USING CHEMICALS AS DEMOLITION AGENTS NEAR HISTORIC STRUCTURES

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ABSTRACT:

When selective demolition of rock and existing concrete is required near historic structures, there are always concerns about vibration-induced damage from either explosives or other percussive means, such as jackhammers. Soundless chemical demolition agents (SCDAs) offer an alternative. Although not widely applied, this non-percussive approach can be highly effective. The following paper outlines a set of usage considerations for SCDAs near historic structures. As part of this, the relative advantages and disadvantages are discussed including appropriate environmental conditions, and the quantity of material needed (along with the affiliated costs). Performance information related to the timing and extent of cracking is also provided. Furthermore, critical portions of this paper relate to the necessary preparatory work, training, safety precautions, and storage requirements needed when using this class of products, including emergency precautions. Finally, this paper briefly summarizes the application of one SCDA product as part of the 2001 Carnegie Hall expansion.

KEY WORDS: Soundless Chemical Demolition Agents, Historic Structures, Cracking, Usage Considerations, Expansive Cements, Non-expansive demolition agent.

1. INTRODUCTION

Construction work in urban areas often involves the selective demolition of nearby rock and/or existing structures. There are several commonly used demolition methods such as jackhammers, explosive, controlled blasting, hydro-demolition, thermal demolition, and diamond wire cutting methods. Unfortunately, these methods produce large levels of noise, vibration and/or dust, thereby making them inappropriate near historic structures, densely populated area, gas lines, or environmentally sensitive areas such as river and forest conservations zones. In such cases, Soundless chemical demolition agents (SCDAs) can be a reliable alternative. SCDA are appropriate for small, defined areas, even within the confines of an existing historic building. SCDAs require only minimal percussion and no special training of personnel, with the added benefit of being safer. A comparison between SCDA and other demolition agents is shown in Table 1.

The objective of this paper is to outline a set of considerations for SCDA usage near or within cultural heritage monuments. This paper presents practical advice including safety considerations, a discussion of the relative advantages and disadvantages, and a brief case history.

Agent	Sensitivity			Toxic or harmful	Skill	Vibration	Noise	Dust	Energy release
	Heat	Shock	Friction						J/gr
Dynamite	X	X	X	X	X	X	X	X	6607
TNT	X	-	-	X	X	X	X	X	2715
Jack hammer	-	-	-	X	-	X	X	X	-
Hydrodemolition	-	-	-	X	-	-	X	-	-
Diamond wire cutting Methods	-	-	-	X	-	X	X	X	-
SCDA	-	-	-	-	-	-	-	-	860

Table 1: Comparison of different removal methods [1, 2, 3]

2. BACKGROUND

2.1 Chemical Composition

SCDAs or Non-Explosive Expansion Materials (NEEMs) were first identified by Cadlot and Micheaelis in the 1890s when ettringite in cement was investigated [4]. The materials are dry and powdery like Portland cement, but with higher percentages of calcium oxide (CaO), thereby including sulphates and aluminates, which when mixed with water expand and produce ettringite crystals [5]. According to Arshadnejad et al. [1] the key reaction that takes place is the hydration of the calcium oxide (CaO) with the evolution of heat:

$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.2 \uparrow (kCal / mol) \quad (1)$$

After a certain period, the material volume expands and produces expansive pressure, through a combination of chemical hydration and ettringite crystal formation (which occurs on the surfaces of the expansive particles or within the solution). Since the crystal growth is thought to be responsible for the expansive pressure, the magnitude of expansion increases with higher contents of $Ca(OH)_2$ [6].

2.2 Technical Aspects

SCDA is delivered from the manufacturer in a powder form and mixed with water to form a slurry. The slurry is poured into drilled holes in concrete or rock. The holes are located in a predetermined pattern, as will be discussed later in this paper. The SCDA solidifies and expands, thereby producing tensile stress along the walls of the drilled hole. When that tensile stress exceeds the tensile strength of the surrounding material, cracking will occur. According to experiments conducted by Hanif [7], the stress increases with time until failure occurs. Cracking first begins at the uppermost portion of the hole opening, where the stress is the highest [7]. This stress fractures the surrounding mass without producing any noise, vibration, toxic gases, or flying debris.

