

Concrete Strength Sensing Using REBEL Sensors

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16. Abstract This study evaluated the use of Resonance-Based Embedded Layer (REBEL) sensors as a nondestructive technology for real-time monitoring of in-place concrete strength in transportation infrastructure. The objective was to assess the accuracy, reliability, and field applicability of REBEL sensors relative to conventional laboratory testing methods used for quality assurance. Six field projects involving bridge decks, pavement patches, and pavement reconstruction across Illinois were instrumented with embedded REBEL sensors and companion laboratory specimens. Conventional laboratory testing, including compressive strength and flexural strength, was conducted in accordance with applicable ASTM and/or Illinois Modified AASHTO standards, and sensor predictions were compared with laboratory measurements using graphical and statistical analyses. The results demonstrated that REBEL sensors were able to predict concrete strength development during curing. According to the regression analysis, the increase in strength in laboratory-cured samples and in field concrete is proportional. However, the Bland-Altman analysis showed that the difference between laboratory-cured samples and field concrete increases logarithmically as the concrete ages. Although several field deployment challenges, including damaged data loggers and intermittent communication issues, were encountered, these operational issues were resolved and did not significantly affect the overall evaluation of the technology. The findings indicate that REBEL sensors provide a practical means of continuously monitoring in-place concrete strength, though a strong correlation between sensor-measured data and laboratory test data could not be established, suggesting the need for more rigorous investigation. The deployment procedures, implementation recommendations, and lessons learned presented in this report can assist transportation agencies and contractors in implementing embedded sensing technology to improve construction quality assurance, reduce testing costs, support earlier construction decisions, and enhance project efficiency.			
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EXECUTIVE SUMMARY

The Illinois Department of Transportation (IDOT) currently relies on destructive laboratory testing of concrete cylinders or beams to verify in-place concrete strength for quality control and acceptance. Although these methods are well established, they require additional labor, materials, and time, and provide only discrete measurements that may not accurately represent the strength development of the concrete in place. This study evaluated the feasibility of using Resonance-Based Embedded Layer (REBEL) sensors as a nondestructive, real-time alternative for monitoring concrete strength during construction.

The study included six field projects across Illinois involving a range of transportation infrastructure applications, including bridge decks, pavement patches, and pavement reconstruction. REBEL sensors were embedded directly into concrete elements and companion laboratory specimens, and conventional laboratory testing was performed on cylinders and beams to determine compressive strength, flexural strength, and modulus of elasticity. Sensor deployment procedures, data logger installation, project setup through the Wavelogix platform, and field implementation challenges were documented to provide practical guidance for future deployments.

The sensor measurements were compared with laboratory test results during concrete curing. Statistical analyses, including linear regression, hypothesis testing, and Bland–Altman analysis, were performed to evaluate the agreement between sensor-predicted and laboratory-measured compressive strengths. The comparisons demonstrated that the REBEL sensing system consistently tracked concrete strength development; although the strength gain in the concrete measured by the sensors and the laboratory-tested samples is proportional, the concrete maturity curves (time vs. strength gain) do not show consistent growth. Hence, in this study, the sensor-measured data and the laboratory-tested data do not show a strong correlation. Although several field deployment challenges were encountered, including damaged data loggers, communication interruptions, and isolated sensor malfunctions, these issues were operational rather than limitations of the sensing technology and were successfully addressed during the study.

The results demonstrated that REBEL sensors provide continuous, real-time information on concrete strength development. The technology offers substantial potential to improve construction quality assurance, reduce testing costs, accelerate construction schedules, and support data-driven decision-making during concrete placement. However, a rigorous study is needed to deploy the sensors in similar and diverse concrete projects and compare laboratory testing data from various sources, such as QA/QC consultants and IDOT laboratory results. The deployment procedures and lessons learned documented in this report provide practical recommendations for future implementation by IDOT and other transportation agencies considering embedded sensing technologies for concrete strength monitoring, pending further field testing and investigation.

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CHAPTER 1: INTRODUCTION

Accurate determination of in-place concrete strength is essential for ensuring construction quality, optimizing project schedules, and avoiding premature structural failures. Conventional methods, such as compression testing of cast cylinders and flexural beam testing, while widely accepted, are destructive, labor-intensive, and time-consuming, often providing results that do not fully represent the actual conditions of the concrete in place. These traditional techniques can delay decision-making because results are obtained only at discrete time intervals rather than continuously. In fast-paced construction environments, such as highway pavements, bridge decks, and airport runways, delays in determining when concrete has reached the necessary strength can result in costly idle time or, conversely, premature loading that accelerates deterioration.

To address these limitations, recent advances in sensing technology have enabled the development of nondestructive, real-time concrete strength measurement systems, such as the Resonance-Based Embedded Layer (REBEL) sensor developed at Purdue University. The REBEL sensor, data logger, and charger are shown in Figure 1 and Figure 2. The REBEL sensor uses piezoelectric materials to directly measure the stiffness of curing concrete through electromechanical impedance and vibrational resonance. Unlike maturity-based approaches, such as the method described in ASTM C1074, which require mix-specific maturity curves, REBEL and similar systems directly correlate stiffness measurements with strength, eliminating the need for extensive pre-calibration.



Figure 1. Photo. REBEL sensor connected to a data logger.

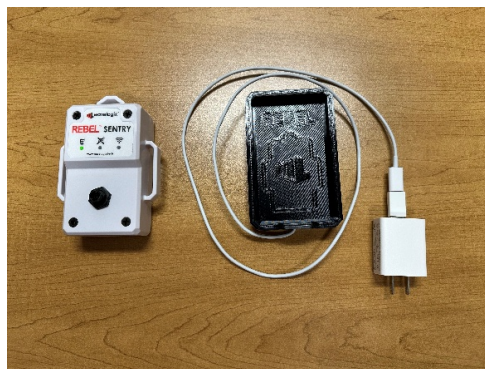


Figure 2. Photo. Data logger and charger.

REBEL and comparable sensors can be embedded directly into the concrete, enabling continuous monitoring from the moment of placement. Data can be transmitted wirelessly to project managers and quality control personnel, potentially reducing the need for repeated site visits and manual testing. This capability aligns with modern infrastructure management strategies that emphasize the use of Internet of Things (IoT)-enabled devices for real-time decision-making. Furthermore, such sensors have the potential to reduce material waste, lower labor costs, and improve safety by minimizing unnecessary handling of test specimens.

Adopting real-time, nondestructive strength measurement in transportation infrastructure construction could improve quality assurance practices. For agencies like the Illinois Department of Transportation (IDOT), which often uses concrete mixtures with high pozzolan replacement levels, elevated cement contents, and region-specific aggregates, it is critical to evaluate whether these sensor systems can deliver reliable results under local conditions. A successful validation would provide a pathway to reducing or eliminating redundant and destructive testing, accelerating project delivery, and generating reasonable cost savings throughout the life cycle of infrastructure assets. The cost savings could come from preparing fewer test samples, resulting in fewer man-hours for testing the samples in the laboratory.

This study evaluates the performance of REBEL sensors for monitoring in-place concrete strength during transportation construction projects in Illinois. Measurements obtained from embedded sensors are compared with results from conventional laboratory testing methods to assess their level of agreement and identify factors that may affect field implementation. The findings are intended to provide an objective assessment of the technology and contribute to future decisions regarding the use of embedded sensing systems in construction quality control practices.

CHAPTER 2: LITERATURE REVIEW

PIEZOELECTRIC AND RESONANCE-BASED SENSING PROCESS

The REBEL sensor operates based on the piezoelectric effect. The sensor is embedded directly into fresh concrete at the time of placement. It generates small vibrations and detects the response of the surrounding concrete through electromechanical interaction. As the concrete hardens, its stiffness and density increase, which causes a change in the resonance frequency measured by the sensor. The sensor records an electromechanical spectrum (EMS) containing a resonance peak related to the dynamic modulus of elasticity of the surrounding concrete. By applying mathematical relationships to the measured resonance frequency, the elastic modulus (E_d or E_s) can be calculated and used to estimate the compressive strength (f'_c) of the concrete. Unlike traditional maturity-based methods, the REBEL sensor provides direct strength measurement. One study on limited samples demonstrated that the accuracy of the REBEL sensor's compressive strength measurements was greater than 95% when compared with standard compressive strength tests using a linear regression, and 90% accuracy using a root mean square deviation analysis (Su et al., 2020). In addition, the REBEL system supports IoT-enabled monitoring. The sensors transmit data wirelessly through long-term evolution (LTE) networks to a cloud-based dashboard. This allows engineers to monitor concrete strength development continuously and remotely, potentially reducing the need for physical testing or site visits.

Development and Improvement of the Sensing Process

Initially, the process used the electromechanical impedance (EMI) method, in which piezoelectric patches containing materials such as lead zirconate titanate (PZT) were bonded to a concrete structure to allow the patch to act as both a sensor and an actuator. Electrical voltage is then applied to these patches, causing them to vibrate and interact with the structure to which they are bonded. The interaction between the patch and the structure allows the sensor to measure the specimen's electrical impedance signature. This process later evolved to use embedded sensors, such as piezoelectric cement (PEC) sensors, which consist of PZT particles blended with cement to improve sensitivity and compatibility with the concrete structure like the one shown in Figure 3. Compared with conventional PZT patches, PEC sensors offer greater durability and provide more consistent conductance data for real-time monitoring of concrete properties such as compressive strength. The use of embedded sensors further extended the EMI approach through the electromechanical impedance resonance (EMI-R) method. With this method, the sensors can identify resonant frequencies within a specimen and isolate their peaks, which are then used to determine the mechanical properties of concrete such as compressive strength and Young's Modulus. This method also enables in-place monitoring of concrete specimens.



