for varying concrete strengths, hole
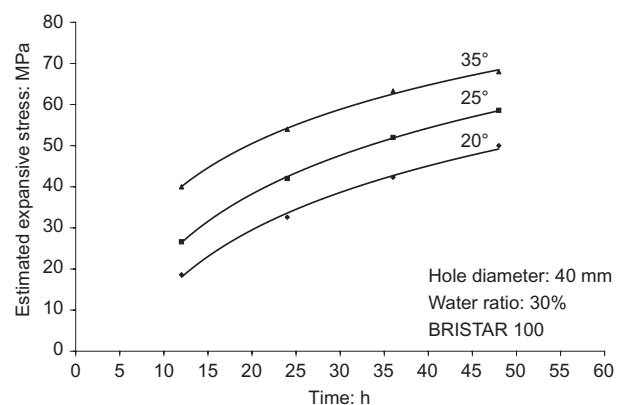

Figure 1. Changes in expansive stress of B-100 (data from Blue Circle Southern Cement (2009))

confinement, post-cracking treatments and temperatures. Results were measured by:

(*a*) time to first crack measured from the time the SCDA was first introduced
(*b*) maximum cumulative crack width at 24 h, as measured by the block's total expansion across its four top face edges and verified by readings along the upper portion of the four side faces
(*c*) minimum time to reach a cumulative crack width of 25·4 mm on the perimeter of the specimen, herein referred to as minimum demolition time (MDT) and measured as for criterion (*b*).

MDT was to be indicative of when removal could begin; an MDT of 25·4 mm may be overly conservative, depending on site conditions and material type. These three criteria were selected as key components to effective removal of fractured material.

Procedure

Thirty-three unreinforced concrete blocks of varying target strengths (3·0–42·9 MPa) were cast in a 1 m^3 wooden formwork, with a vertical, centralised hole (Figure 2); reinforcing was omitted to limit the number of variables. Each hole was precast (as opposed to field-drilled) to avoid introducing undetectable microcracks in the concrete, prior to the SCDA's introduction. The 38 mm diameter boreholes were 640 mm deep (70% of specimen depth, as per manufacturer's recommendations) (Blue Circle Southern Cement, 2009); Gambatese (2003) proposed 85–90%, but the 70% worked without fail. A spacing ratio $k = 12$ ($L = 457·2$ mm and $D = 38·1$ mm) (Gomez and Mura, 1984) was selected to accommodate the largest variability in material strength, while maintaining geometric uniformity between tests. Two Bristar SCDA mixes (A and B) were tested. These differed by ambient temperature usage recommendation and chemical component quantities (Table 3). In all cases, SCDA was poured into the hole within 10 min of mixing with water, as specified by the manufacturer (Blue Circle Southern Cement, 2009).

Instrumentation

The size and geometric symmetry of the blocks were selected to minimise scaling and boundary condition problems within available resources. They can be considered as representative of individual footings. Although alternative geometries and restraint conditions would alter the specific, quantitative results, they are unlikely to change the general trends reported herein. All block faces were monitored for displacement and cracking. Prior to attaching displacement gauges, a 102 mm square grid was overlain on each face to facilitate consistent instrument placement and easy visual referencing for crack documentation (Figure 2). After SCDA introduction, crack formation, propagation and expansion were recorded hourly directly on the blocks, with each new increment labelled by date and time. Displacements were measured by way of dial gauges at three heights along each of the four vertical faces, with horizontal rulers affixed at one edge for redundancy. Displacements along the block's top were measured by four gauges in each direction, with rulers for redundancy (Figure 2). After each test's conclusion, every block face was photographed (e.g. Figure 3) and a rubbing was made, which was then photographed and enhanced in a graphics program to incorporate a scaled grid and to transfer recorded, timed, crack lengths and widths for each crack (e.g. Figure 4). Table 4 summarises testing configurations and results.

Material properties

The concrete comprised sand, cement, fly ash and water (Table 5); larger aggregate was excluded to promote homogeneity, thus applicability to materials with higher strengths, reinforcement or natural rock has yet to be confirmed. A local ready-mix company provided concrete approximating target strengths; the material's commercial nature precluded more precise identification of mix components. Prior to testing, wave propaga-

Figure 2. Instrumented block (uncracked)

Figure 3. Post-test block with Y-shaped crack

Figure 4. Enhanced photograph of rubbing

tion velocity was measured by way of impact-echo. Accelerometers mounted on the concrete's surface recorded stress wave signal traces. The most dominant signal frequency was isolated, from which wave speed was determined.

