FINAL PROGRAM

ASCE FORENSIC ENGINEERING 8th CONGRESS

Austin, Texas | November 29 – December 2, 2018

Forging Forensic Frontiers

Sheraton at the Capitol

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FORENSIC ENGINEERING 2018

Forging Forensic Frontiers

PROCEEDINGS OF THE EIGHTH CONGRESS ON FORENSIC ENGINEERING

November 29–December 2, 2018
Austin, Texas

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Forensic Engineering Division
of the American Society of Civil Engineers

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Preface

Forensic Engineering 2018: Forging Forensic Frontiers is a collection of 111 peer-reviewed technical papers presented at the Forensic Engineering 8th Congress, sponsored by the Forensic Engineering Division (FED) of the American Society of Civil Engineers (ASCE). The Congress took place from November 30 to December 2, 2018, at the Sheraton Austin Hotel at the Capitol in Austin, Texas. The goals of the Congress were to bring together leading forensic engineering practitioners, researchers, designers, project and construction managers from around the world to allow attendees to learn about current evaluation techniques and investigative methods. These efforts align with the mission of FED to enhance the forensic engineering profession, develop guidelines for conducting failure investigations, disseminate failure information, promote forensic curriculum in engineering education, share practices to reduce failures, and improve performance of the built environment.

Each paper in this collection was subjected to a double-blind review process, with review comments distributed to authors, author revisions as appropriate, and final review by the proceedings editors. Paper submission began with published calls for abstracts and at least two positive indications from reviewers before invitation to submit full papers. The review process determined whether each paper was applicable, useful, and relevant to forensic engineering; whether the paper had been published previously; whether the methodology was satisfactorily explained; whether the references were verifiable, whether the tables, figures, and photographs complemented the paper; whether the conclusions were clear and justified; whether the elements of the paper related logically to the paper; and whether the writing style, grammar, and formatting were appropriate. Each paper received a minimum of two positive reviews in order to be published. Papers in this collection cover a wide array of forensic topics pertaining to the built environment, with some taking new approaches to historic failure events and others exploring new frontiers in forensic evaluation and analysis methods. The Congress also included papers of local and regional interest, such as assessment of damages from recent Hurricanes Irma, Harvey, and Maria.

Two half-day workshops held on November 29, prior to the official start of the Congress, involved guidance in operation of a forensic engineering practice and conducting forensic engineering investigations. These workshops were sponsored by FED Committees on Forensic Practice and Forensic Investigation, respectively. The morning workshop on *The Practice of Forensic Engineering* was presented by James S. Cohen, Leonard J. Morse-Fortier, Clemens J. Rossell, and Lloyd M. Sonenthal.

The afternoon workshop, *Conducting Failure Investigations*, was presented by Ronald W. Anthony, Richard S. Barrow, Kimball J. Beasley, Jeffrey A. Travis, and Stewart M. Verhulst. The workshop speakers formulated their presentations, in part, on FED sponsored publications Guidelines to Forensic Engineering Practice, 2nd edition, ASCE Press 2012, and Guidelines to Forensic Investigations, 2nd edition, ASCE Press, 2018.

The Congress opened with a featured keynote presentation by accomplished researcher and structural engineer Ahmed Amir Khalil, PhD, P.E. His presentation *High Fidelity Numerical Simulations in Forensic Analysis and Urban Search and Rescue* focused on the use and challenges of high-fidelity numerical modeling in forensic investigations and the use of such to aid in planning for and implementing urban search and rescue operations.

In addition to the presented papers, the Congress also included panel discussions, networking socials, a welcoming reception, an awards luncheon, and committee meetings. Finally, a student paper competition was held that included poster presentations from a number of our future professional forensic engineers.

It has been our pleasure and privilege to be part of this Congress. Happy reading!