Figure 3. Image. Mortar specimens with embedded piezoelectric sensors cured in water.

Source: Pan and Huang (2018)

Resonance- and piezoelectric-based sensing methods and technologies have been refined over time. Initially, a thin PZT patch was bonded to the specimen surface to obtain EMI signatures over a specified frequency range. These patches were connected to an impedance analyzer and a computer with data acquisition software for measuring electrical conductivity and admittance values. This method later evolved to use patches embedded within specimens, expanding its application to concrete beams, slabs, and other structural elements. To protect the embedded patches and extend its capabilities, various coatings were evaluated to determine their effects on sensor performance and their ability to protect the sensors from concrete alkalinity. Figure 4 shows an example of embeddable sensors being applied to a concrete beam. The sensor is placed on the first layer of concrete after which it will be covered by additional layers.



Figure 4. Image. Embedded sensors for a concrete beam.

Source: Kong (2023)

Deep-learning AI models have also been incorporated into sensor-monitoring systems. These models can improve the analysis of complex electromechanical-spectrum data and account for external factors such as temperature and environmental conditions. Han et al. (2025) incorporated a deep-learning model into a monitoring system and evaluated its performance during deployment. The authors developed a one-dimensional convolutional neural network (1D CNN) to interpret complex EMI signals and account for variation among multiple sensors. The model interpreted complex EMI signals with an R^2 of 0.94 and an error margin within 15%. Though the error margin is reasonable, the deep-learning estimated results do not align with ASTM C39 standards, which state that the percent error cannot exceed 1% with a precision range of 7.8% for laboratory-conditioned or 9.5% for field-conditioned specimens. Also, IDOT's properly conducted tests from two laboratory-tested samples should not differ by more than 14% from the average.

Applications of the EMI Method

Piezoelectric sensors have been used in a wide range of applications within civil engineering. Aydin and Çelebi (2023) examined applications of piezoelectric sensors and the properties of piezoelectric materials. They found that these materials have been used for structural control, energy harvesting, and structural health monitoring. They found that piezoelectric materials can convert mechanical stress into electrical energy and electrical energy into mechanical deformation, making them sensitive to localized damage or deformation. However, they noted that ceramic piezoelectric materials are fragile, which can limit their use in some applications unless the piezoelectric elements are adequately protected.

Structural control systems using piezoelectric materials can help protect structures from external forces, including high wind loads and seismic activity. These applications include active-vibration control and piezoelectric friction dampers, which take advantage of the materials' vibration sensitivity and rapid response. Active vibration-control systems use piezoelectric materials to sense structural vibrations and then act as actuators to counteract those vibrations, with Figure 5 showing an example of this system. Piezoelectric friction dampers use ceramic materials to adjust the contact force between friction surfaces. By leveraging the material's sensitivity, the dampers can adjust their resistance to structural movement rapidly.

Piezoelectric materials' ability to convert mechanical stress or vibrations into electrical energy makes them well suited to energy-harvesting applications. Materials such as PZT and polymers such as polyvinylidene fluoride (PVDF) have a high longitudinal dielectric coefficient, making them suitable materials for these applications. These materials can power devices operating at lower frequencies more efficiently than those operating at higher frequencies, possibly because of PZT's brittleness and sensitivity to high stresses and vibrations. The review article notes that powering high-frequency devices requires maximizing the dielectric coefficient and pairing the piezoelectric materials with more conductive materials, such as graphene. A study noted within the review demonstrated the use of piezoelectric materials to harvest energy from transportation-related loading, including one roadway application reported to generate approximately 250 kW/km (Aydin and Çelebi, 2023; Xiong et al., 2012).

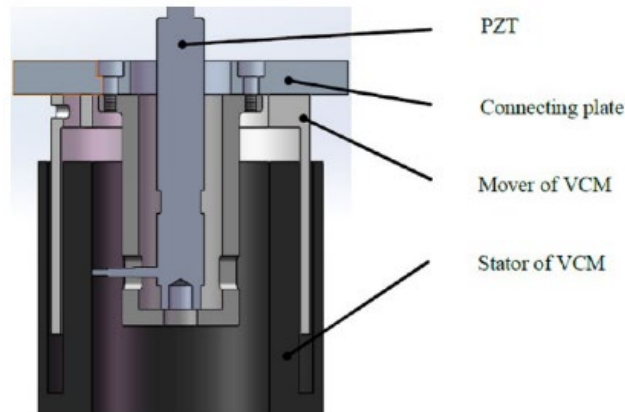


Figure 5. Image. Proposed active vibration-control system.

Source: Aydin and Çelebi (2023)

In structural health monitoring applications, piezoelectric materials are used to monitor and evaluate structural integrity. One common monitoring technique is the EMI method, which detects localized structural damage by comparing baseline signatures before and after damage occurs. Another technique uses piezoelectric materials as both a sensor and an actuator, where one device transmits signals through the structure, and another device receives them like the one shown in Figure 6. The receiving device can detect changes caused by cracking or other forms of damage. Another monitoring technique uses a “smart aggregate,” in which a PZT patch is coated in a protective layer and embedded in a concrete or cement block before being placed in the structure during a concrete pour. Smart aggregates have been used for early-age strength monitoring and seismic-response monitoring, such as monitoring the impact of earthquakes on a structure.

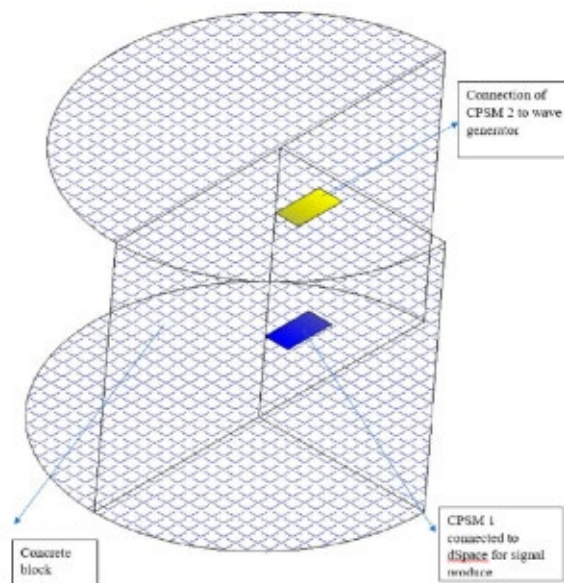


Figure 6. Image. Concrete block and proposed placement of piezoelectric sensor and actuator.

Source: Aydin and Çelebi (2023)

Structural Health Monitoring Applications Within Concrete

The sensing capabilities of piezoelectric materials have advanced over the past several decades through continued research and improvements in sensor technology. Using the EMI method, PZT sensors can act as both an actuator and receiver using a set of sensors or a single sensor. Previous studies have identified important sensor design considerations and improved how PZT sensors apply the EMI principle. Kong and Lu (2020) demonstrated that a single PZT sensor could act as both an actuator and receiver, eliminating the need for separate actuating and receiving sensors. In a Purdue University dissertation, Kong (2023) introduced a novel PZT sensor intended for potential use in large-scale concrete projects. This sensor uses a custom waveguide enclosure around the piezoelectric core to measure the bulk physical properties of the surrounding concrete. The waveguide enables the sensor to generate a localized structural resonance in a larger volume of surrounding concrete rather than sensing only the concrete in direct contact with the sensor surface. Kong (2023) demonstrated the sensor's performance through laboratory testing and field implementation.

Applications of PZT sensors in structural health monitoring have expanded considerably over the past several decades. Shin et al. (2008) reported an early application of PZT patches and the EMI method for monitoring concrete strength development. The study found a correlation between the frequencies obtained from a concrete structure using the PZT patch and the strength development profile of a concrete structure from destructive compressive testing, showing that the EMI method is effective for monitoring strength gain in concrete over time. Using a similar approach, Kong and Lu (2020) used the EMI-R method to extract the first two longitudinal resonant frequencies to calculate Young's Modulus and Poisson's ratio as a concrete specimen hardened. This expanded the application of PZT sensors beyond compressive strength monitoring to the estimation of additional mechanical properties from the EMI spectrum.

For concrete applications, the EMI method has been used to monitor hydration, strength development, and other material properties. PZT sensors have been shown to monitor hydration in concrete specimens with various water-to-cement ratios (Narayanan et al., 2017). PZT sensors also detected changes in electrical admittance in specimens containing supplementary cementitious materials, such as fly ash and silica fume (Ghafari et al., 2018). The EMI method has also been investigated as a nondestructive method for monitoring concrete strength development. Subsequent research examined more specific relationships between concrete strength gain and changes in the measured frequency spectrum. Su et al. (2020) evaluated the phase-angle spectrum and indices derived from it, finding that the first local phase-angle peak-value index could serve as a predictor of concrete strength gain. Pan and Huang (2020) also used the EMI method with PZT and PEC sensors to examine strength-related changes in cement mortar and cement paste. Beyond strength monitoring, the EMI method has also been investigated for monitoring the rheological properties of fresh concrete. This application monitors properties such as elastic modulus during the first several hours after concrete placement (Han et al., 2021). Although rheological monitoring may not be necessary for every project, it can be important for applications such as three-dimensional concrete printing, as these properties are important to ensure that the concrete is feasible for the application. Another application of the EMI method is damage detection. The EMI method has been used to detect early-stage cracking before it becomes visible, which can be useful for monitoring the physical health of concrete throughout its lifecycle (Saravanan et al., 2017).