Construction practices

To verify whether confinement was a negligible factor, as proposed by the manufacturer (Blue Circle Southern Cement, 2009), product usage conditions including loss of confinement through destruction of the naturally occurring seal and artificial confinement were tested. Additionally, post-crack wetting was tested. After SCDA introduction, some specimen holes were left uncovered, while others were capped with a 2·26 kg mass placed on top of plastic sheeting; the manufacturer recommends covering the hole to prevent moisture loss through steam or introduction of external water, even though confinement was listed as unnecessary

Table 4. Test block specifications and results
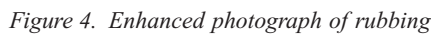
Block number	Strength: MPa	Age: days	Young's modulus: MPa	Wave velocity: m/s	SCDA mix	Average ambient temperature: °C	Wetting	Artificial cap/broken seal	Time to first crack: h	Cumulative crack width at 24 h: mm	MDT: h	Crack shape
1	30·1	51	4227	—	A	21	N	Y/N	32	—	—	Y
2	30·1	51	4227	3735	A	21	N	Y/N	20	4	30	$\frac{1}{2}$
3	30·1	51	4227	3677	A	21	N	Y/N	19	4	30	$\frac{1}{2}$
4	42·7	106	4702	3456	A	21	N	N/N	13	12	24	Y
5	42·7	106	4702	3594	A	21	N	Y/N	11	20	20	Y
6	42·7	106	4702	3456	B	20	N	N/N	16	9	25	Y
7	7·9	89	382	3331	B	21	N	N/N	11	29	19	Y
8	7·9	89	382	3230	A	21	N	Y/N	12	1	32	Y
9	7·9	89	382	3309	A	21	N	N/N	13	1	32	Y
10	8·2	43	479	3331	A	21	N	Y/N	16	8	26	Y
11	8·2	43	479	3230	A	20	N	N/N	25	0	36	X
12	8·2	43	479	3309	B	20	N	N/N	13	21	21	Y
13	24·5	36	4823	3758	A	20	N	N/N	12	8	25	Y
14	24·5	36	4823	3677	A	19	N	N/N	11	1	33	Y
15	24·5	36	4823	3735	B	20	N	N/N	13	40	18	Y
16	23·0	73	3650	3968	A	23	N	N/N	11	42	17	Y
17	23·0	73	3650	4006	A	23	N	N/N	13	39	19	Y
18*	23·0	73	3650	4012	A	23	N	N/N	—	—	—	—
19	22·3	73	4302	3749	A	23	N	N/N	16	19	26	$\frac{1}{2}$
20†	22·3	73	4302	3751	A	23	Y	N/N	44	0	54	Partial
21	22·3	73	4302	3731	A	23	N	N/N	14	25	25	$\frac{1}{2}$
22‡	42·9	73	3926	4218	A	38	N	N/N	8	44	22	Star
23	42·9	73	3926	4222	A	24	N	N/N	15	59	23	$\frac{1}{2}$
24	42·9	73	3926	4239	A	24	N	N/N	21	2	26	$\frac{1}{2}$
25	42·9	76	3853	4105	A	22	Y	N/N	23	9	36	Y
26	42·9	76	3853	4094	A	22	N	N/N	15	50	9	Y
27	42·9	76	3853	4061	A	22	Y	N/N	15	15	26	$\frac{1}{2}$
28	3·0	68	423	2968	A	23	N	N/N	11	43	17	Y
29	3·0	68	423	3042	A	23	Y	N/N	13	36	18	Y
30	3·0	68	423	2978	A	23	Y	N/N	13	39	14	Y
31	3·0	71	425	2873	A	23	Y	N/Y	18	19	26	$\frac{1}{2}$
32	3·0	71	425	2892	A	23	Y	N/Y	21	5	25	$\frac{1}{2}$
33	3·0	71	425	2888	A	23	Y	N/Y	18	14	25	Y

* Formwork problems resulted in an unusable test specimen.
† Experiment with high-strength pipe.
‡ Experiment with superheated block.

