Design and Development of Drill-Resistance Sensor Technology for Accurately Measuring Microbiologically Corroded Concrete Depths

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Abstract -

Microbial corrosion of concrete is a severe problem that significantly reduces the service life of underground sewers in countries around the globe. Therefore, water utilities are actively looking for in-situ sensors that can quantify the biologically induced concrete corrosion levels, in order to carry out preventive maintenance before any catastrophic failures. As a solution, this paper introduces a drill-resistance based sensor that can accurately measure the depth of the microbiologically corroded concrete layer. A prototype sensor was developed and evaluated in laboratory test conditions. The lab experiments proved that the developed sensor has the ability to measure the depth of the microbiologically corroded concrete with millimeter level of accuracy. Additionally, the sensor can also locate and accurately measure the size of concrete aggregates as well as potential cracks, effectively creating a sub-surface 'scan' of the concrete at the targeted point of interest. Therefore, providing valuable extra information for assessing the condition of the sewer concrete.

Keywords -

Concrete, corrosion, drill resistance, measuring, sensor, sewer.

1 Introduction

Reinforced concrete sewers undergo significant microbiologically induced corrosion caused by sulphuric acid producing bacteria, particularly in countries with warm climate conditions. This sewer concrete corrosion leads to sewer pipe deterioration and consequential structural failures by incurring losses that are estimated to be in the order of billions of dollars per year worldwide.

Furthermore, microbial corrosion of concrete increases the likelihood of catastrophic structural failures that can cause not only detrimental damage/harm to urban-dense populations but also irreversible damage to the surrounding environment. The annual cost of corrosion for drinking water and sewer systems in the United States alone is about USD36 billion [1] including maintenance, rehabilitation, and replacement. In the United Kingdom, the total replacement cost of sewer mains was estimated to be 104 billion pounds [2] whilst in Germany, the rehabilitation cost for sewer concrete corrosion was estimated to be 100 million Euros [3]. In addition, the rehabilitation of sewer concrete pipes cost AUD40 million annually in Australia [4]. Therefore, sewer corrosion is a significant problem worldwide which needs to be identified promptly, so water utilities can intervene and carryout the the necessary maintenance before any catastrophic failure [5].

A key parameter that water utilities use for decision making in sewer infrastructure maintenance is the estimation of the Remaining Service Life (RSL) of the sewer pipe, which is often estimated by measuring the depth of the remaining intact concrete left to the reinforcement bars. RSL gives an estimation of how many years the sewer can be used without further rehabilitation. In general, sewer wall corrosion rates are very slow (could be less than a millimeter per year) and hence, depth of the microbiologically corroded concrete layer needs to measured precisely to accurately estimate the RSL. However, due to the non-homogeneous nature of concrete combined with the harsh conditions of a sewer pipeline, particularly with extremely high humidity and acidity, conventional sewer monitoring sensors are prone to malfunctions [6, 7], struggle to reliably and accurately measure the depth of the microbiologically corroded concrete in field conditions. The most conventional way for measuring the depth of the corroded concrete is done by taking core samples from the sewer walls, which is a time consuming process and expensive endeavour. Additionally, prolonged exposure to sewer environments poses serious occupational health and safety issues for the workers in the sewers [8]. Hence, wastewater managing utilities are looking for innovative sensing technologies which can assess the level of the microbial induced corrosion of concrete accurately and quickly so the required maintenance can be carried out promptly.

Over the years, there have been remarkable strides in developing drill-technology capable of operating in challenging conditions. Drills are often perceived to be destructive tools, yet we often overlook that there are many precise and delicate micro-invasive applications for drills, such as in brain surgery or orthopaedic repair.

Drill-resistance based measuring methods are a useful sensing option for differentiating non-homogeneities in a given material as the mechanical drilling component guarantees penetration through the material. Unfortunately, due to the misconceived destructive nature associated with drills, this sensing approach has not been so widely adopted in the past. However, the unique ability to accurately characterize many materials at various given depths (i.e. whether the material at a certain unit of depth is hard or soft) below the surface in real-time makes drill-resistance based measuring an excellent candidate for developing a sensor technology that can accurately measure the depths of corrosion in concrete for both human operator and autonomous robotic applications.