IMPORTANCE OF IN-PLACE CONCRETE STRENGTH MONITORING

In-Place Destructive Test

Drilled Core Test

In-place concrete strength has traditionally been assessed using destructive testing methods. Drilled-core testing is widely regarded as one of the most reliable methods for determining the in-place compressive strength of concrete (displayed in Figure 7). Procedures for extracting and testing concrete are outlined in ASTM C42. Compressive-strength testing of concrete specimens is conducted in accordance with ASTM C39. Previous research has shown that measured concrete strength can vary depending on curing conditions, moisture content, and the presence of reinforcement (Szpetulski et al., 2025). Destructive testing gives reliable strength values, but it permanently damages the structure. As a result, these methods are not suitable for continuous strength monitoring.



Figure 7. Image. Drilled core testing on site.

Source: Szpetulski et al. (2025)

Break-off Test

The break-off test is used to estimate in-place concrete strength by measuring the force required to break a small cylindrical core from the concrete surface (displayed in Figure 8). A special form is placed in the fresh concrete, or a core is removed in the hardened concrete, after which a hydraulic loading device applies force until the specimen breaks. Break-off test results have been found to correlate reasonably well with concrete compressive strength, although aggregate characteristics and localized failure patterns can increase variability (Johansen, 1979; Naik et al., 2004). The test gives localized data near the surface of a concrete member and can be conducted in place. Additionally, the test is relatively minimally destructive, generally requires only localized surface repair, and is less expensive than full-depth coring. However, break-off test results must be calibrated in relation to standardized compressive-strength test results to provide reliable strength estimates.

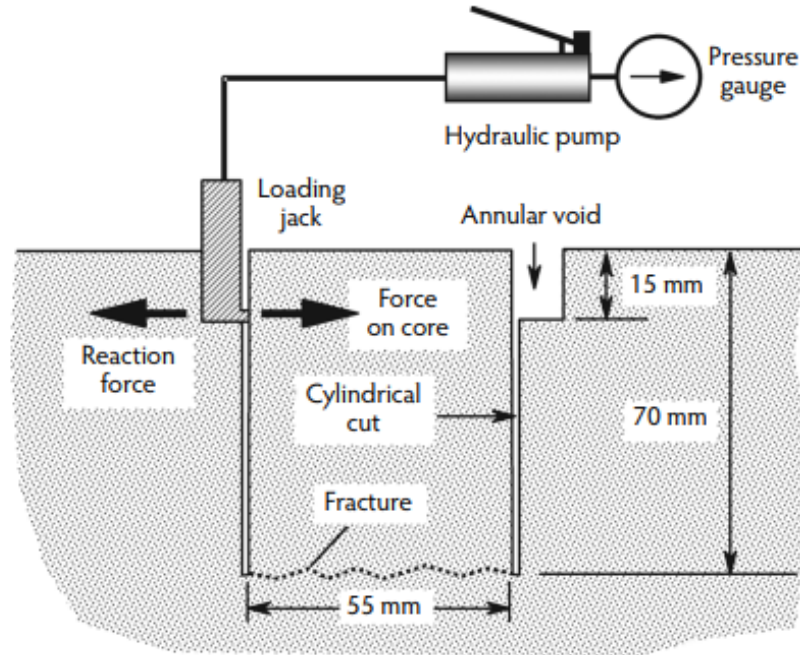


Figure 8. Image. Schematic of break-off test.

Source: Johansen (1979)

In-Place Nondestructive Test

To address these limitations, nondestructive testing (NDT) methods have been used as alternative tools for evaluating in-place concrete strength. Common NDT techniques include rebound hammer testing (ASTM C805; Figure 9), ultrasonic pulse velocity testing (ASTM C597), penetration resistance testing, and pullout testing (ASTM C900). These methods allow concrete strength to be assessed with little or no damage and can often be performed rapidly in the field. However, their accuracy can be affected by material variability, surface conditions, and environmental factors. Previous studies have shown that NDT results generally require correlation with destructive-test data to produce reliable strength estimates (Demir et al., 2023; Al-Neshawy et al., 2025). The maturity method, standardized under ASTM C1074, is also commonly used to estimate early-age concrete strength. However, this method requires mix-specific calibration and is sensitive to changes in materials and curing conditions (Malhotra and Carino, 2004).



Figure 9. Image. Rebound hammer testing.

Source: Popovics et al. (2016)

Ultrasonic Pulse Velocity Test (ASTM C597)

Ultrasonic pulse velocity (UPV) testing is a nondestructive method used to evaluate the uniformity and quality of concrete and, when appropriately calibrated, estimate certain concrete properties. During UPV testing, ultrasonic transducers are positioned at selected locations on the concrete surface. One transducer generates an ultrasonic pulse that travels through the concrete to a receiving transducer. The equipment measures the transit time required for the pulse to travel between the transducers. Pulse velocity is calculated by dividing the measured path length by the transit time. Oke and Abuel-Naga (2023) reported that UPV testing can use different wave modes, including compression waves and shear waves. Compression waves are commonly designated as P-waves, whereas shear waves are designated as S-waves. A coupling material is applied between each transducer and the concrete surface to provide adequate acoustic contact.

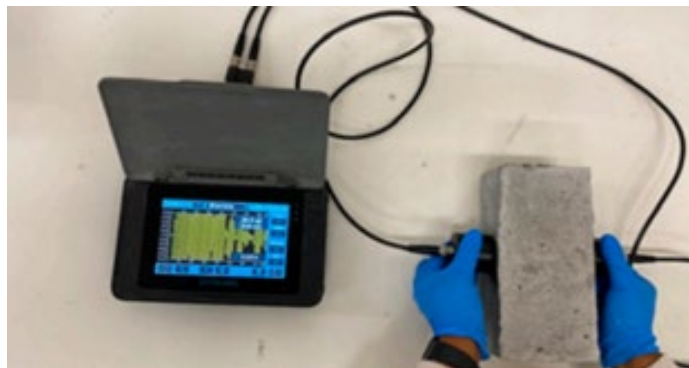


Figure 10. Image. Measurement of P-wave velocity.



Figure 11. Image. Measurement of S-wave velocity.

The study found that UPV results were strongly correlated with material strength when appropriate predictive models were applied. The relationship between wave velocity and material strength had a correlation of approximately 0.96, indicating a strong association between the variables. The authors also noted that the accuracy of UPV-based estimates depends on factors such as material composition, curing conditions, specimen dimensions, and moisture content. Despite these limitations, UPV testing can provide rapid, repeatable, and nondestructive evaluation of concrete strength, particularly when destructive testing is impractical or when continuous monitoring of structural condition is required.

Penetration Resistance Test (ASTM C803)

In-place nondestructive and minimally destructive methods for estimating concrete strength are useful when drilled-core testing is impractical. Maliha et al. (2020) presented an in-place penetration-resistance method for estimating concrete strength. In this method, the depth to which a small pin penetrates the concrete is measured to deduce the strength of concrete. Penetration depth generally decreases as concrete compressive strength increases.

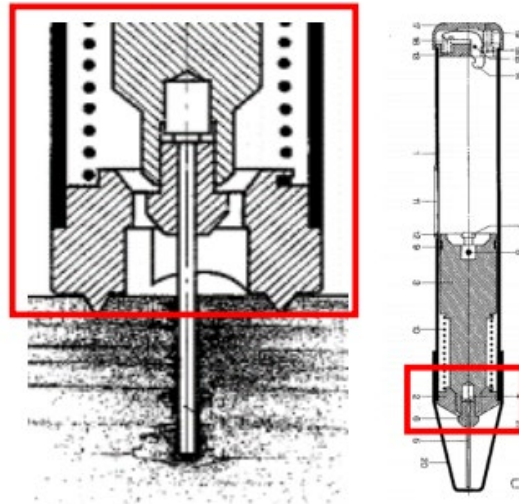


Figure 12. Image. Cross-section of the device.



Figure 13. Image. Pin penetration test.

The study also explored various pin sizes and shapes and found that a 2.5 mm diameter pin with a sharp point produced the strongest correlation with compressive strength. Regression analysis

showed a linear correlation between penetration depth and compressive strength, with coefficients of determination (R^2), ranging from 0.62 to approximately 0.64. Although test results can be affected by factors such as surface irregularities and material variability, the study identified methods for reducing their influence, including averaging multiple measurements. This test is also essential to detect concrete with compressive strengths below 9 MPa in existing structures when core testing would be excessively damaging to the structure.

CONVENTIONAL METHODS FOR CONCRETE STRENGTH EVALUATION

Flexural Strength Test of Beam

The flexural strength of concrete is determined by testing a cured concrete beam under bending using the IDOT procedure specified in Section 1202.09. The beam is positioned on two supports and subjected to a continuously increasing load until it fractures (Figure 14). The maximum load at failure, along with the beam's dimensions and span, is used to calculate the modulus of rupture (flexural strength) of the concrete. This test provides an indication of the concrete's ability to resist tensile stresses caused by bending and is particularly important for evaluating concrete used in pavements and other flexural applications.