Table 5. *Target mix design for concrete blocks*

Target concrete mix	Mix label	Water–cement ratio	Parts sand/parts cement	Average 28-day strength of three cylinders: MPa
Weak	A	0·82	3/2	13·8
Medium	B	0·57	3/2	27·6
Strong	C	0·41	5/1	58·6

(Blue Circle Southern Cement, 2009). Another confinement issue related to the skin that forms on the SCDA's surface during initial set (30 min to 1 h). To determine its effect, some blocks had this skin removed. Post-crack surface wetting of the concrete (a manufacturer's recommendation to expedite crack propagation and increase crack width) was also tested (Blue Circle Southern Cement, 2009). Two wetting methods were employed:

(*a*) surface spraying along cracks
(*b*) pouring water directly into the cracks.

Furthermore, ambient temperature and mix water temperature were examined with block numbers 22–24 cast from the same concrete, using SCDA mix A. The control block (number 24) was tested according to normal procedures at an average ambient temperature of 23·9°C, while block number 22 was tested at 38·3°C, and number 23 was tested at 23·9°C (like the control block), but the mix water used to mix was heated to 37·8°C (2·52 times the control block's water temperature).

Results

For each test, time to first crack, MDT and maximum cumulative crack width at 24 h were recorded (Table 4). Data were analysed as a function of material properties and external factors.

Temperature effects

Temperature was previously identified as a critical variable (Hinze and Brown, 1994). When Dowding and Labuz (1982) decreased ambient temperature by 10°C expansive pressure decreased approximately 30% at 24 h and 10% at 48 h; increased cement temperature also increased expansive pressures. To understand this

better, ambient temperature and mix water temperature were altered. Ambient temperature ranged from 19–24°C (averaging 22·1°C), and average mix water was 15°C, except for numbers 22–24, as previously described (Figure 5 and Table 6).

When ambient temperature increased 14°C (58·33%), time to first crack decreased by 61·90% (13 h) compared to the control block and was 48·31% (7·48 h) faster than the average value of other samples of that strength (Table 4). Maximum cumulative crack width at 24 h was 140·63% more than the average value of equally strong blocks. Furthermore, MDT was 15·38% (4 h) less than the control block number 24, and 10·64% (2·62 h) lower than average of similar specimens.

When water was heated an additional 152% (22·8°C) beyond the control, time to first crack was 28·57% (6 h) less than the control block and 18·92% (3·5 h) less than for other similar blocks. Maximum crack width at 24 h was 126·92% (33 mm) higher than the average value, and MDT decreased 11·54% (3 h) compared to the control block number 24 (Figure 5). Simi-
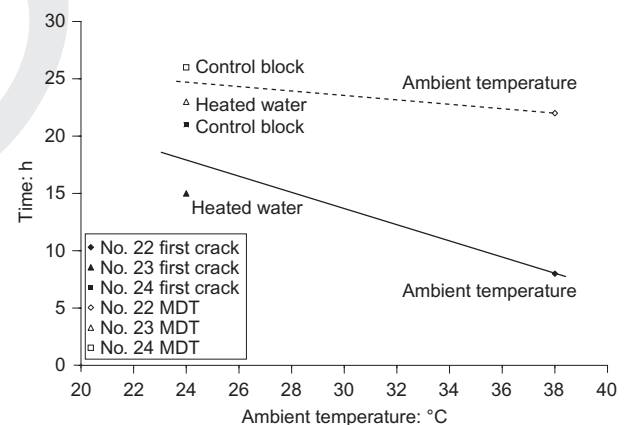

Figure 5. *Effect of high as opposed to low ambient temperature conditions*

Table 6. *Control block specifications and results*

Block number	Ambient temperature: °C	Water temperature: °C	Time to first crack: h	Cumulative crack width at 24 h: mm	MDT: h
22	38·3	15	8	44	22
23	24	37·8	15	59	23
24	24	15	21	2	26

larly, when mix B (designed for colder ambient temperatures (10–20°C)) was used, better and more consistent performance was achieved (Figure 6).