Rock generally has low tensile strength due to the existence of microcracks. That combined with variations in geology cause the tensile strength in rock to vary greatly. The expected range of tensile strengths for a sampling of rock types is provided in Table 2 [9]; these values will be lower where microcracking or jointing is present. In contrast, the tensile strength of concrete is a function of its compressive strength [10]. ACI 363R-10 notes that for lower strength concrete, its tensile strength may be up to 10% of the compressive strength but only 5% for higher strength concrete [11]. In contrast, Eurocode 2 [12] defines various mean tensile strengths for specific strength classes of concrete. For example for concrete C25/30, the mean axial tensile strength is 2.6, while the mean splitting tensile strength is 2.8, and the mean flexural tensile strength is 3.8. These results are dependent upon the testing arrangement.

Although there are no published studies of SCDA usage for masonry demolition, it should be possible. In that case, the controlling factor would be the tensile strength at either the mortar/masonry unit bond or within the mortar itself. In either case, the masonry's tensile capacity typically would be below that of rock and concrete. Samples tested by Drysdale and Hamid [13] measured the tensile strengths of 0.45 to 2.57 MPa for brick masonry for a wide range of standard mortar mixes.

Rock	**Tensile Strength (MPa)**
Basalt	10-30
Gneiss	7-20
Granite	7-25
Limestone	6-25
Sandstone	4-25
Schist	4-10

Table 2: Tensile Strength of different rocks [values taken from 9]

3. USAGE CONSIDERATIONS

The effect of the SCDA is not instantaneous. The expansive pressure builds over several hours or even days. When that pressure exceeds the tensile capacity of the surrounding material, fracturing begins. That portion of the process may also from a few hours to several weeks. However, once cracking begins, it is usually sufficient extensive for the surrounding material to be easily removed by non-percussive means within half a day. While expansive stresses up to 120 MPa have been reported [14], as well as the on set of cracking in less than an hour, there are many factors that influence the expansive pressure and, thus, cracking time. These include temperature (ambient and mix water), slurry composition, and borehole diameter.

3.1 Temperature

While most SCDAs are designed to be used over a wide range of ambient temperatures, most manufacturers restrict usage to the ambient temperature range of 0°C to 40°C, although some claim applicability in temperatures as low as -8°C and as high as 50°C [15]. Some manufacturers offer multiple products to be used in different temperature ranges. Since most projects are outdoors with temperatures varying significantly over the course of 24 hours, in the experience of these authors, the products should be selected based on the coldest temperature likely to be encountered.

(a) SCDA powder (b) Adding water (c) Mixing (d) Pouring into predrilled holes

Figure 1: SCDA instruction steps [8]

Ambient temperature influences the Time to First Crack (TFC) and the time at which there is sufficient cumulative cracking that the surrounding material can be removed mechanically without any percussive action. This has been termed the Minimum Demolition Time (MDT) – often taken as a cumulative width of 25.4 mm [2, 15]. Research by Laefer et al. [16] showed that higher ambient temperatures contributed to faster cracking (both TFC and MDT) and that products designed for colder temperatures can be used in warmer environments to accelerate cracking. In a study by Hinze and Brown [17], when the ambient temperature was increased from 20 °C to 30°C samples in steel tubes experienced a doubling in the expansive pressure, from that recorded at the lower temperature. Conversely, Dowding and Labuz [18] showed that when the ambient temperature was decreased by 10°C, the expansive pressure decreased by 30% at 24 hours and 10% at 48 hours. Introducing warmer mix water has also been shown to reduce the TFC and MDT. When Laefer et al [16] heated the mix water by 22.8°C, the TFC was reduced by 6 hours and the MDT by 3 hours in large-scale concrete blocks.