Rui Liu, PhD, P.E., M.ASCE
Kent State University
Proceedings Editor-In-Chief

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Element Analytical, PLLC
Congress Chair

Acknowledgments

The Steering Committee of the Forensic Engineering 8th Congress expresses its sincere appreciation to the Proceedings Editorial Board, the Executive Committee of FED, its membership, cooperating organizations, ASCE staff, and most especially to the authors, panelists, presenters, peer reviewers, moderators, track chairs, and sponsors for making this Congress a success. Special thanks to our families, without your support this work would not have been made possible.

The guidance, dedication, and commitment of the following individuals contributed to the planning and development of all aspects of the congress venue, program, and activities.

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Tile Tap Method: Human and Auditory Scientific Analysis

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ABSTRACT

This study examined the scientific basis for the tile tap method by comparing the results obtained using the human ear to sensitive auditory equipment. The study was composed of six tasks: (1) create a representative non-bonded tile, (2) identify the best tapping instrument, (3) evaluate tapping on different tiles, (4) identify the predominant sound frequencies from bonded and non-bonded tiles, (5) determine whether distinct frequencies could characterize non-bonded areas of tile above and below the thin set, and (6) determine the detection limit for increasingly smaller portion of non-bonded tiles. This study examined six types of floor tile (ceramic, travertine, marble, porcelain, limestone, and sandstone) and used wax paper beneath the tile to provide the best non-bonded sound. Among these tile types, marble exhibited the most modest difference between bonded and non-bonded areas. In general, the sound frequencies were lower and louder among portions for non-bonded tiles when tapped. Among the 18 different tapping instruments tested, a 2-inch steel ring produced the most distinctive sound for human ear perception to both bonded and non-bonded tiles. Microphonic analysis, unlike the human ear, was capable of distinguishing the difference in sound frequency produced between the non-bonded areas above and below the thinset. Finally, the detection limit for the tapping could distinguish area separations of approximately 9 in^2. The study concluded that the tapping method supported the non-bonded versus bonded distinction by the scientific method though some tapping instruments were shown to be better than others.

INTRODUCTION

Tile tapping identifies debonded tiles as a "hollow sound" between the floor tile and the underlying substrate. Tapping is a qualitative forensic method that requires the user to interpret the sound using a variety of instruments. We examined the effectiveness of various "tapping instuments" and their "acoustical" signatures.

Surface delamination literature identified several acoustical techniques. Two ASTM Standard Test Methods (E 1007; C 627) and one ASTM Standard Practice (D 4580) offered methodologies to examine patterns of acoustical behavior among flooring or bridge deck materials. Delamination between the overlay and the bridge deck of concrete bridge decks (ASTM D 4580) was measured using three techniques (electro-mechanical sounding device, chain [steel rod and hammer drag], and rotary percussion). All three techniques incorporated a form of "tapping" with various tools. Sound testing is used as a method to identify faulty concrete.

Photo 1: Floor tiles (*i.e.*, ceramic, porcelain, limestone, marble, travertine and sandstone) tap tested for audible character and predominant frequency.

Photo 2: Tile tap test of floor tiles with hollow portions either above or below the thinset. Tiles on the left have nonbonding below the thinset while tiles on the right have nonbonding above the thinset

Acoustical techniques known as "pulse-echo testing" identifies defective concrete by inducing a sound from a transmitter that travels through the concrete reflecting cracks and materials with different densities thus revealing internal defects (Muenow and Randall, 1986). Nondestructive techniques have been used for identifying improperly installed decorative bonded tiles on high-rise buildings in Hong Kong where "tile dropping accidents" occur from adhesive failure or tile bonding defects (Tong *et al.*, 2005). A recent test method known as Principal Component Analysis (PCA) evaluates tile bonding by obtaining an impact acoustical signature.

The Tile Counsel of North America (TCNA) recognizes that hollow-sounding tiles can arise from a number of circumstances where the bond between the tile and the underlying surface has failed (TCNA, 2014).

Photo 3: A 2-inch diameter stainless steel ring provided the most distinctive frequencies to distinguish bonded from nonbonded tiles.