Figure 14. Image. Concrete beam flexural test in the laboratory.

A portable beam tester (Humboldt, 2025; Figure 15) can be used to determine the flexural strength of concrete by applying center-point loading to a cured concrete beam until failure. The beam is positioned on the apparatus supports, centered under the loading head, and loaded hydraulically at a controlled rate. The maximum load at fracture is recorded, and the beam width, depth, and span are measured. These measurements are then used to calculate the concrete's modulus of rupture. The portable design allows the test to be performed conveniently in the field or laboratory and provides a rapid quality-control method for evaluating concrete flexural strength.



Figure 15. Image. Portable concrete beam tester by Humboldt.

Source: Humboldt (2025)

Split Tensile-Strength Test Using Cubes

The splitting tensile-strength test is a destructive laboratory test conducted on standardized concrete specimens after curing (Figure 16). For this test, the concrete sample is laid horizontally in the compression testing machine, and a compression force is applied along its length. As a result, it is split along its vertical length to form two equal halves. Because the specimen fractures during testing, the method is destructive. Jinping et al. (2019) reported that splitting tensile strength depends on curing age and increased rapidly during the first 7 days, reaching approximately 70% of the measured 28-day value. Although the test provides useful information about tensile strength and cracking resistance, it cannot be performed directly on in-place concrete and does not provide continuous strength measurements.



Figure 16. Image. Cube splitting test.

Source: Zhuang et al. (2019)

Compressive Strength Test Using Cylinders

One of the most common methods for measuring concrete compressive strength is testing concrete cylinders in compression with standard test methods, such as those specified in ASTM C39. The procedure involves collecting fresh concrete at the time of placement and casting it in 6 by 12 in. cylindrical molds. The concrete is then consolidated in three layers by tamping to reduce entrapped air and produce a uniform specimen. After casting, the specimens are cured under controlled conditions specified in ASTM C31. Usually, specimens are placed in a curing room at constant moisture levels and a temperature of $70 \pm 3^{\circ}\text{F}$ until testing.



Figure 17. Image. Cylinders cast at site.

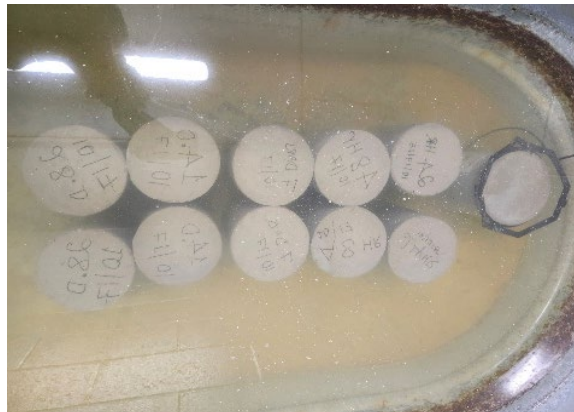


Figure 18. Image. Cylinders placed in a curing tank.

Concrete compressive strength is commonly conducted using hydraulic testing machines in accordance with ASTM C39. A compressive axial load is applied to each molded cylinder until the specimen fails. The maximum load recorded at failure is divided by the cylinder's cross-sectional area to calculate compressive strength. Although this method is widely accepted and provides reliable strength values, it is time consuming and destructive.



Figure 19. Image. Compression testing setup.

Source: Kong (2023)

Maturity Method

Another widely used approach is the maturity method, described in ASTM C1074. A maturity curve describes the relationship between concrete compressive strength and a maturity index that accounts for the combined effects of time and temperature during strength development (Figure 20). The strength–maturity relationship is developed by relating laboratory-measured compressive strengths of concrete cylinders to their calculated maturity indices in accordance with ASTM C1074. Using a maturity chart, the strength of the in-place concrete at any given time can be determined using the temperatures at the construction site.

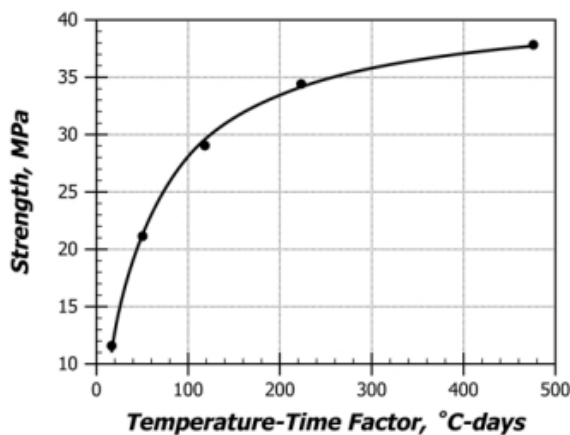


FIG. 1 Example of a Relationship Between Compressive Strength and Temperature-Time Factor

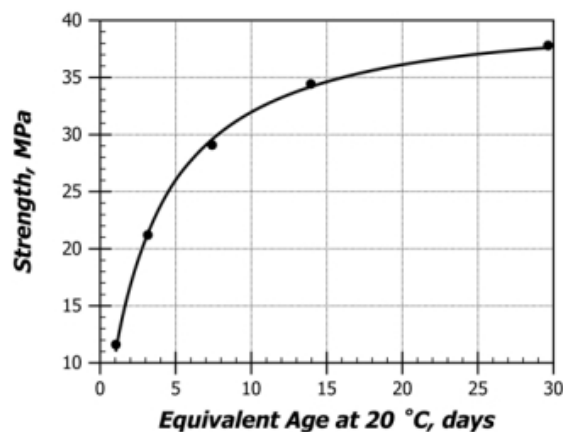


FIG. 2 Example of a Relationship Between Compressive Strength and Equivalent Age at 20 °C

Figure 20. Image. Relationship between compressive strength and equivalent temperature/age at 20°C.

Source: ASTM C1074 (2019)

Split Tensile-Strength Test Using Cylinders

Another method for evaluating concrete tensile strength is the splitting tensile-strength test, which is commonly used for pavement and structural concrete applications (Figure 21). This test involves placing a concrete cylinder horizontally in a compression-testing machine and loading along its vertical diametral plane. Even though the applied load is compressive, a nearly uniform tensile stress develops perpendicular to the loading direction, causing the specimen to split along its vertical diameter. The procedure is standardized in ASTM C496 and can be performed using conventional compression-testing equipment.



Figure 21. Image. Typical fracture plane of splitting tensile-strength test specimen.

Source: Melis et al. (1985)

Melis et al. (1985) reported that the splitting tensile test is reliable, repeatable, and has variability equal to or lower than that of flexure beam testing when standard 6 × 12 in. cylinders were used. This conclusion was supported by coefficients of variation of splitting tensile strength that were comparable to those for flexural strength, indicating acceptable accuracy for quality-control purposes. Moreover, cylindrical specimens are less susceptible to drying and handling-related problems than flexure beam specimens. Consequently, splitting tensile testing is particularly advantageous for field and laboratory use. The splitting tensile-strength test therefore remains a useful alternative to flexural testing, particularly for concrete pavement applications, because it requires simpler specimen preparation and less handling.

Compressive Strength Test Using Cubes

Concrete cube testing is also widely used in the laboratory to assess concrete compressive strength (Figure 22). The fresh concrete is placed in steel molds measuring 150 × 150 × 150 mm and consolidated in layers to remove any entrapped air. The specimens remain in the molds for approximately 24 hours at room temperature, after which they are removed and the cubes immersed in clean water for curing until testing at 7 or 28 days.

After curing, the surfaces of the cube specimen are cleaned and positioned in a compression-testing machine (CTM). A uniformly increasing load is applied without shock until the specimen fails. Compressive strength is determined by dividing the maximum load at failure by the cross-sectional area of the cube. Experiments have demonstrated that compressive strength of a cube improves with its age and is dependent upon curing and compacting (Choure et al., 2022). Although cube tests can

provide strength measurements for quality-control purposes, cube specimens generally produce higher measured compressive strengths than comparable cylinder specimens.



Figure 22. Image. Compressive-strength testing on concrete cubes.

Source: Choure et al. (2022)

Recent studies have focused on developing embedded sensor-based systems for concrete monitoring to overcome the limitations of both destructive and conventional nondestructive testing methods. Technologies such as embedded resistance sensors, piezoelectric sensors, and Internet of Things (IoT)-based monitoring systems can provide real-time concrete behavior measurements within the concrete structure itself (Nkongolo & Kevern, 2024; Porras et al., 2025). These developments demonstrate growing interest in in-place monitoring technologies that can relate sensor measurements to concrete strength and other mechanical properties.

CHAPTER 3: SENSOR SETUP

In the following projects, REBEL sensors were used to measure concrete strength. These sensors were either embedded directly in the concrete (Figure 1) or placed at the bottom of 6 × 12 in. cylinders (Figure 23). The sensors must be connected to data loggers to record the data. The data loggers are charged before placement and may require recharging during the project (Figure 2).



Figure 23. Image. 6 × 12 in. cylinder with sensor.

The data loggers, where the data is stored, transmit data to the Wavelogix web platform, and can be viewed remotely. Before the concrete is poured, however, the project must be configured on the Wavelogix platform. The steps to set up the project are presented in the tutorial below. The sensors are designated for the pour once they are added to the project in Wavelogix. The sensors must be connected to the data loggers an hour before concrete is poured over them.