3.2 Layout

3.2.1 Drill Hole Spacing Design

Drill hole spacing is one of the main parameters in controlling SCDA fracturing. To determine appropriate drill hole spacing, the hole diameter, SCDA maximum pressure, and surrounding material fracture toughness all play a part. If all else is the same, stronger materials require closer hole spacing to achieve similar cracking levels. To assist with this, Arshadnejad et al. [19] proposed a numerical model to determine the optimum SCDA drill hole spacing (eqn 2)

$$S = \left[-0.0888\left(\frac{P}{\sigma_t}\right)^2 + 1.0824\left(\frac{p}{\sigma_t}\right) - 2.1583\right]\frac{P^2 d^2}{K_{IC}^2} \quad (2)$$

In Eqn 2, S is the optimum borehole spacing P is the SCDA expansive pressure. σ_t is the tensile strength of the material to be demolished d is the drill hole diameter, and K_{IC} is the fracture toughness of the material to be demolished. Since K_{IC} is often not readily available. Gomez and Mura [20] suggested that for a drill hole of diameter D, by a distance L (in a straight line), the minimum spacing required to start cracking can be L=kD, where k is a constant and dependent on the material to be cracked. Values of k were established experimentally to be k<10 for hard rock, 8<k<12 for medium hard rock, 12<k<18 for soft rock and concrete, and 5<k<10 for prestressed concrete. If holes are more widely spaced, less SCDA is required but cracking is delay [18].
In an experiment on small-scale concrete specimens (152×152×76mm) Gambatese [21] noted that closer borehole spacing with the SCDA introduced in only every other hole resulted in the development of earlier cracking, greater levels of crack migration, and higher levels of material cracking. To date no there are no published large-scale sample studies investigation such a configuration.

3.2.2 Drill Hole Geometry

Drill holes are generally 30-65mm in diameter, space 20-70 cm from each other and drilled to 70-90% of the intended material removal depth depending on material to be cracked, with distances between holes as much as 100 cm apart, although typically the distance between holes ranged from 20-70 cm [2, 19].

3.3 Timing

Studies by Dowding and Labuz [18, 22] of SCDA in steel cylinders and rock in laboratory and fields test indicated that the pressure was independent of borehole diameter but heavily influenced demolition time, which was also a function of the volume of SCDA introduced. However the borehole diameter is a reflection of the quantity of the SCDA material introduced and according to Dessouki and Mitri [14] larger drill holes generated faster cracking. They also characterized the expansion time as being directly proportional to the percentage of sulfate in the mixture. Typically, SCDAs develop pressures that exceed the tensile strength of concrete within 10-20 hours [23].
Based on experiments of 33 unreinforced concrete blocks of $1m^3$ with 38mm diameter boreholes and 640 mm deep [15], when using Bristar high strength surrounding material (43 MPa vs 25 MPa or vs the 5.5 MPa) needed a further 36% more time to develop its first crack and 15% extra time to achieve MDT, while maximum cumulative crack width at 24 hours was 9.08 mm larger than the medium strength material. The medium material need (25 MPa) 1.5 hours more time to first crack and 2.5 hours additional time to achieve MDT and reached 3.58 mm less cumulative crack width at 24 hours than week material (5.5 MPa). (Figure 2)