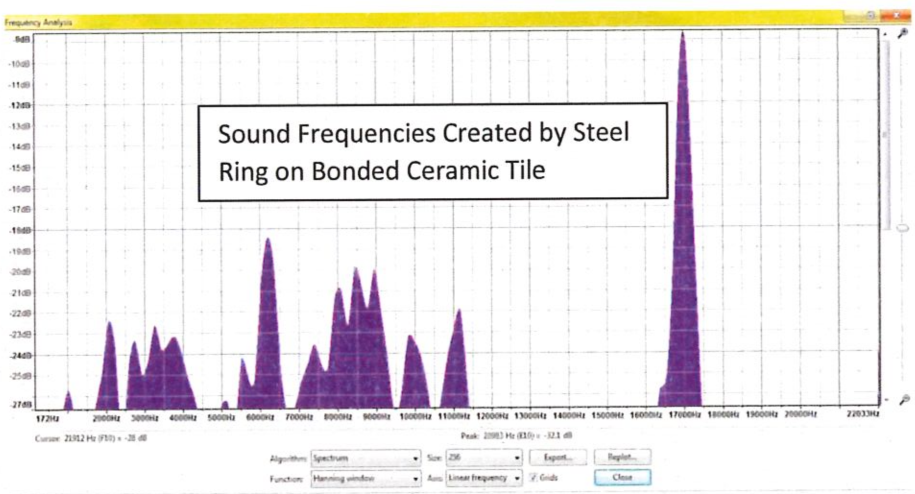

Diagram 1: Two-inch metal ring on bonded ceramic tile. This waveform diagram depicts a predominant frequency at ≈17,000 Hz.

IDENTIFYING A TAP TEST DETECTION LIMIT

One of the distinctions between human hearing and a sound frequency analysis is a human's ability to detect Just Noticeable Differences in Frequency (JND Hz). The ability to distinguish frequencies is best at low frequencies and poorer at high frequencies (Dr. Kelly King, personal communication). The human ear can distinqish low sound frequencies (500 Hz) at about 1 Hz allowing frequencies between 500 and 501 Hz to be distinguised Above 2,000 Hz, the human ear requires a minimal separation of 6-8 Hz.

MATERIALS AND METHODS

Nonbonded tiles: Nonbonded tiles were prepared to identify specimens that represented different bonding percentages when tapped; four approaches were used to create a tile-thinset separation: 1) no application of thinset between the tile and the substrate and the placement; 2) black plastic (2 mil) film; 3) aluminum foil (Reynolds®); and 4) wax paper under the tile secured in place with a small amount of blue painter's tape. The separation method that was easy to create and produced the best audible sound clarity was selected.

A 240 square foot (ft^2) section of concrete floor was prepared for tile installation using mechanical scarification, cleaning with soap and water, cleaning with soap and water followed by excess water extraction using a wet-dry vacuum and floor-fan drying. Six floor tile materials (porcelain, ceramic, limestone, marble, sandstone and travertine) were applied to a concrete foundation for audible and frequency testing (**Photo 1**).

Floor tiles were laid out based on percentage bonded using a Merkrete 710 Premium Set Plus thinset mortar that. met or exceeded industry requirements ANSI A118.4 for latex Portland cement mortar and ANSI A118.11 for EPG latex Portland cement mortar. ANSI A108.5 was followed for the tile installation. A ¼" x ¼" x ¼" square notch trowel was used to apply the thin set mortar to the concrete substrate. Tiles were slightly dampened with a water mister and pushed into place by hand pressure. Plastic spacers (¼") were used to separate and keep the joints squarely aligned.

All tiles cured for a minimum of 30 days before tap testing. The tile tap study consisted of nine 100 percent completely bonded ceramic tiles (control), twelve tiles were set with the separation below the thinset , and twelve ceramic tiles where the thinset mortar bonded to the concrete floor (hollow space separation was above the thinset. Twenty-six remaining ceramic tiles and the sets (two each) of porcelain, limestone, marble, travertine, and sandstone placed with thinset bonded to concrete With bonding percentage of 12%, 17%, 25%, 50%, 75%, 90%, and 100% (control). These percentages were selected to demonstrate the audible distinction of the nonbonded portion versus the bonded portion of each tile.