Previously, drill-resistance based sensors have been developed for sampling the ring-growth pattern in tree-trunks [9, 10, 11], which was later evolved into using the sensing approach to measure decay in trees - substituting the use of X-ray as result of several advantages such as simplicity, portability, and accessibility in comparison. Later on, drill-resistance based sensing was adapted for assessing the strength of fire-damaged concrete [12, 13] yet it was not until early this decade drill-resistance based sensing was developed for measuring the decay in natural stone and marble as part of conservation projects of irreplaceable cultural heritage monuments and buildings [14]. Whereas this paper will go into the design and development of a prototype, which is the first of its kind to demonstrate accurate depth of the boundary layer between corroded and intact concrete, even with the presence of hard aggregates within the relatively soft corroded layer. The sensor can provide a scan of any corroded concrete target area in real-time without any need for calibration or advanced/heavy post-processing.

2 Background

2.1 Concrete Corrosion

Figure 1 shows the microbiologically induced corrosion process inside sewer system. Sulphate-producing bacteria that reside in sewage produce dissolved H_2S in wastewater under anaerobic conditions. This dissolved H_2S is released as a gas phase due to turbulence in the wastewater as it flows down the pipeline. In general, surface pH of newly installed sewer concrete pipes ranges approximately between 12-13. When the pH value falls to 9, the bacteria begin to colonize on the concrete surface [16]. The chemoautotrophic bacterium that exists on the sewer concrete surface oxidizes the gas phase H_2S into biogenic sulphuric acid H_2SO_4, which reacts with the cementitious material of concrete leading to concrete corrosion [17, 18]. The corrosion process transforms the effected concrete into calcium sulfide, commonly known as gypsum - a soft brittle material whose presence introduces focused areas of strength loss in a structure. In addition, gypsum is moderately water soluble - the combination of a soft brittle gypsum under structural load in a highly humid environment makes the gypsum layer prone to breaking off with the subsequent material loss in the pipeline structure, leading to structural failure if left untreated.

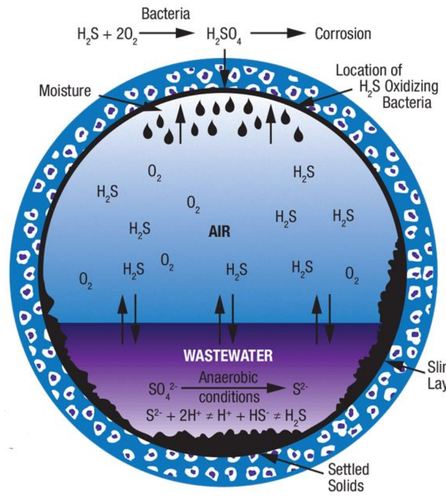

Figure 1. Sewer Corrosion Process [15].

2.2 Conventional NDT Sensing Modalities

Conventional Non-Destructive Testing (NDT) sensing systems like Ground-Penetrating-Radar (GPR) and ultrasound sensors are widely used for detecting concrete defects like delamination in concrete civil infrastructure. Therefore, these sensors have the potential for detecting the depth of the boundary layer between the microbiologically corroded concrete and intact concrete. However, use of these sensors for detecting microbiologically corroded concrete in sewer environment is challenging. The GPR signal measurements can be potentially affected by the moisture conditions of the exposed sewer surface [19], and the ultrasound techniques need sound coupling with the sewer wall [20], making it practically challenging to use on uneven rough surfaces of the sewer pipes. Besides direct measurements, predictive models have been developed for estimating the corrosion throughout the sewer network. Quality of such model prediction rely on the data supplies by the sensors [21, 22, 23, 24].