Material properties effects

Figure 7 compares three material strengths (5·50, 24·98 and 42·90 MPa) demolished using mix A. Time to first crack range was 13–19·67 h, with a 15·48 h average for all specimens, with the stronger materials having cracked later. The medium material (354·09% (19·48 MPa) stronger than the weak material) required 11·54% (1·5 h) more time to first crack, 10·61%

(2·46 h) more time to reach MDT and achieved 16·80% (3·58 mm) less cumulative crack width at 24 h (Figure 6) than the weak material. The high-strength material (71·77% (17·93 MPa) stronger than the medium material) needed a further 35·63% (5·17 h) more time to develop a first crack and 14·47% (3·71 h) additional time to reach MDT, while the maximum cumulative crack width at 24 h was 51·17% (9·08 mm) larger than for the medium material. Overall, MDT was within 24 h (23·17 h) for the weakest material and increased to 25·63 h, and 29·33 h, respectively for the medium and strong materials.
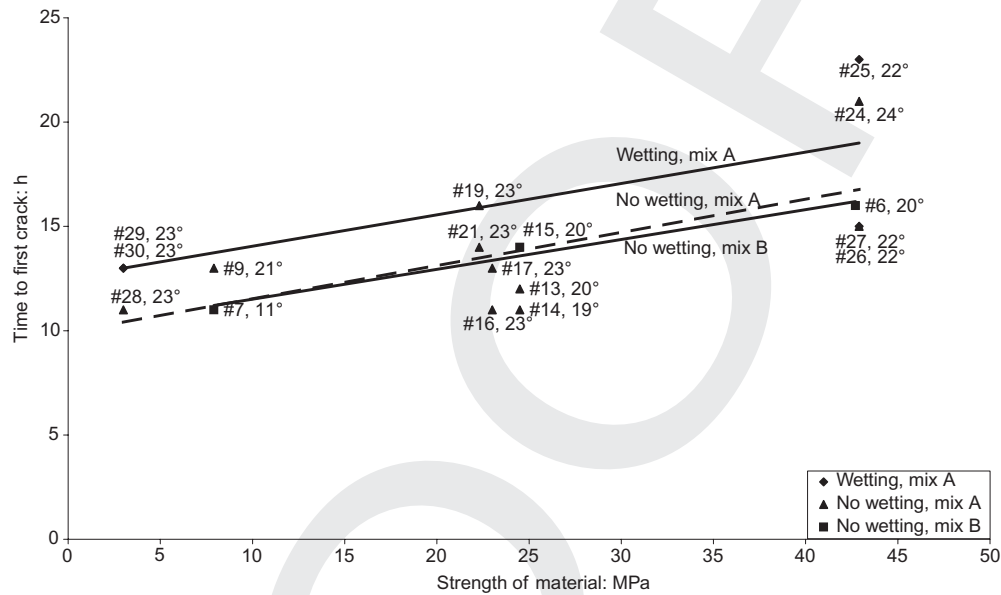

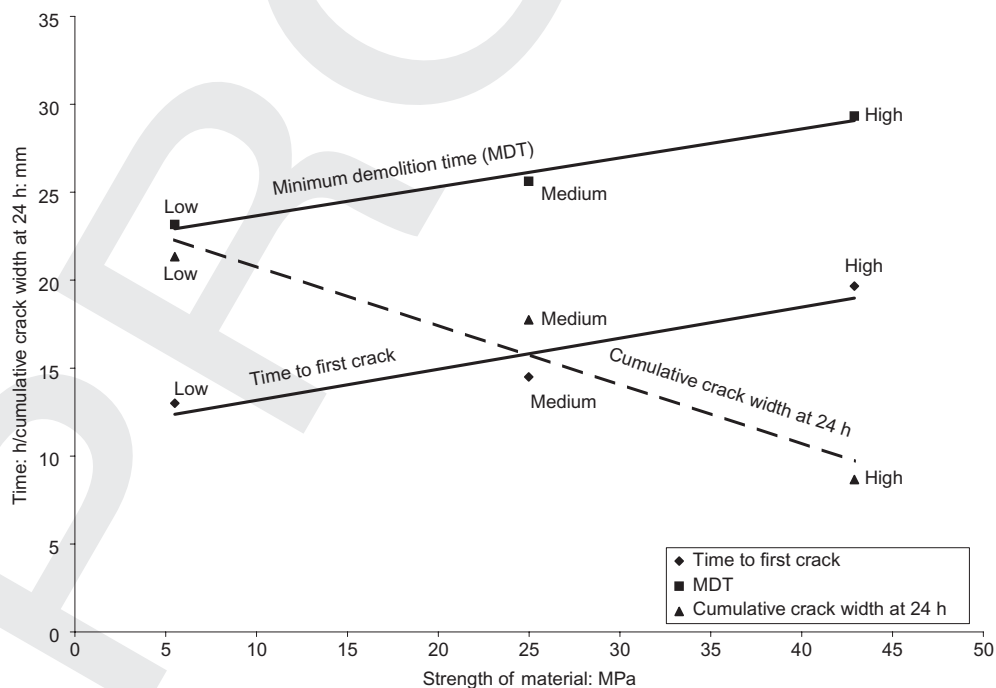Figure 6. Effect of wetting on time to first crack