Tapping instruments: Eighteen tapping instruments (aluminum, galvanized conduit and steel rods; copper tubing, PVC and CPVC pipes, wood dowels, knife handle, plyers, screw driver, hammer, golf ball, house keys, large and small chains, steel ring, wood and aluminum yard sticks, and retractable antenna) were evaluated for sound quality and audible frequencies. The survey revealed that the most distinctive audible sounds and frequencies were produced using a stainless steel 2-inch diameter ring.

Tapping effectiveness on different tiles: Six tile types (ceramic, porcelain, travertine, marble, limestone and sandstone) were prepared by attaching a piece of 4-inch by 4-inch wax paper on the backside (in duplicate) before bonding to the floor with thinset. The bonded and nonbonded portions of each tile were tapped repeatedly with the stainless steel ring and the sound recorded for frequency analysis.

Predominant frequencies: Tile tap frequency evaluations were conducted using a computer (Lenovo, T530), the application Audacity®, a multitrack audio editor and recorder, and a microphone (CAD U37 Audio Cardioid Condenser Microphone).

Frequency comparisons produced among the tapping instruments was based on the predominant frequencies produced as those that were at least 10 decibels or higher than all other frequencies (Daniel Hess, Ph.D. Personal communication). Sound frequencies produced during the first five milliseconds were used for tap frequency comparisons. This approach allowed identification of the initial tap-sound frequencies and avoided reverberation and harmonic resonances.

Tile tapping was performed by hand because hand motion proved uniform in application and quiet when compared to mechanical tapping devices. Several taps were obtained to acquire an average value. The sound frequencies obtained from each set of impacts were recorded at two locations per tile (bonded and nonbonded).

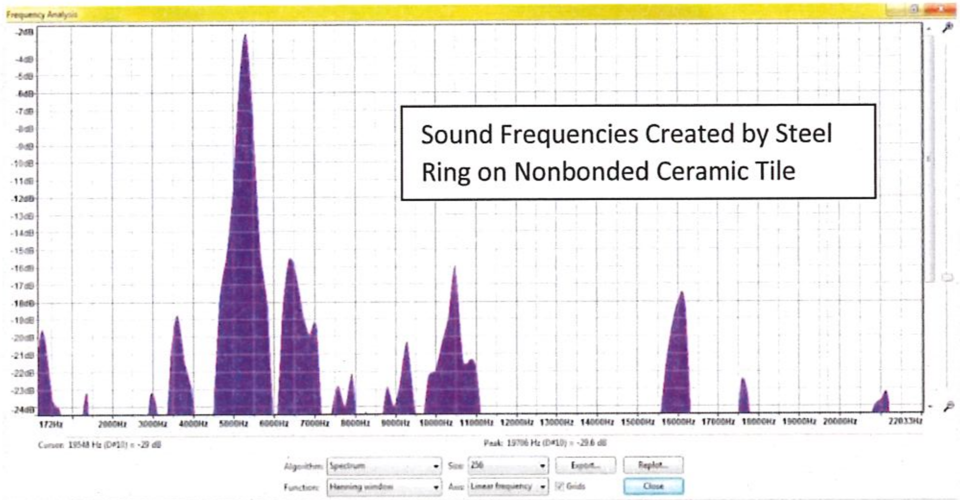

Diagram 2: Two-inch metal ring on nonbonded ceramic tile. This waveform diagram depicts a predominant sound frequency at ≈5,500 Hz.

Detecting nonbonding above and below the thinset: Thirty-six ceramic tiles (18 pairs) were bonded to the concrete floor in various percentages of nonbonded tile areas. The size and location of nonbonded areas were created by placing pieces of wax paper above or beneath the thinset. (**Photo 2**).