WAVELOGIX TUTORIAL

To create a project on the Wavelogix platform (<https://rebel.wavelogix.tech/auth/email>), select the Projects tab and then select New Project (Figure 24).

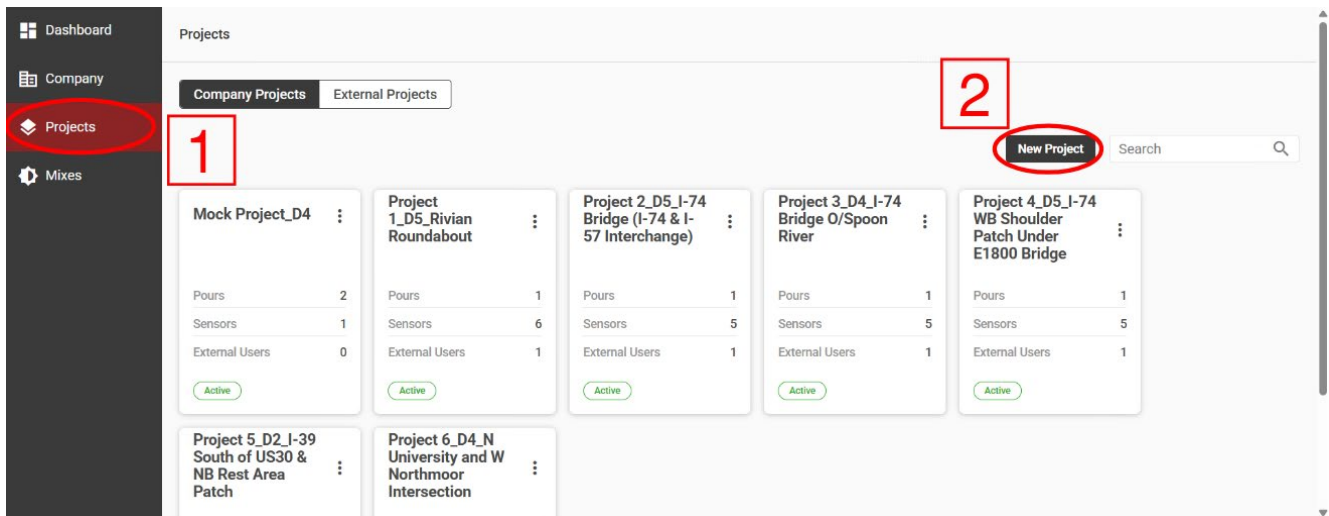


Figure 24. Screenshot. Wavelogix projects page.

Next, enter the project name and location, and select Create (Figure 25).

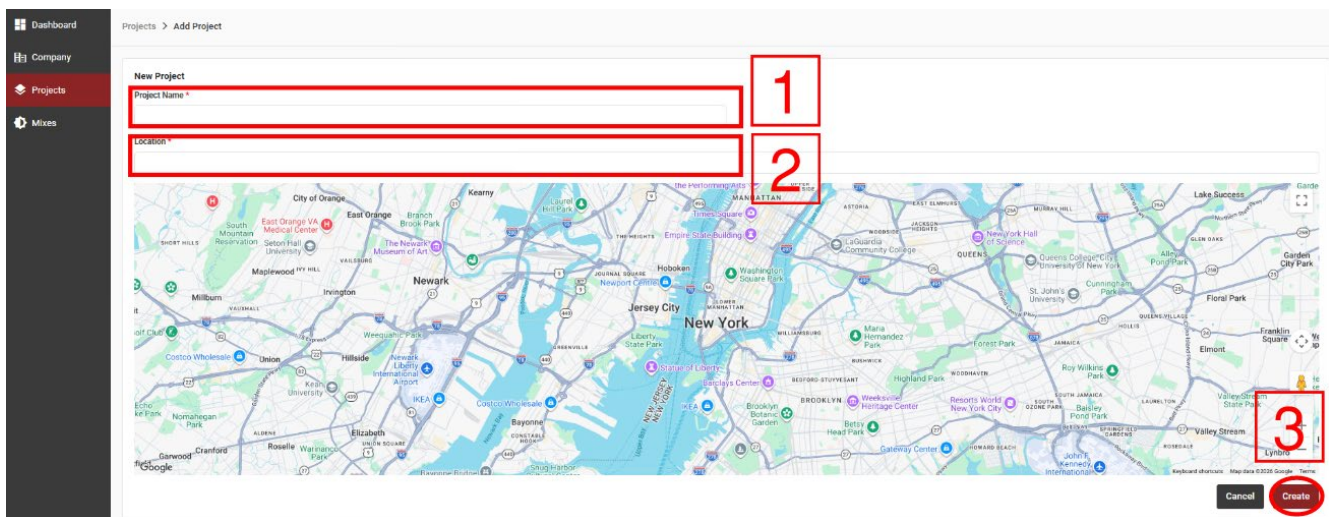


Figure 25. Screenshot. Creating a new project.

The new project tile should appear under the Projects tab. Select this tile to open the project information and add a pour (Figure 26 and Figure 27).

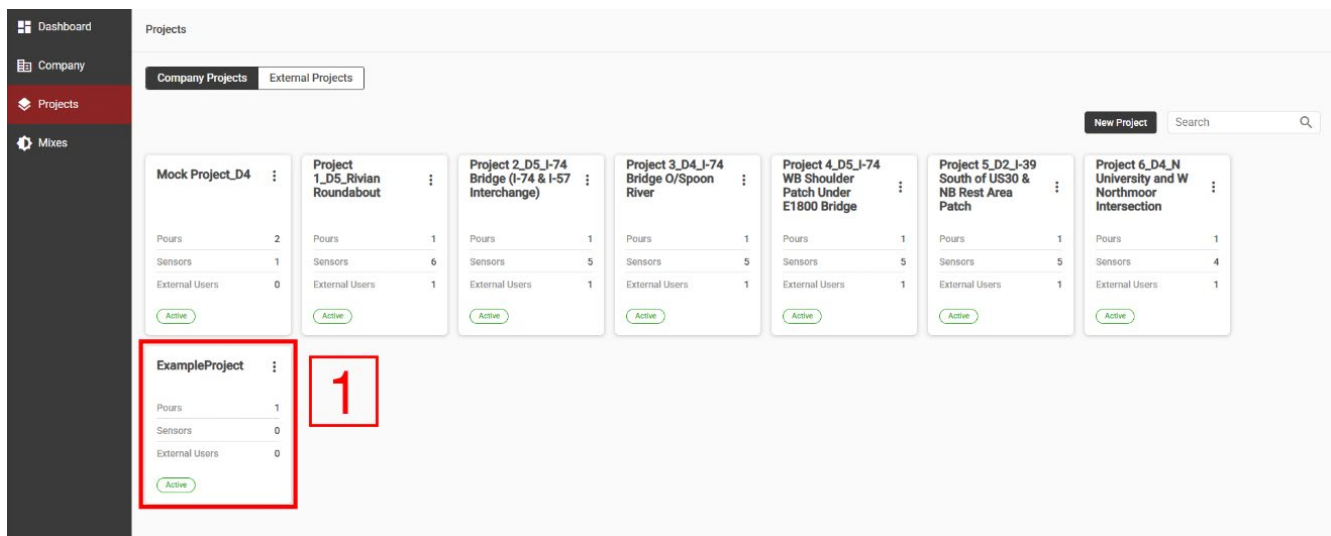


Figure 26. Screenshot. The project tile on the Projects page.

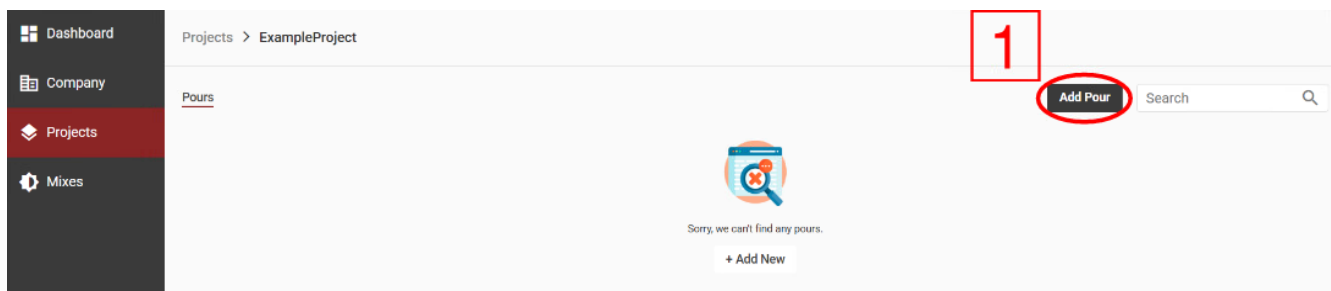


Figure 27. Screenshot. Initial project page for adding pour information.

First, enter names for the pour and the concrete mixture (Figure 28 and Figure 29).