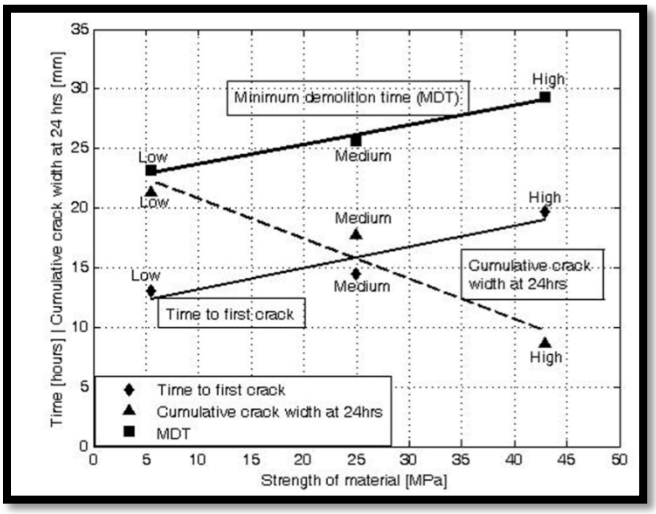

Figure 2: Crack patterns plotted against strength of material [16].

3.4 Remedial Measure

Little has been written about remedial measures in the case insufficient cracking for material removal is obtained at the end of the pressure expansion, but tests by Huynh et al. [24] demonstrated that lining the boreholes of the demolished material with plastic sheeting increased expansive pressures, prevent undesired mixture of atmospheric moisture with the SCDA, and enabled incompletely cracked large-scale specimens to be further cracked.

3.5 Safety

According to manufacturer's guidelines, rubber gloves, safety goggles, facemasks and protective clothing should be worn when handling the SCDAs. SCDAs can cause serious eye and skin irritation. It is also recommended to use SCDAs outdoors or in well-ventilated areas. Similarly, eating, drinking and smoking should be prohibited in areas where SCDAs is handled, stored, and processed. They should be stored in their original packing in a cool, well-ventilated area and protected from direct sunlight in a dry [25]. Finally, since the hydration heat of a SCDA mixture can be as high as 150°C, if free water is trapped in the SCDA, superheated steam could be produced resulting in SCDA being ejected from the borehole [26]. Appropriate safety precautions should be taken with respect to workers not hovering near or looking into the drill hole once the slurry is introduced.

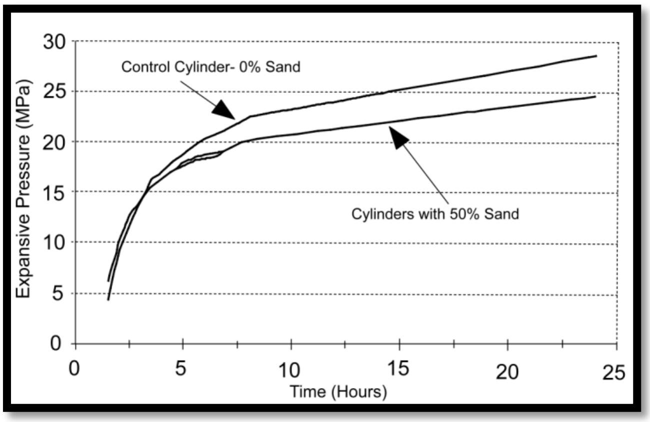

Figure 3: SCDA performance with 50% sand additive [26].

3.6 Cost

One disadvantage of SCDAs is cost. When compared to common explosives, such as dynamite or percussive methods, SCDAs are more expensive (Table 3)[16]. To reduce costs Hinze and Nelson [26] proposed adding inert material such as sand, which acts like filler to the SCDA mixture. Since, the inert materials are comparatively cheap, achieving more economical mixture is possible. In that experiment, the expansive pressure was reduced by less than 5% for a 50% SCDA replacement (Figure 3). Hinze and Nelson [26] also investigated decreasing the water to SCDA ratio to generate higher pressures. While they reduce the water to SCDA ratio to 27.7%, a superplasticizer was required to increase the workability of the mixture. Specimens with 30% water generated 30.55 MPa at 24-hour, while specimens with 27.7% water reached a pressure of 36.6 MPa at the end of first day. SCDA manufacturers usually specify a W/C ratio of 30-35%; below that expansive cement becoming unworkable although expansive pressure will increase.