Identifying a detection Limit: The installed ceramic tiles (144 in^2) represented various nonbonded percentages (12% [9 in^2], 17% [24 in^2], 25% [35 in^2], 50% [72 in^2] and 75% [108 in^2] and 90% [126 in^2]) using wax paper attachments, as described above. The various nonbonded percentages allowed for detecting a threshold limit on audible differences by the human ear and microphone using a two-inch diameter stainless steel ring as the tapping instrument.

RESULTS

Creating a Nonbonded Tile

Attempts to apply thinset in various bonding percentages proved inconsistent and was not considered further. Placement of black plastic sheeting or aluminum foil created a muffled bonded sound that lacked the distinctive "hollow sound". Wax paper produced the most "authentic" hollow sound quality similar to nonbonded tiles and was easy to use. It was selected for all subsequent tests.

Best Tapping Instrument for Audible and Frequency Analysis

Selection of the best tapping instrumentswas based on audible sound and frequency response. When all instruments were compared, the two-inch stainless steel ring (**Photo 3**) and a metal telescopic (radio) antenna performed the best.

A tap frequency comparison illustrated the quantitative sound distinctions using a two-inch stainless steel ring on both bonded and nonbonded tile (**Diagrams 1 and 2**). Hard, metal objects (*i.e.,* keys, screwdrivers, small hammers, rings) created the clearest sounds and the least complicated waveform data.

Comparative examination of the sound frequencies obtained from eighteen tapping instrument revealed two differences. First, several instruments (chains and steel ring) produced distinctive sound frequencies that provided easy audible recognition between bonded and nonbonded tiles. Second, most instruments produced louder sounds on nonbonded than bonded tiles making identification on nonbonded tiles easy. Repeated testing proved the steel ring was best suited because the sound produced was easiest to hear for either bonded or nonbonded tiles.

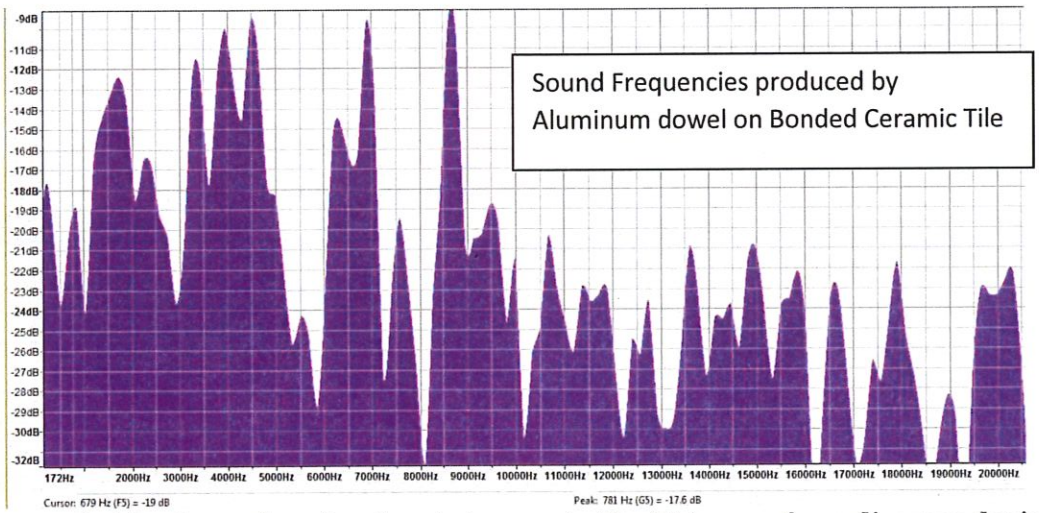

Diagram 3: Aluminum dowel on bonded ceramic tile. This waveform diagram depicted multiple sound frequencies throughout the entire hearing range.