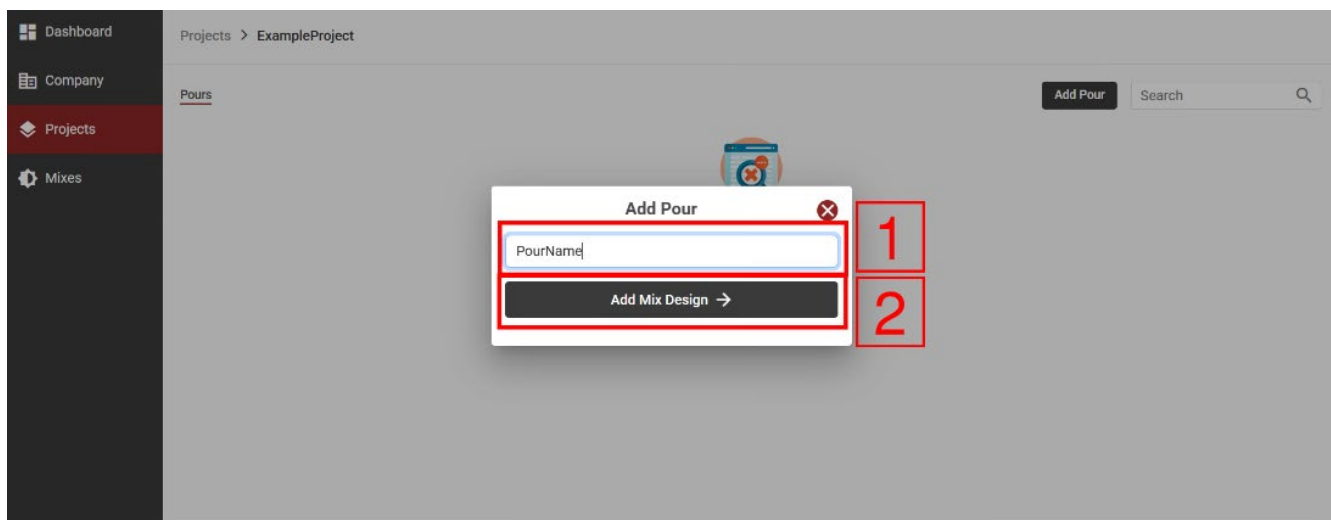


Figure 28. Screenshot. Naming the pour.

Figure 29. Screenshot. Naming the mix.

Next, add all concrete mixture ingredients to the pour information. Enter the cement, water, and coarse and fine aggregate quantities in this section. Figure 30 displays the actions available in the ingredients section: (1) indicates the ingredient information to be added, including a drop-down menu for the cement type; (2) displays the drop-down menu for changing the units; (3) displays the button to remove an ingredient from the list; (4) allows the ingredient to be renamed based on more specific information; (5) indicates the additional ingredients that can be added; (6) allows the user to select Next after all required information has been entered.

Figure 30. Screenshot. Adding the mix ingredients.

Next, enter the admixture information, followed by the slump, air content, and w/c ratio. If there are no admixtures, they can be removed using the minus signs (Figure 31 and Figure 32).

Projects > ExampleProject > Add Mix

Mix Template Search

✓ Set Mix Name

✓ Add Ingredients

3 Add Admixtures

Admixtures

✓ Air Entrainment

Select Water Reducer Type

Water Reducer

+ Accelerator

+ Air Entrainment

+ Water Reducer

+ Mono Siles

+ Retarder

+ Strength Enhancer

+ Other

Back

Next

4 Mix Statistics

5 Strength Specification

Figure 31. Screenshot. Entering information about the admixtures.

Projects > ExampleProject > Add Mix

Mix Template Search

✓ Set Mix Name

✓ Add Ingredients

✓ Add Admixtures

4 Mix Statistics

Slump

Air Content

Target W/C Ratio

Back

Next

5 Strength Specification

Figure 32. Screenshot. Entering the mix slump, air content, and w/c ratio.

Finally, enter the expected concrete strength at different time intervals. The time intervals can be added or edited as needed (Figure 33).

Dashboard > Projects > Project 'S22-09 South of 1030 & NB Reed Ave Patch' > RSPCCS002 > Mix Details > Add Mix

Mix Template Search

Set Mix Name

Add Ingredients

Add Admixtures

Mix Statistics

Strength Specification

Certification Strength

Days / Hours

PSI

Edit in Hours

Expected Mix Strength

Days / Hours

1 day / 24 hrs

PSI

3 days / 72 hrs

PSI

7 days / 168 hrs

PSI

14 days / 336 hrs

PSI

28 days / 672 hrs

PSI

Add

Submit

Save

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Figure 33. Screenshot. Expected concrete strength.

Once the pour is added to the project, it can be selected, and sensor and break-result information can be added (Figure 34).

Dashboard > Projects > ExampleProject

Pours

Add Pour

Search

#	Name	Concrete Mix	Created Date	Sensor	Status	Action
1	PourName	MixName	Jun 03, 2026	0	Active	

1

Figure 34. Screenshot. Pour is now added to the project.

To add a sensor, select New Sensor. The sensor ID can be found on the sensor tag (Figure 35). The tag can either be scanned to add the sensor, or the sensor ID can be entered manually. Each sensor should be given a distinct name for identification (Figure 36 and Figure 37).



Figure 35. Image. Sensor ID.

Dashboard
Company
Projects
Mixes

Projects > ExampleProject > PourName

PourName

Active Created: 06/03/26 Mix: MixName

Add Pour Info Manage Break Results Export Report

Sensors

Sensor Name	Sensor ID	Last Recorded	Live Strength	Status	Signal Strength	Action
 Sorry, we can't find any sensors. + Add New						

1 New Sensor

Figure 36. Screenshot. Adding a new sensor to the project.

Dashboard
Company
Projects
Mixes

Projects > ExampleProject > PourName

PourName

Active Created: 06/03/26 Mix: MixName

Add Pour Info Manage Break Results Export Report

Sensors

Sensor Name	Sensor ID	Last Recorded	Live Strength	Status	Signal Strength	Action
 Sorry, we can't find any sensors. + Add New						

1 Scan Sensor ID

2 Sensor ID *

3 Sensor Name *

4 Add

Figure 37. Screenshot. Either scan or type the sensor ID and name the sensor.

Break data are entered by selecting Manage Break Results. From there, the test method and sample are selected from the drop-down menus. The results are entered in the text box, designating the time the samples were broken, as well as the measured strength (Figure 38 and Figure 39).

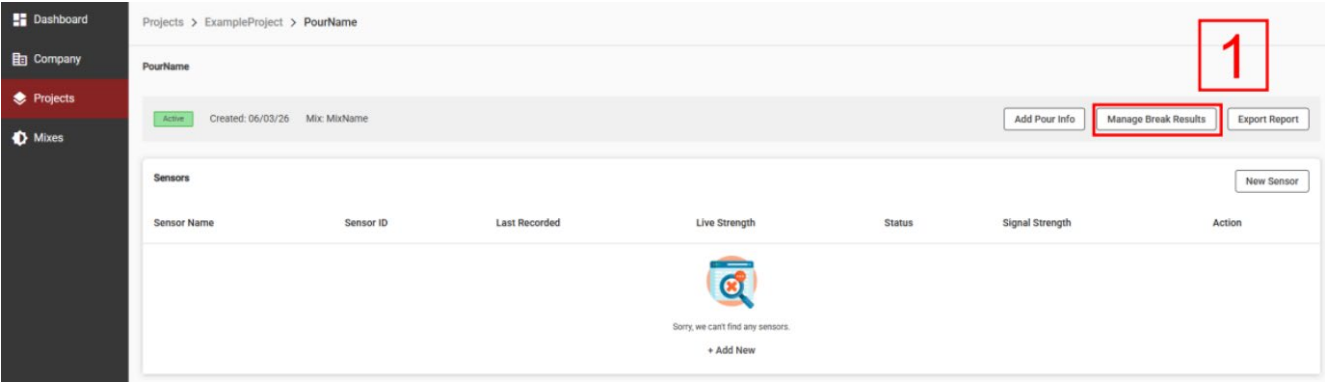


Figure 38. Screenshot. Adding the break results.

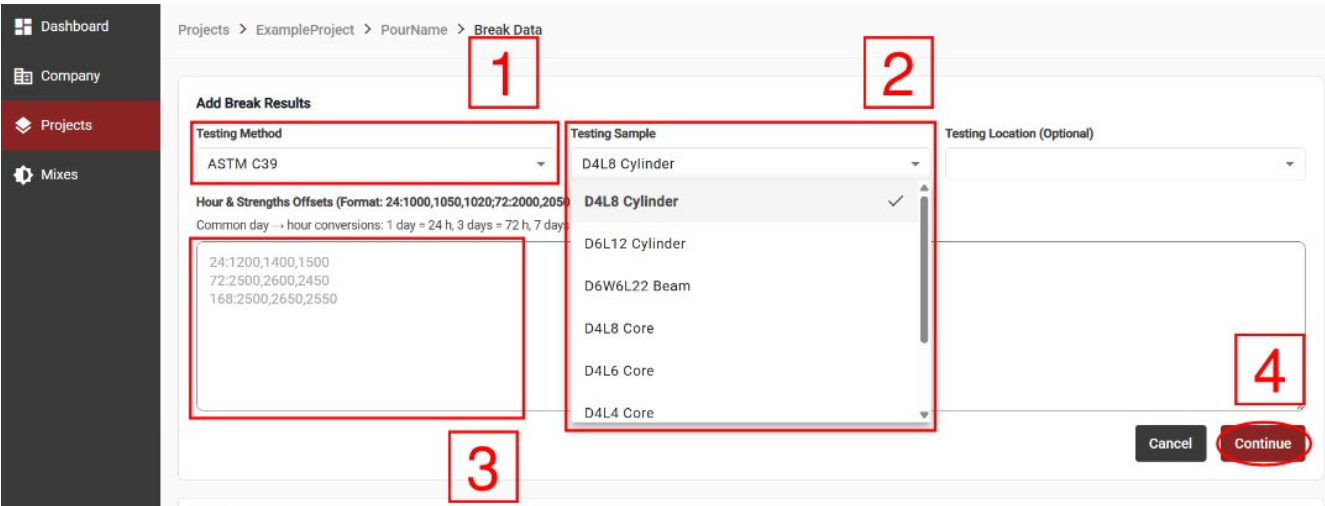


Figure 39. Screenshot. Select the test method, test sample, and enter the results.