Figure 7. Crack patterns plotted against strength of material

Construction practice effects

Compared to other blocks of similar strength and similar temperature conditions, specimens with an artificial cap required 22·26% (3·05 h) more time to first crack and 28·82% (6·6 h) longer to reach MDT and had a 81·52% (18·75 mm) smaller average cumulative crack width (Figure 8). Similarly, specimens with broken seals required 38·69% (5·3 h) longer average time to first crack and 10·63% (2·43 h) longer to achieve MDT and had a 44·93% (10·33 mm) smaller cumulative crack width at 24 h. However, all blocks eventually cracked and reached minimum crack width.

The last variable was post-crack wetting. Despite this being a manufacturer's recommendation (Blue Circle Southern Cement, 2009), effects were uniformly detrimental: reducing maximum cumulative crack width at 24 h by 14·91% (3·43 mm) and increasing MDT by 6·05% (1·39 h). In summary, the study demonstrated that poor construction practices could negatively impact performance.

Geometric observations

During testing, one of two distinct crack patterns formed across the top of the block: a Y-shape and a bisecting line (Figures 3 and 9). Generally, samples that cracked later bisected, while those that cracked earlier did so in a Y-shape (Figure 10). Furthermore, data analysis (Table 4) showed that Y-shaped cracks generated a wider crack width at 24 h and had shorter MDTs than biscected blocks. Additionally, bisected cracks consistently occurred only 14 h or more after SCDA introduction (estimated pressure 24 MPa based on Figure 1).

Finally, the SCDA manufacturer suggested a two-
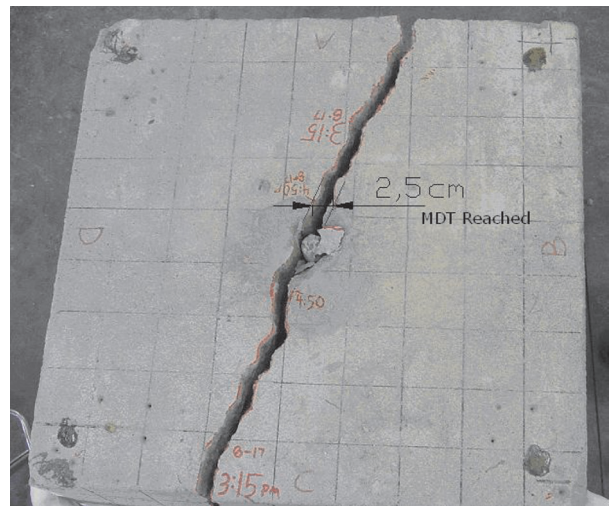
Figure 9. Example of a bisecting crack (1/2 crack)

phase, two-part crack pattern (Figure 11); however, such a phenomenon was not seen in any of this study's 33 specimens, whereas cracking consistently began around the hole and then progressed across the block's top to the nearest edge and down the adjacent side to the block's bottom, while one to two similar cracks began at 120–180° from the first crack and immediately progressed in a likewise fashion.

Conclusions and recommendations for future studies

Soundless chemical demolition agent fracturing of isolated blocks of sand–cement–fly ash mixtures indicate that performance is a function of construction and