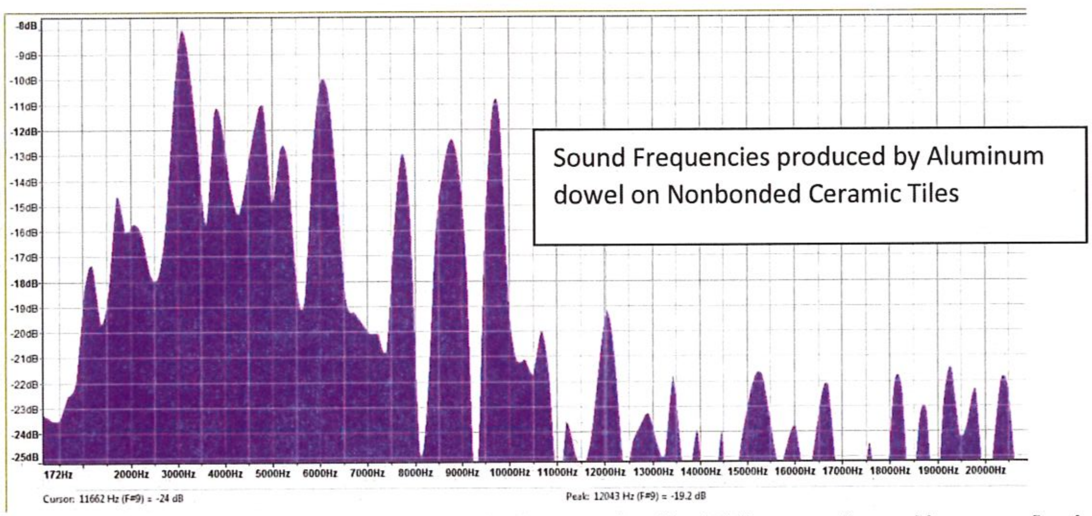

Diagram 4: Aluminum dowel on nonbonded ceramic tile. This waveform diagram depicted a multitude of sound frequencies that do not easily distinguish by comparison bonded from nonbonded tiles.

Some tapping instruments such as an aluminum rod or copper tubing produced an array of extraneous frequencies from both bonded and nonbonded tiles (**Diagrams 3 and 4**). The human ear detected vibration and reverberation that emanated from the tapping instrument rather than from the tile surface.

Large and small metal chains and wooden dowels created extraneous frequencies and reverberation that resulted in a broad mixture of audible frequencies. PVC and CPVC pipe, aluminum rods and golf balls produced sounds that distinguished bonded from nonbonded tile areas, but produced extraneous frequencies and lacked clarity.

- Each instrument created a unique pattern of waveform data when applied to bonded and nonbonded tiles.
- Bonded tiles produced higher predominant frequencies than nonbonded tiles.
- Some instruments created extraneous frequencies that made both audible (qualitative) and frequency analysis (quantitative) too indeterminate.
- Most instruments produced louder sounds on nonbonded tiles than bonded tiles.

Tapping Effectiveness on Different Floor Tiles

Ceramic, travertine and porcelain tiles produced the most distinctive audible (human ear) sound. The predominant frequencies captured by the microphone confirmed this finding (**Table 1**). Marble expressed minimal audible and measurable distinctionmaking itthe least preferred candidate for the tile tap method.

Table 1: Predominant sound frequencies produced on different bonded and un-bonded tiles with a 2-inch diameter stainless steel ring

Tile Types	Bonded (Hz)	Nonbonded (Hz)
Travertine	6,100	2,500
Marble	6,100	6,050
Porcelain	3,000	4,200
Ceramic	17,000	5,500
Sandstone	3,800	1,800
Limestone	7,700	5,000

Other than marble tile, all tapping efforts produced distinct audible and sound frequencies between bonded and nonbonded tiles that were a minimum of 1,200 Hz apart. The sound frequency analysis substantiated the use of tapping as a predictable and scientifically-based method for distinguishing bonded from nonbonded tiles.