2.3 Drill-Resistance Sensing

Drill-resistance is an unconventional sensing approach in the sense that it is an integration of multiple sensors functioning in parallel but also that the main principles of drill-resistance based measurements are based on mechanical principles rather than physical phenomena. There is a direct correlation between the reaction force exerted on the drill-bit and drill-bit penetration per drill-bit revolution [25]. Therefore, the penetration rate of the drill (Δd_p) and the drill speed (ω_d) must be kept constant in order for the reaction force per ongoing depth measurement to show an accurate and valid representation of the material being drilled. Assuming those parameters are kept constant, the hard material will exert a higher reaction force on the drill-bit compared to a softer material as more energy is required for penetrating into the harder material per unit distance per drill-bit revolution.

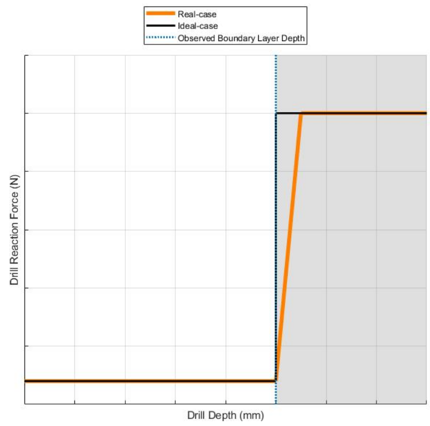

Figure 2. Boundary layer identification between two different materials based on force-depth readings: The point where there is a significant change in force-depth gradient signifies a different material at that corresponding drill-depth.

Figure 2 shows a simplified example of the measured thrust (reaction) force acting through the drill-bit per increment in drill depth whilst drilling through two different material layers. The depth where there is significant change in the force-depth gradient signifies a different material at that depth. Maximising the drill-bit penetration per drill-bit revolution (or $\Delta d_p : \omega_d$ ratio) will cause the force-depth readings to become closer to the ideal case (i.e. creates a sharper force-depth gradient) - making significant points of inflection, and therefore, boundary layers easier to identify. Consequently, doing so can increase wear on the drill-bit and reduce its effectiveness to cut through material [26]. In addition, it can also increase the likelihood of exceeding the load capacity rating of any force-measurement sensors embedded in the drill assembly. Alternatively, reducing the $\Delta d_p : \omega_d$ ratio scales down the reaction forces acting on the drill as the drill-bit is removing material significantly faster than it is penetrating material - consequently reducing the sensitivity to changes in force due to changes in material, leading to losses in accuracy as well as operation time due to the subsequently slower penetration rate.

3 Drill-Resistance Prototype Development

In this design iteration, a stand-alone drill-resistance prototype was developed with a modular design to carry out a vast array of tests with controlled concrete lab samples. This prototype is capable of drilling depths up to 120mm without any need for physical interaction/bracing from a human or robotic operator. This decision was made to ensure result validity and repeatability of measurements under various test cases. Figure 3 shows the overall breakdown of the prototype, which consists of an off-the-shelf cordless drill that was reverse-engineered into a custom 3D-printed housing - allowing the drill to be fitted with a load-cell for thrust force measurements, and an independently driven lead-screw for controlling the penetration rate.

The prototype works by using the lead-screw to push the drive plate at a constant rate which in turn achieves a constant penetration rate for the drill assembly into the concrete. As a result, the reaction force along the drill axis is transfered along the drill assembly, allowing this force to be measured by the load-cell sub-assembly. Simultaneously, the linear position of the drill assembly along the drill axis is measured using a linear potentiometer - thus allowing a measured drill-reaction-force to be linked to its corresponding drill depth at its given instance in time. Therefore, allowing the ongoing force-depth readings to be acquired as the drill penetrates the concrete - showing the changes in material and building a subsurface ‘scan’ of the targeted corroded concrete area in real-time as demonstrated in Figure 4.

4 Methodology

This paper focuses on tests with controlled concrete lab-samples with gypsum layers with and without aggregates as shown in Figure 5. A fixed high-speed drill setting (1200 rpm) is used to maintain a low penetration rate to drill speed ratio whilst using a 5mm diameter tungsten-carbide masonry drill-bit. In addition, no hammer drilling was used in the reported experiments in order to see if it is possible to acquire accurate results without the risk of propagating micro-stress cracks [27].