Figure 8. Effect of an artificial cap

Figure 10. Influence of crack shape
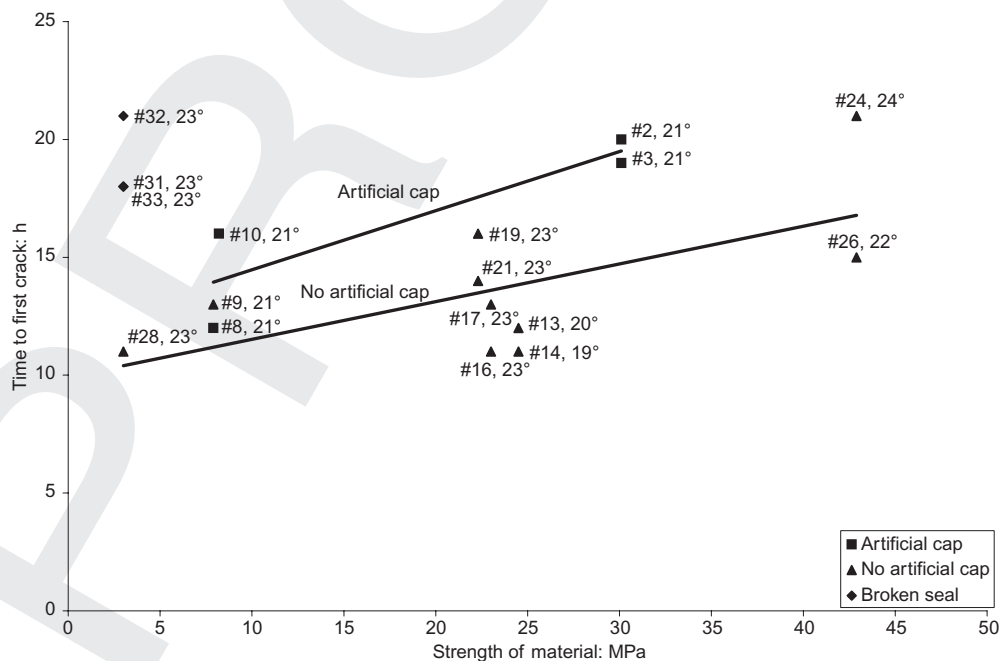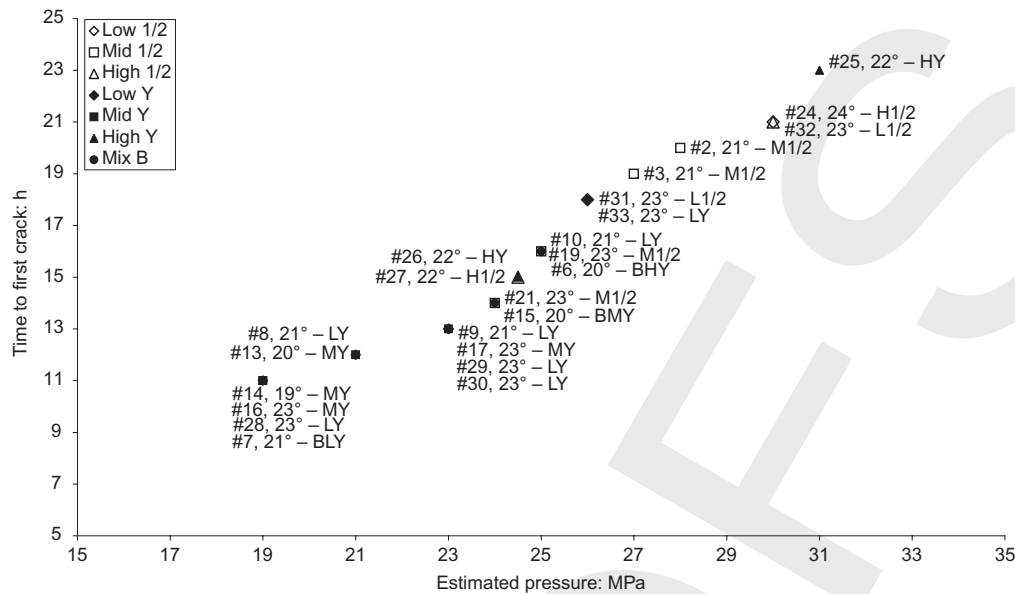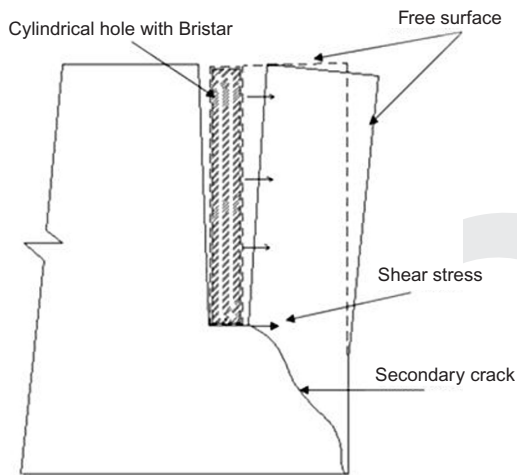

Figure 11. Sectional view of the crack formation with two free surfaces (Blue Circle Southern Cement (2009))

environmental factors, plus material properties. While the manufacturer proposed a time to first crack of 10−20 h and a window of more than a day for crack width development to 25·4 mm (Blue Circle Southern Cement, 2009), average time to first crack in the present study was only 15·48 h and crack widths of 25·4 mm were achieved around 24·62 h.