Agent	Dollars per 0.76 m^3 of source rock
Dynamite	<2
Air Hammer	24.55
SCDA	41.8

Table 3: Cost comparison of removal methods [16].

4. CASE HISTORY

To understand how SCDAs work in practice, the following case history is presented. In 1889 the Willian Burnet Tuthill undertook the construction of Carnegie Hall in New York City. The plan was a rectangular, six-story structure, housing three performance spaces: the Main Hall, the adjacent Chamber Music Hall and the Recital Hall to be located beneath the Main Hall. The building, with its striking Italian Renaissance-style façade of terra cotta and iron-spotted brick, employ concrete and masonry walls without any steel support to achieve better acoustics. The building contains Guastavino tiled arches, cast iron columns, and cut stone footings. Over the next 100 years, the building was restored several times including a 7- month closure in 1986 [27]. The structure gains preservation protection status in 1967.

In 1999 work began for a $50 million project to install a 600-seat auditorium beneath the main hall. The project required the excavation of over 4,600 m^3 of Manhattan rock (typical compressive strength 80 -140 MPa). The bedrock at the site consisted of mica schist. The predominant characteristic of the mica schist of the Harland Formation (with only one pegmatite intrusion noted) consists of a layered or foliated structure associated with the planar plate-like nature of the mica minerals. The bedrock was, slightly to moderately fractured. During the excavation the primary foliation was found to be nearly vertical in orientation. The RQD values showed a slightly to moderately fractured designation (estimated in excess of 90%), with a range of 63% to 98% locally. The quality of the exposed rock and the interpretation of the rock quality, based on review of the boring logs, were consistent with New York City building code classification 1b, which has an allowable bearing capacity of 3.83 MPa [28]. It was recommended that during excavation, a maximum allowable exposed rock face be 1.5 m by 1.5 m.

The site posed extremely challenging conditions. First the work was being done in a confined space beneath a heavy, but fragile structure. Furthermore, the excavations were close to the 7th Avenue subway on one side and a major water tunnel abutting a different side. Additionally, construction noise was a concern because the performance hall had performance and rehearsal schedules that had to be maintained. Finally, vibrations were a worry given the historic plasterwork in the main hall's interior.

Because of these concerns, specific machinery, such as vibratory hammers within 22.9 m of the subway and hoe arms within 7.6 m were simply forbidden. Given that the subway flanked the entire Westside of the project and that the lot was barely 30 m deep, these were important restrictions. Specific techniques were also regulated. For instance, only light charges for blasting could be used if rock was found below the top of the subway structure, and in such a case, underpinning was required. With the subway being located as little as 2.7 m away, the Transit Authority's concerns were not unfounded.

The building posed the dual challenge of being both heavy and fragile. The large quantity of decorative plaster served as the focus for potential threats related to architectural damage. The concern was that blast-generated vibrations would cause cracks in the plaster of the Main Hall. A vibration-based, peak particle velocity limit was set at 12.7 mm/sec. based on research done by the U.S. Bureau of Mines [29]. It was estimated that at 6 m from the actual rock chopping, vibration levels would be 2.5 mm/sec. There were also concerns about the frequency response of building, but an acoustical assessment proved these fears to be unfounded given the mass and geometry of the building with respect to the proposed construction activities.

The agreed upon demolition solution involved a combination of highly limited blasting, hydraulic hammer usage, and SCDA application, followed by mechanical removal. Firstly, a special drill was used to carve out 0.41 m holes to support 13.7 m temporary steel columns. These temporary steel columns were used to support the building during the excavation phase until the new structure was built and loads could be transferred from the temporary columns (fig. 4a) to the new structure (fig. 4b). That part of the construction process was documented by Laefer in 2001 [30].


a) Temporary supportive structure


b) Permanent columns


c) Usage of hydraulic hammer for preparing site to apply SCDA


d) Removing fractured rocks

Figure 4: Excavation steps of Hall.