The first main experiment uses the concrete lab-sample with a 20 ($\pm$1)mm layer of gypsum without any aggregates on top of a 30mm layer of intact concrete. The Drill-Resistance prototype is placed on top of the target sample and the depth where the drill-bit meets the surface of the lab sample is recorded for reference. For example, the drill is measured to have moved 42mm from its starting

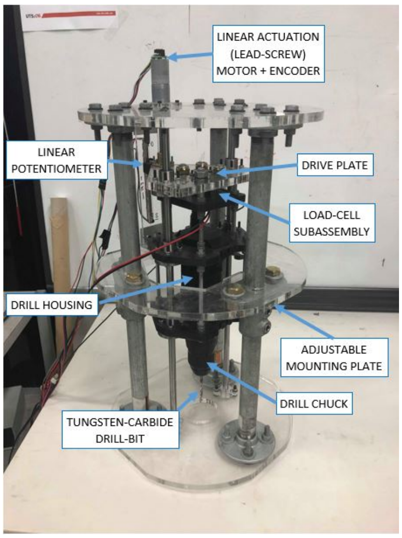

Figure 3. Drill-resistance system prototype design.

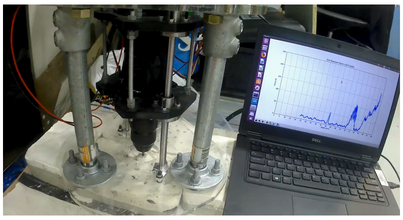

Figure 4. Drill-Resistance real-Time force-depth readings of a concrete lab sample with the presence of aggregates.

Figure 5. Concrete lab samples - 20mm gypsum layer with no aggregates (right) and 30mm gypsum layer with 10mm aggregates (left).

Algorithm 1 Boundary Layer Depth algorithm

$i = 2$ ▷ Start index at 2nd data point to ensure a (i-1) and (i+1) data point
$d_m = \infty$ ▷ Set large initial value for measured depth
while $i \leq (n-1)$ **do** ▷ where n is the sample size
  $F\dot{D}(i) = (F(i+1) - F(i-1))/(2\Delta d)$ ▷ calculate gradient
  $F\ddot{D}(i) = (F(i+1) - 2F(i) + F(i-1))/(\Delta d^2)$
  if $F\dot{D}(i) \geq \alpha \wedge F\ddot{D}(i) \geq \beta$ **then** ▷ significant increase check
    if $d(i) < d_m$ **then**
      $d_m = d(i)$ ▷ Records first depth of significant force increase
$D_B = d_m - d_s$ ▷ Boundary layer depth w.r.t surface

position (i.e. drill depth = 0mm) when the drill-bit comes into contact with the surface of the concrete. The drill is then reset back into its starting position before engaging both the drill and linear actuating motors to drill into the concrete sample and observe the force-depth readings in a controlled manner. The drill is retracted once the force-depth real-time plot shows there has been an increase and then plateau, signifying the hard intact concrete layer has been reached and slightly penetrated. This experiment was designed to investigate the Drill-Resistance prototype's ability to accurately distinguish the boundary layer between a homogeneous soft gypsum and hard concrete depth from the surface. In addition, this experiments tests an algorithm that was developed for autonomously measuring the depth of the boundary layer between a homogeneous gypsum layer and intact concrete. The pseudocode for autonomous boundary layer depth measurement of no-aggregate gypsum is given in Algorithm 1.

The second experiment is a repeat of the first experiment except the concrete lab-sample has a 30 ($\pm$1)mm gypsum layer with 10mm aggregates present to investigate the Drill-Resistance prototype's ability to accurately distinguish the boundary layer with hard obstructive material present, similar to those in corroded layers of concrete. Finally, the third experiment is a variant of the second by adjusting certain lengths in the prototype (such as the adjustable mounting plate - refer to Figure 3) - causing reference lengths to change, thereby altering the surface relative to the drill depth. For instance, initially the drill came into contact with the surface at 42mm relative to the starting position of the drill - the linear potentiometer mounting position is shifted 10mm along the drill axis and away from the concrete surface - now the surface relative to the drill depth becomes 52mm. This experiment was added to see if the surface could be detected by only allowing the linear actuator motor to run, such that when the static drill-bit meets the surface, a sudden force spike would be registered at the corresponding depth. This information could then be used as a marker for identifying the surface relative to the drill depth within the force-depth readings rather than recording this reference value separately before drilling. If successful, this allows all relevant information to be contained in one data set (i.e. the force-depth readings) for easier interpretation of results. Thus, streamlining the operation for users measuring the depth of the boundary layer relative to the surface of the material being drilled.