Identifying Discrete Separations Above and Below the Thinset

Tapping to distinquish separations between the tile and thinset and the thinset and the concrete foundation produced slight audible and frequency differences and proved to difficult to distinguish by most human participants. The frequency analysis of the waveform data identified a modest difference of approximately 750 Hz between the hollow locations. Two examples are provided.

A portion of nonbonded ceramic tile (C25) was approximately 9 in^2 (**Diagram 5**) with separation above the thinset while tile C37 was separated below the thinset (**Diagram 6**). The predominant frequency for each nonbonded section of tile was 5,584 Hz (separation above thinset) and 5,328 Hz (separation below thinset). The human audible analysis was nearly indistinguishable.

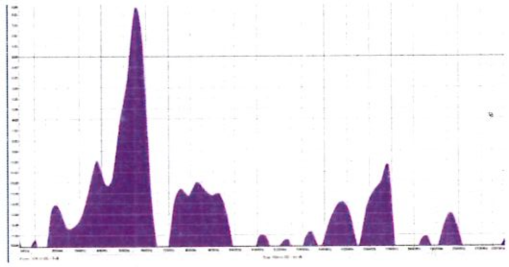

Diagram 5. Hollow Portion above thinset (5,584 Hz)(C25).

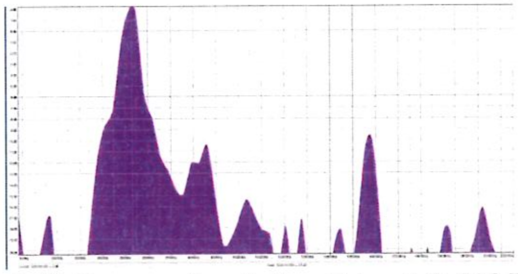

Diagram 6. Hollow portion below thinset (5,328 Hz) (C37)

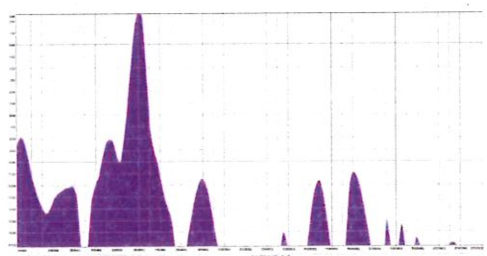

Diagram 7. Hollow Portion above thinset (6,026 Hz) (C24)

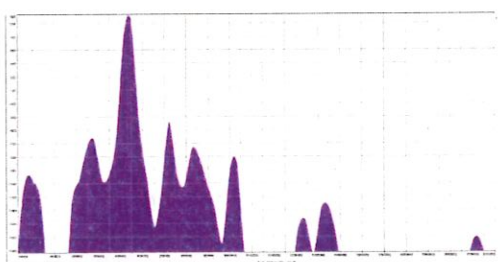

Diagram 8. Hollow Portion below thinset (5359 Hz) (C36)

Similarly, nonbonded ceramic tiles C24 and C36 represented a 9 in^2 of separation (**Diagrams 7 and 8**). C24 is separated above the thinset while C36 is separated below the thinset. The predominant frequency for each nonbonded section of tile was 6,026 Hz (separation above thinset) and 5,359 Hz (separation below thinset); however, the human ear could not easily distinguish this difference.

Determining a Detection Limit for Nonbonded Tiles

Audible and frequency analysis revealed that as the percentage of nonbonding increased, the audible sound pitch decreased. Small nonbonded areas (<17%) exhibited higher pitched frequencies as compared to the characteristic "clanging sound" produced among larger nonbonded areas (>50%). The sequence of diminishing pitch was measured in the tapping frequencies of nonbonded tiles 9,000 Hz (17% nonbonded), 8,300 Hz (50% nonbonded), 3,700 Hz (75% nonbonded) and 7,800 Hz (90% nonbonded).