For the blasting, small diameter holes were drilled on 30 cm to 60 cm spacing within those areas and they were loaded by blast powder Emulex, since Dynamite is prohibited in New York City. A central rectangle of overall building plan was blasted. Excavation perimeter was channel drilled and deepest portion of cut was towards the south, approximately underneath the proscenium of the main stage above. The cut ranged from about 1.5 m to 4.5 m.

Seismograph	Position
Chiller room	S1
Hall	One floor above blasting
Dome	S3
North wall	S2
Subway	174 m from the south end of the platform
Subway	180 m from the south end of the platform

Table 4: Location of Seismographs.

Vibrations were monitored constantly with six seismographs: two in 7th Avenue subway station, one in chiller room, one in North wall, one in hall and one in Dome (Figure 5).

Holes were drilled into which the SCDA Da-mite was poured. This allowed rock fracture without causing any vibration, noise or dust. After fracturing, rocks were removed by air hoist from constriction site. Using an SCDA helped the construction team to accelerate demolition and facilitate removing of rocks without causing any magnificent vibration to the adjacent subway and water tunnel.

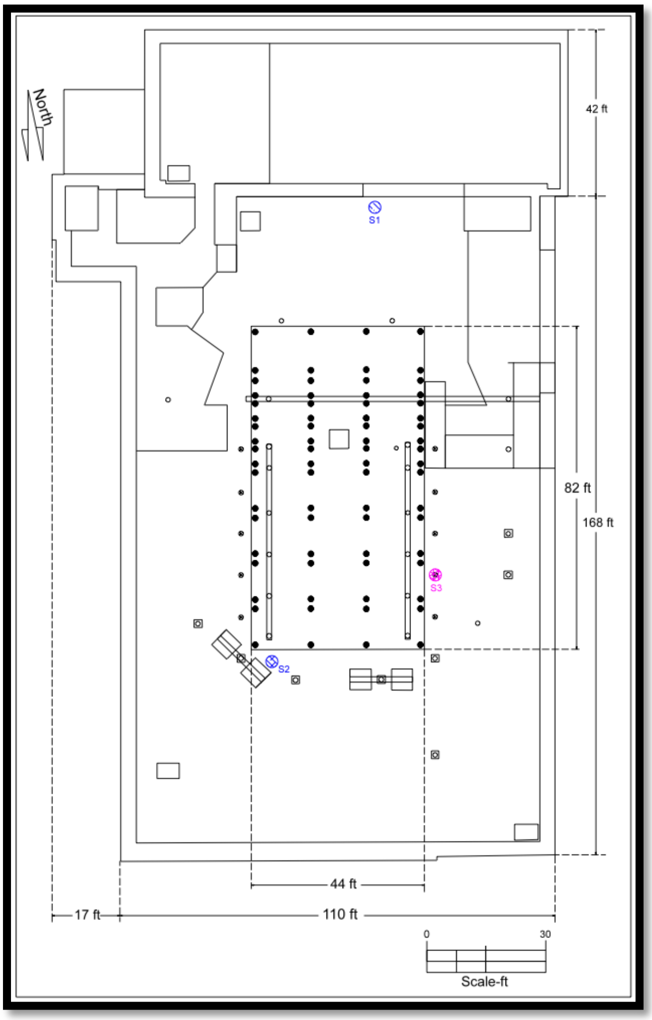

Figure 5: Plan of hall: S1, S2 and S3 are Seismographs. Bolded dots are temporary support steel columns.

5. CONCLUSIONS

SCDAs could be an effective alternative method for demolition of structures especially in urban areas. They can be used without producing noise, explosions, vibration, dust or toxic fumes. However, some technical aspects should be taken into consideration in establishing the viability of the procedure such as ambient temperature, borehole diameter, and slurry composition, which could influence SCDA's expansive pressure significantly. Moreover, SCDA is chemical material and safety precautions must be taken including proper storage.

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