5 Experimental Results

5.1 Drilling Without Aggregates

Initial assessment of Drill-Resistance prototype readings through the no aggregate gypsum layer concrete lab sample shows remarkable accuracy in measuring the depth of the boundary layer between the gypsum and concrete layer (see Figure 6). The surface relative to the drill depth was measured at 59mm, therefore with a 20mm gypsum layer, the drill depth of the boundary layer of the lab sample would be expected at 79mm. The point at which the force-depth readings exhibit a significant increase can be observed at a drill depth of 78mm, which would result in a measured boundary layer depth of 19mm from the surface with an error of -1mm.

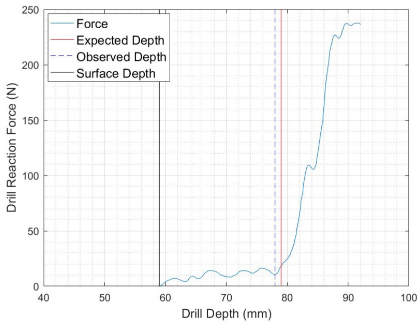

Figure 6. Drill-Resistance prototype force-depth readings of concrete with 20mm gypsum layer with no aggregates present: Increase and plateau in force can be observed to begin at 78mm drill depth, indicating the boundary layer - the surface was recorded at 59mm drill depth resulting in a measured gypsum layer depth of 78 - 59 = 19mm from the surface.

Figure 7 shows the developed Boundary Layer Depth algorithm being applied to the 'No-aggregate gypsum' experimental results from Figure 6. The calculated boundary layer depth of 19.45mm (+0.55mm error from the expected 20mm depth) is more precise than the observed depth of 19mm, thereby demonstrating a proof-of-concept towards autonomously measuring the boundary layer depth correctly and accurately.

5.2 Drilling With Aggregates

Experimental results of the Drill-Resistance prototype through a 30mm gypsum layer with 10mm aggregates consistently reveal the depth of the boundary layer between the gypsum and concrete layer. The surface relative to the drill depth was measured at 58mm, therefore with a 30mm gypsum layer, the drill depth of the boundary layer of the lab sample would be expected at 88mm. The Drill-Resistance prototype force-depth readings shown in Figure 8 detects

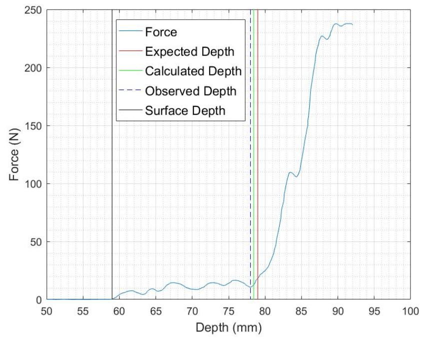

Figure 7. Boundary Layer Depth algorithm applied to the 'No-aggregate gypsum' lab sample data. The resulting calculated boundary layer depth was 19.45mm from the surface compared to an observed depth of 19mm

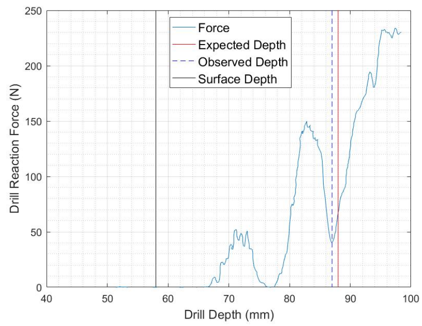

Figure 8. Drill-Resistance prototype force-depth readings of concrete with 30mm gypsum layer with 10mm aggregates present - boundary layer observed at 87mm despite going through two aggregates at 66-76mm and 78-88mm. The surface was recorded at 58mm drill depth, resulting in a measured gypsum layer depth of 87 - 58 = 29mm from the surface.