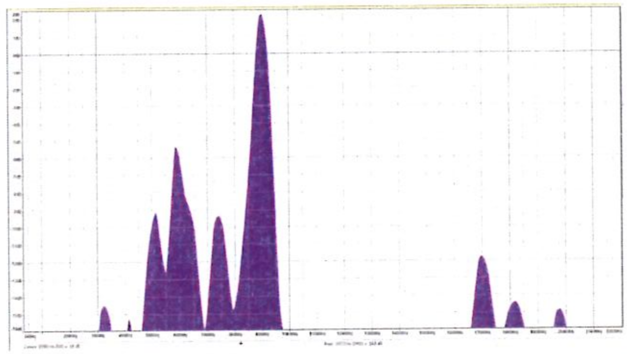

Diagram 9. 17% Nonbonded Ceramic Tile (9,000 Hz)

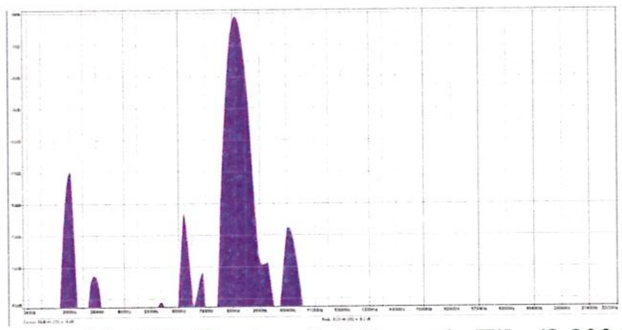

Diagram 10. 50% Nonbonded Ceramic Tile (8,300 Hz)

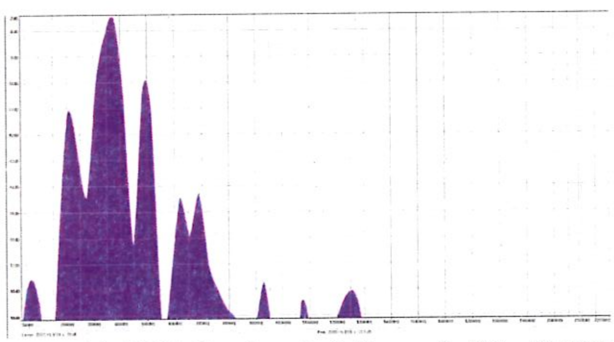

Diagram 11. 75% Nonbonded Ceramic Tile (3,700 Hz)

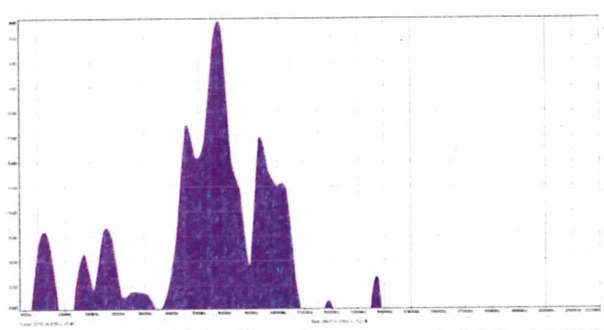

Diagram 12. 90% Nonbonded Ceramic Tile (7,800 Hz)

The tapping survey suggested that a trained ear can sense different degrees of debonding in the field using an appropriate tapping instrument.

CONCLUSIONS

The tile tapping method is scientifically defensible based on the analysis of distinct sound frequencies produced and the audible differences (loudness) detected by the human ear. We concluded that the best tapping instrument was the 2-inch stainless steel ring because it was distinquished from the other instruments in both frequency differences and loudness. Tile tapping is appropriate for the six types of tile tested although the audible distinction obtained from marble was harder to detect. Quantitative analysis revealed notable differences in sound frequencies that easily distinquished bonded from nonbonded tiles. When tapped, nonbonded tiles are louder than bonded tiles. The location of a tile separation above or below the thinset was not easily distinquished by the human ear; however, is was observable in the waveform analysis. The detection limit for identifying nonbonded tiles by the tapping method is approximately 9 inch^2.

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