CHAPTER 4: SENSOR DEPLOYMENT

PROJECT 1

The first project was in Normal, Illinois, within IDOT District 5. The existing T-intersection at Route 150 and College Avenue was being reconstructed into a roundabout. At this location, Route 150 is also known as the Rivian Motorway, so the project was referred to as the Rivian Roundabout. The sensors were deployed during one of the concrete pours of this project.

The concrete pour began at 9:30 a.m. on November 24, 2025. Six sensors were used in this project: three were embedded in the in-place concrete, one was placed in a half-filled 6 × 12 in. cylinder, one was placed in a fully filled 6 × 12 in. cylinder, and one was placed in a 6 × 6 × 21 in. beam specimen. The project was created on the Wavelogix platform on November 20, 2025, using the concrete mixture design summarized in Table 1 and designated 85PCCK017 (RMSK007).

Table 1. Project 1 Concrete Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	475	lb/cy	Type II
Water	32	gal/cy	
Coarse Aggregate	1,742	lb/cy	
Fine Aggregate	1,200	lb/cy	
Fly Ash	160	lb/cy	
Slump	4	in.	
Air Content	6.1%		
Target w/c Ratio	0.42		
Certification Strength	3,500	psi	At 14 days (336 hr)

On November 21, 2025, the site was analyzed for sensor placement. Proposed sensor locations were marked (Figure 40), and a stake was placed on the side of the road to support data loggers during the 28-day monitoring period. Additionally, a trench was dug outside the formwork to route the sensor cables to the data loggers without creating a tripping hazard (Figure 41).



Figure 40. Photo. Initially suggested sensor locations.



Figure 41. Photo. Trench for sensor cables.

On November 24, 2025, the sensors were nailed to the base concrete in place near the previously marked locations. The three sensors were placed in a triangular pattern with approximately 2 ft between adjacent sensors (Figure 42). Once the sensors were in place, the cables were routed beneath the formwork and through the trench. The ends of the cables connect to the data loggers, which were zip-tied to a post several feet from the side of the road to minimize inconvenience for workers (Figure 43).



Figure 42. Photo. Sensors nailed in place.



Figure 43. Photo. Data loggers secured to a post with zip ties.

When the crews placed concrete over the sensors, the research team cast cylinder and beam samples at the same time. Note that the same concrete that was placed over the sensors from the mixture truck was taken from the truck to make cylinders and beams. Ten 6 × 12 in. cylinders were cast for compressive testing at specified time intervals. Two additional 6 × 12 in. cylinders contained sensors at the bottom of the molds: one was filled completely, and the other was filled halfway. We cast one cylinder halfway because the sensor needs only 4 in. of concrete above it to estimate the compressive strength. Additionally, two 6 × 6 × 21 in. beam specimens were cast: one contained a sensor at the bottom, and the other was used for a three-point bending test. During casting, the cylinders were rodded but did not compact properly, resulting in slight honeycombing (Figure 44).



Figure 44. Photo. Honeycombing in the sample.

PROJECT 2

The second project was in Champaign, Illinois, within IDOT District 5. IDOT was reconstructing the I-74/I-57 interchange, including replacing the I-74 bridge. The sensors were placed in the bridge deck. The concrete pour began at 10:45 a.m. on February 27, 2026. Five sensors were used in this project: three were embedded in the bridge deck, one was placed in a half-filled 6 × 12 in. cylinder, and one was placed in a fully filled 6 × 12 in. cylinder. The project was created on the Wavelogix platform on February 26, 2026, with the mix design summarized in Table 2 and designated as 85PCCB009.

Table 2. Project 2 Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	463	lb/cy	Type II
Water	30.2	gal/cy	
Coarse Aggregate	1,422	lb/cy	CA-16
Fine Aggregate	1,233	lb/cy	FA-01
Slag	154	lb/cy	
Air Entrainment	2.8	oz/cy	
Water Reducer	28.3	oz/cy	High-Range
Retarder	24.4	oz/cy	
Superplasticizer	1.8	oz/cy	
Slump	5	in.	
Air Content	6.7%		
Target w/c Ratio	0.4		
Certification Strength	4,000	psi	At 14 days (336 hr)

Several days before the pour, the IDOT plans were analyzed for sensor placement. The sensors require a 4 in. clear concrete cover above their upper surfaces. The bridge deck slab is 8.25 in. thick and has two layers of rebar reinforcement. The bottom layer of rebar has 1 in. of clear cover from the underside of the slab, leaving sufficient height above for the sensors. Therefore, the sensors were secured to the bottom reinforcing layer with zip ties. The sensors were also positioned beneath openings in the upper reinforcing layer to avoid interference in sensor readings (Figure 45 and Figure 46).



Figure 45. Image. Sensor secured to the bottom reinforcement with zip ties.



Figure 46. Image. Three sensors placed in bridge deck.

The sensor cables were routed along the bottom of the slab and up the side of the form where they were connected to the data loggers. The data loggers were zip-tied to the outside of the form supports, which proved problematic (Figure 47). Within the first 24 hours, two of the three data loggers were damaged when workers walked along the narrow walkway adjacent to the formwork (Figure 48). When the test samples were collected 24 hours after the pour, the damaged data loggers were replaced. The replacement data loggers were zip-tied to the underside of the formwork supports, and no further damage occurred (Figure 49).



Figure 47. Image. Data loggers zip-tied to outside of formwork.



Figure 48. Image. Damaged data logger.



Figure 49. Image. Repositioned data loggers.

To pour the bridge deck, concrete trucks were positioned below the bridge on I-57, and the concrete was pumped to the deck. The test samples were made as the concrete was poured over the sensors. Ten 6 × 12 in. cylinders and two 6 × 6 × 21 in. beam specimens were cast for testing. Two cylinders with sensors at the bottom were also cast: one was filled completely, and the other was filled halfway.

Technical Difficulties

An issue occurred with the sensor in the half-filled cylinder after approximately 90 hours (3.75 days) of operation. At that point, the sensor status on the Wavelogix platform changed to Offline, and the data logger was replaced. After the data logger was replaced, the status changed to Ready rather than the expected Active status. This was problematic because the compressive data was not being collected. After troubleshooting with the Wavelogix director of product development, it was determined that this is a rare issue that occurs only 1% of the time. The data logger and sensor pair failed to recall that the sensor was embedded in concrete. Consequently, the data logger was not transmitting the strength data to the Wavelogix platform. As a workaround, the Wavelogix director of product development manually initiated data collection approximately every 2 hours. This data collection resumed 140 hours (5.8 days) after the pour.

Temperature data collection was not affected in the same way as the strength collection. There was a lull between 95 and 126 hours, but otherwise, the temperature data was collected very frequently, several times per hour throughout the entire project. This collection frequency was unusual because sensors typically collect data more frequently at the beginning of the project, when concrete strength changes more rapidly, and less frequently as the concrete ages. This frequent collection also occurred in Embedded Sensor 1, depleting the data-logger batteries and requiring their replacement between 7 and 14 days after the pour.

After the data loggers were replaced, Embedded Sensor 3 showed poor signal strength. It was a concern that the placement of data loggers below the formwork resulted in this reading. Further troubleshooting showed that the most recent signal reading was zero, which was below the accepted range, resulting in a poor status. However, the Wavelogix indicated that the zero value was just an isolated erroneous reading and that subsequent measurements were expected to show a normal signal and resume data transmission. This did indeed occur, and data collection resumed normally.

The sensor in the half-filled cylinder continued to collect temperature data and was disconnected after 695 hours (29 days). However, this sensor did not collect any strength data after 480 hours (20 days). Therefore, the data analysis is missing the 28-day data points from this sensor.

PROJECT 3

The third project was in IDOT District 4, where I-74 crosses Spoon River. The sensors were placed in the eastbound I-74 bridge deck during concrete placement. The concrete was placed on April 7, 2026, at 9:10 a.m. Five sensors were used in this project: three were embedded in the bridge deck, one was placed in a 6 × 12 in. cylinder that was half-cast, and one was placed in a 6 × 12 in. cylinder that was

fully cast. The project was created on the Wavelogix platform on April 6, 2026, using the mix design presented in Table 3, which was designated 84PCC340G.

Table 3. Project 3 Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	490	lb/cy	Type II
Water	30.3	gal/cy	
Coarse Aggregate	1,328	lb/cy	CA-111
Coarse Aggregate	493	lb/cy	CA-161
Fine Aggregate	1,245	lb/cy	FA-01
Fly Ash	125	lb/cy	Class C
Air Entrainment	0.85	oz/cy	DRAVAIR140
Water Reducer	4.5	oz/cy	Mid-range; MIRA 95
Slump	5.5	in.	
Air Content	6.1%		
Target w/c Ratio	0.41		
Certification Strength	4,000	psi	14 days (336 hr)

The setup for Project 3 was similar to Project 2. On April 6, 2026, the sensors were zip-tied to the bottom layer of rebar, and the cords were run along the bottom of the deck, as shown in Figure 50. This time, however, the cords passed through a gap in the side of the formwork rather than over the top (Figure 51). The sensor cords were then connected to the data loggers, which were then zip-tied to the underside of the formwork supports (Figure 52).