an aggregate via the force increase at 66mm and 78mm drill depth and respective force decrease at 76mm and 88mm (thus validating 10mm aggregate sizes). A larger force is observed to begin and plateau at 87mm which indicates the concrete layer has been reached, indicating a boundary layer depth of 29mm from the surface resulting in -1mm error.

Another Drill-Resistance prototype measurement was taken from where an aggregate was visible to the surface on the same concrete lab sample, where such a harder material on the surface would reflect most ultrasound or GPR signals before reaching the gypsum itself, let alone the boundary layer. Before this sample was taken, a replacement drill-bit that was 3mm shorter was installed, resulting in a change in the measured surface relative to drill depth to become 55mm. Figure 9 shows reaction force on the drill rise and fall at 55mm (surface) and 64mm drill depth respectively. The low forces observed between drill depths 64mm and 85mm signifies the soft gypsum material. The sharp force increase observed at 85mm signifies the boundary layer was reached, which matches the expected boundary layer drill depth, measuring a 30mm boundary layer depth from the surface.

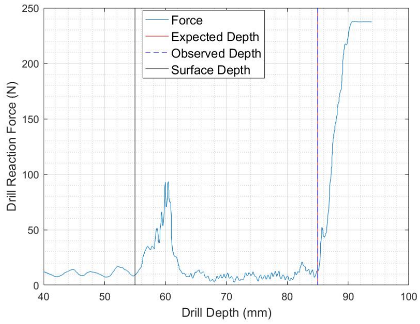

Figure 9. Drill-Resistance prototype force-depth readings of concrete with 30mm gypsum layer with 10mm aggregates present - boundary layer detected at 85mm despite an aggregate (55-64mm) at the surface (55mm) - resulting in a measured gypsum layer depth of 85 - 55 = 30mm from the surface.

5.3 Surface Detection

Figure 10 and Figure 11 demonstrate the Drill-Resistance prototype can also be used to detect the surface relative to the drill depth as in Figure 10, which shows the surface to be detected at drill depth 53mm, resulting in an expected boundary layer drill depth of 83mm. A 10mm aggregate is detected at 71mm drill depth as seen by the increase in drill reaction force which then subsides at 81mm drill depth, followed by a larger increase in force observed starting at 84mm drill depth, resulting in a measured boundary layer depth of 31mm from the surface (+1mm error). Similarly, Figure 11 records a surface detection at 51mm, prompting an expected boundary layer depth of 81mm for the given 30mm gypsum layer. A 10mm aggregate can be observed between 69mm and 79mm drill depth followed by a force increase and plateau at 81.5mm, resulting in a measured boundary layer depth of 30.5mm from the surface (+0.5mm error).

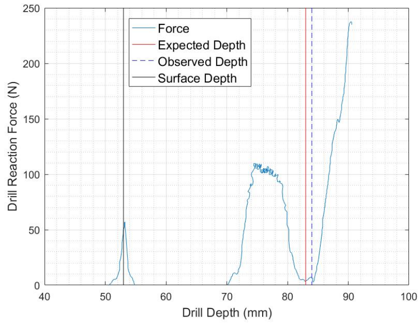

Figure 10. Drill-Resistance prototype force-depth readings of concrete with 30mm gypsum layer with 10mm aggregates present - surface (53mm), aggregate (71-81mm) and boundary layer (84mm) all mapped in this one data set. The measured boundary layer is 84 - 53 = 31mm from the surface.