Construction practices and temperatures exerted significant influence. Artificial or damaged seals slowed first crack development 3·05−5·30 h, reduced average crack width 10·33−18·75 mm at 24 h, and increased MDT 2·43−6·60 h. Sample wetting after cracking generated 3·43 mm smaller maximum crack width at 24 h and increased MDT 1·39 h. Increasing ambient temperature 16·2°C increased maximum cracking at 24 h by 25·71 mm and reduced MDT by 2·62 h. Additionally, water heated an extra 22·8°C reduced time to first crack by 6 h and decreased MDT by 3 h. Similarly

using a mix designed for colder temperatures improved results.

The higher the material strength, the longer it took to generate the first crack and obtain 25·4 mm of cumulative crack width, with less cumulative crack width at 24 h. If material strength was less than 12 MPa, 25·4 mm was consistently obtained within 24 h. In high-strength material (42·9 MPa) crack widths at 24 h were generally half that of weaker material.

Further testing including alternative geometries and restraint conditions could provide a baseline for expected performance and greatly promote the usability of SCDAs by increasing the ability to predict cracking times and widths of other materials. Moreover, a particularly important aspect would be any change of pressure once an initial crack began. Use of SCDAs is far from optimised currently and further testing is necessary to improve the application of this product group.

References

Blue Circle Southern Cement (2009) Product overview. See http://www.bluecirclesoutherncement.com.au for further details (accessed 09/04/2009).

Dowding CH and Labuz JF (1982) Fracturing of rock with expansive cement. *Journal of Geotechnical Engineering, ASCE* **108(10)**: 1288−1299.

Dowding CH and Labuz JF (1983) Fracturing of rock with expansive cement – closure. *Journal of Geotecnical Engineering, ASCE* **109(9)**: 1208−1209.

Gambatese JA (2003) Controlled concrete demolition using expansive cracking agents. *Journal of Construction Engineering and Management ASCE* **129(1)**: 98−104.

Gomez C and Mura T (1984) Stresses caused by expansive cement in borehole. *Journal of Engineering Mechanics* **110(6)**: 1001−1005

Haneda H, Tsuji Y and Hanada M (1994) Expansive energies of non-explosive demolition agent. *Proceedings of the 3rd International RILEM Symposium on Demolition and Reuse of Concrete Masonry* (Lauritzen EK (ed.)) **XX**, 255−262. E and FN Spon, London.

1

Hinze J and Brown J (1994) Properties of soundless chemical demolition agents. *Journal of Construction Engineering and Management, ASCE* **120(4)**: 816–827.

Hinze J and Nelson A (1996) Enhancing performance of soundless chemical demolition agents. *Journal of Construction Engineering and Management, ASCE* **122(2)**: 193–195.

Mehta PK and Lesnikoff G (1973) Hydration characteristics and properties of shrinkage compensating cements. *Proceedings of the Klein Symposium on Expansive Cement Concretes, ACI, Detroit* **38**, 89–106.

Polivka M (1973) Factors influencing expansion of expansive cement concretes. *Proceedings of the Klein Symposium on Expansive Cement Concretes, ACI, Detroit*, **38**, 239–250.

SBCCI (Southern Building Code Congress International Inc.) (2001) *North Carolina Fire Prevention Code*. Southern Building Code Congress International, Birmingham, Alabama, pp. 257–272.

Sickler RA (1992) *Explosives Principles: An Essential Guide to Understanding Explosives and Detonations*. Paladin Press.

Taylor HFW (ed.) (1997) *Cement Chemistry*, 2nd edn. Thomas Telford, London.

2

Discussion contributions on this paper should reach the editor by ???

1: Can you supply vol. no. for this series event publication?
2: Location of publisher?
3: Editorial office to add accepted date.