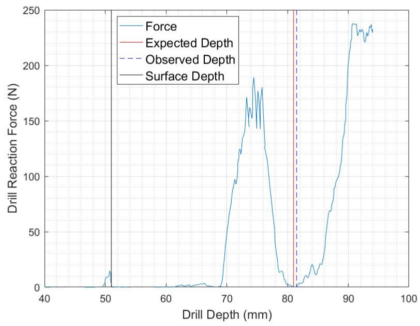

Figure 11. Drill-Resistance prototype force-depth readings of concrete with 30mm gypsum layer with 10mm aggregates present - surface (51mm), aggregate (69-79mm) and boundary layer (81.5mm) all mapped in this one data set. The measured boundary layer is 81.5 - 51 = 30.5mm from the surface.

6 Discussion

All the experiments were conducted within the iPipes Lab facility. Gypsum layered samples were fabricated as an alternative to the real corroded layer [28] for the preliminary sensor evaluation. The gypsum layer brittleness is similar to corroded concrete. After assessing all experimental results, the maximum deviation in observed/measured boundary layer depth from the expected boundary layer depth was 1mm regardless if aggregates were/were not present in the gypsum layer of the concrete lab sample being analysed. We must disclose that during the final experiment with regards to surface detection, there were observed instances of mechanical compliance along the drill axis (i.e. the drill could slightly move freely along its axis) because of frequent ongoing tests. This behaviour can be observed in the beginning of Figure 10 and Figure 11 where although the drill was in contact with the surface, there was slack in the mechanism that would allow the drive plate (and therefore linear potentiometer) to still move a few more millimeters – resulting in a 'wind up' of force across a small distance. Hence, the true surface relative to drill depth is when the force asymptotically increases with no increase in drill depth. In addition, allowing the drill mechanism to wind-up the reaction force at the surface removes the mechanical compliance whilst drilling into the concrete, thereby eliminating the error in the force-depth readings as a result of mechanical error. We must also highlight that the concrete lab sample fabrication/curing process has a ±1mm tolerance when pouring/layering the concrete and gypsum into the mould. Hence a 20mm or 30mm gypsum layer could range between 19-21mm and 29-31mm respectively. Therefore, the maximum error in results of 1mm reflects exactly this sizing tolerance of the depth/thickness of the gypsum layer (boundary layer depth), making the force-depth readings an entirely valid pin-point subterranean 'scan' of a gypsum-concrete section – with the potential for sub-millimetre accuracy.

The results from the first experiment, shown in Figure 6 demonstrate the Drill-Resistance prototype can accurately measure the depth of a boundary layer between a soft homogeneous material and hard non-homogeneous material respectively from the surface with millimetre accuracy compared to NDT sensors such as ultrasound or GPR. However, in the case of the second experiment, the presence of large aggregates either obstructs conventional NDT sensors from detecting boundary layers or inhibits their ability to do so accurately and reliably. Whereas the Drill-Resistance prototype can penetrate through these large, hard aggregates – providing force-depth readings like the ones shown in Figure 8 and Figure 9 that provide a complete/detailed 'scan' of the gypsum layer; not only revealing the boundary layer depth between gypsum and concrete within 0-1mm error but also revealing/validating the depth and thickness of the aggregates themselves. Furthermore, not having the drill running before coming into contact with the surface in the final experiment shows the Drill-Resistance prototype can also detect the surface relative to itself – making it an entirely self-sufficient sensor with no need for reference/calibration values such as material density or signal velocity or in this case, surface depth relative to drill depth, to be known prior to using the sensor to find and measure the boundary layer depth. The Drill-Resistance prototype can be placed over any point and drill accordingly to provide an accurate real-time force-depth 'scan' of the subsurface.

7 Conclusion and Future Work

This paper introduced a novel drill-resistance based sensor for detecting the depth of the concrete affected by microbial corrosion. According to our knowledge, this is the first instant that such a sensor was developed and verified. Several lab experiments were carried out to validate the sensor measurements on carefully prepared lab samples. The lab experiments revealed the developed drill-resistance sensor is capable of measuring the corroded concrete depths with mm accuracy. In addition, the sensor has the ability to accurately identify aggregate location which could be useful in evaluating concrete structures.

In the future, the developed prototype can be miniaturized based on the requirements of the sewer operators and lab testing will be done on the corroded samples obtained from the Sydney based sewer.

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