Figure 50. Image. Sensors zip-tied to rebar.

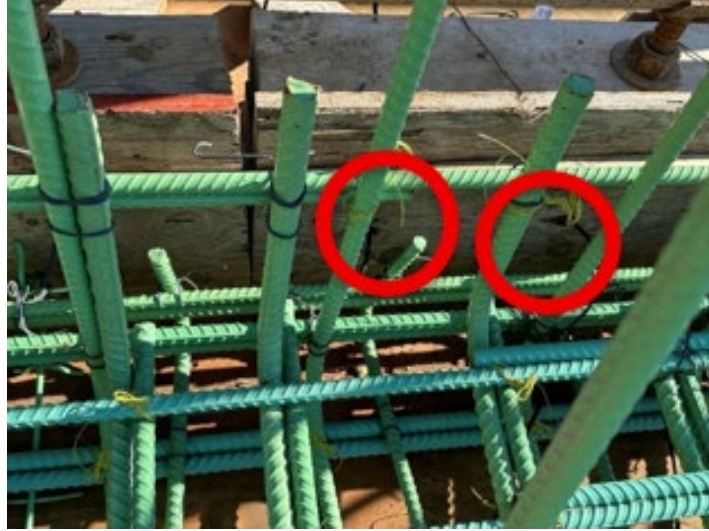


Figure 51. Image. Sensor cords going through the formwork.



Figure 52. Image. Data loggers zip-tied to formwork supports.

When the concrete trucks arrived, they backed down a slope to the riverbank, where the concrete was pumped up to the bridge deck, as shown in Figure 53. After the concrete was poured over the sensors in the bridge deck, test specimens were cast along the riverbank using concrete from the same truck. This time, 4 × 8 in. cylinders were used for testing. A total of 15 4 × 8 in. cylinders and two 6 × 6 × 21 in. beams were cast for testing, along with two 6 × 12 in. cylinders with bottom sensors,

one fully cast and the other half-cast. The test specimens were compacted using a concrete vibrator, as shown in Figure 54. A vibrator was used only in the District 4 projects, as QA/QC samples were also prepared using the vibrator for those projects.



Figure 53. Image. Concrete truck down the slope to pump concrete to the bridge deck.



Figure 54. Image. Compacting the test specimens with a concrete vibrator.

PROJECT 4

This project was in IDOT District 5, near Carlock, Illinois. The sensors were placed in a shoulder patch on westbound I-74 under the E 1800 North Rd Bridge. The concrete was placed on May 4, 2026, at 2:40 p.m. Five sensors were used in the project: three were embedded in the shoulder patch, one was placed in a fully cast 6 × 12 in. cylinder, and one was placed in a partially cast 6 × 12 in. cylinder. The project was created on the Wavelogix platform on the morning of May 4, 2026, using the mix design presented in Table 4, which was designated 85PCCK010 PP-1.

Table 4. Project 4 Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	535	lb/cy	Type IL
Water	32.6	gal/cy	
Coarse Aggregate	1,791	lb/cy	
Fine Aggregate	1,121	lb/cy	
Fly Ash	180	lb/cy	
Air Entrainment	0.85	oz/cy	DRAVAIR140
Water Reducer	225	oz/cy	Low-range; ZYLA630
Water Reducer	153	oz/cy	High-Range; Superplasticizer
Slump	4	in.	
Air Content	5.5%		
Target w/c Ratio	0.33		
Certification Strength	3,200	psi	2 days (48 hr)

The existing shoulder was removed on May 4, 2026, so setting up the sensors in advance was not possible. After the shoulder had been removed and the formwork installed, the sensors were placed. The sensors were nailed to the ground to secure them in position. Because the rebar was sufficiently elevated above the ground, Sensor 2 was placed directly beneath it, as shown in Figure 55. Sensor 3 was placed at least 2 ft from Sensor 2 to ensure the rebar did not cause interference (Figure 56). The cords passed beneath the formwork, and a small trench was dug to bury them in the ground (Figure 57). The cords were connected to the data loggers, which were zip-tied to a high-tension barrier terminal (Figure 58).



Figure 55. Image. Sensor 2 under the rebar.



Figure 56. Image. Sensors nailed in place.



Figure 57. Image. Sensor cords buried outside of the formwork.



Figure 58. Image. Data loggers zip-tied to high-tension barrier terminal.

The test samples were prepared in accordance with ASTM C31. Fifteen 4 × 8 in. cylinders and two 6 × 6 × 21 in. beams were cast for testing, along with two 6 × 12 in. cylinders with sensors (Figure 59).



Figure 59. Image. Casting samples.

PROJECT 5

This project was in IDOT District 2, in Paw Paw, Illinois. Concrete patching was being performed on I-39, including at the northbound Willow Creek Rest Area. The sensors were placed in a patch in the rest area automobile parking lot. The concrete was placed on May 14, 2026, at 11:40 a.m. Five sensors were used in the project: three were embedded in the patch, one was placed in a fully cast 6 × 12 in. cylinder, and one was placed in a partially cast 6 × 12 in. cylinder. The project was created on the Wavelogix platform on May 13, 2026, using the mix design presented in Table 5, which was designated 83PCC110S PP-2.

Table 5. Project 5 Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	625	lb/cy	Type IL
Water	31	gal/cy	
Coarse Aggregate	1,782	lb/cy	CM11 R-T
Fine Aggregate	1,116	lb/cy	FM02 F-S
Slag	110	lb/cy	
Air Entrainment	0.6	oz/cwt	
Water Reducer	5	oz/cwt	High-range
Retarder	1	oz/cwt	SikaTard 10
Slump	4	in.	
Air Content	6%		
Target w/c Ratio	0.352		
Certification Strength	3,200	psi	2 days (48 hr)

The sensors were nailed to the ground where there was a gap in the reinforcement above them (Figure 60). The cords ran along the bottom of the patch and up the side of the existing concrete. The grassy area where the data loggers were zip-tied to a post was approximately 3 ft away. The cords were zip-tied at the bottom of the post to reduce the risk of someone tripping over them, as shown in Figure 61.



Figure 60. Image. Sensors placed in patch.



Figure 61. Image. Project setup.

The test samples were prepared in accordance with ASTM C31. Fifteen 4 × 8 in. cylinders and two 6 × 6 × 21 in. beams were cast for testing, along with two 6 × 12 in. cylinders with sensors.

PROJECT 6

The final project was in IDOT District 4, in Peoria, Illinois. The sensors were placed during a staged pavement replacement at the intersection of North University Street and West Northmoor Road. The concrete was placed on May 27, 2026, at 7:30 a.m. Four sensors were used in the project: three were embedded in the pavement, and one was placed in a concrete-half-cast cylinder. Due to a shortage of data loggers, a sensor was not placed in a fully cast 6 × 12 in. cylinder. The project was created on the Wavelogix platform on May 26, 2026, using the mix design presented in Table 6, which was designated 84PCC061P-21605.

Table 6. Project 6 Mix Design Summary

Ingredient/Characteristic	Value	Unit*	Notes
Cement	435	lb/cy	Type IL
Water	29.2	gal/cy	
Coarse Aggregate	1,821	lb/cy	CA-11
Fine Aggregate	1,271	lb/cy	FA-01
Fly Ash	145	lb/cy	Class C
Air Entrainment	1.1	oz/cy	AEA 14 Sika
Water Reducer	4	oz/cy	Low-range
Retarder	2	oz/cy	SikaTard 440
Slump	5.5	in.	
Air Content	6%		
Target w/c Ratio	0.419		
Certification Strength	3,500	psi	14 days (336 hr)

The pavement included dowel bars at the transverse joints (Figure 62). The sensors were nailed to the ground in a row in one of the spaces between dowel bars. The cords were running along the ground while in the pavement space. The cords then passed beneath the formwork and were buried in the ground outside the pavement until they were connected to the data loggers. The data loggers were zip-tied to a post between the lanes of traffic (Figure 63).



Figure 62. Image. Dowel bars ready for concrete pour.



Figure 63. Image. Sensor setup.

The test samples were made and compacted using a concrete vibrator. Fifteen 4 × 8 in. cylinders and two beams were cast for testing, along with the 6 × 12 in. half-cast cylinder with the sensor in the bottom.

CHAPTER 5: LABORATORY TESTS

OVERVIEW

For each project, three properties of the concrete were measured: compressive strength, flexural strength, and Young's Modulus. These were measured at specific time intervals. The compressive strength and Young's Modulus were measured/calculated at 1, 3, 7, 14, and 28 days, and the flexural strength at one day (24 hours). All sensor data were exported from the Wavelogix platform, and the values closest to each specified concrete age were used.

The laboratory compressive strength was measured directly (Figure 64), and Young's Modulus was calculated according to the following ACI 318 for normal-weight concrete. Young's Modulus was initially calculated in psi and then converted to ksi. (1 psi = 0.001 ksi).

$$E_c = 57,000\sqrt{f'_c}$$

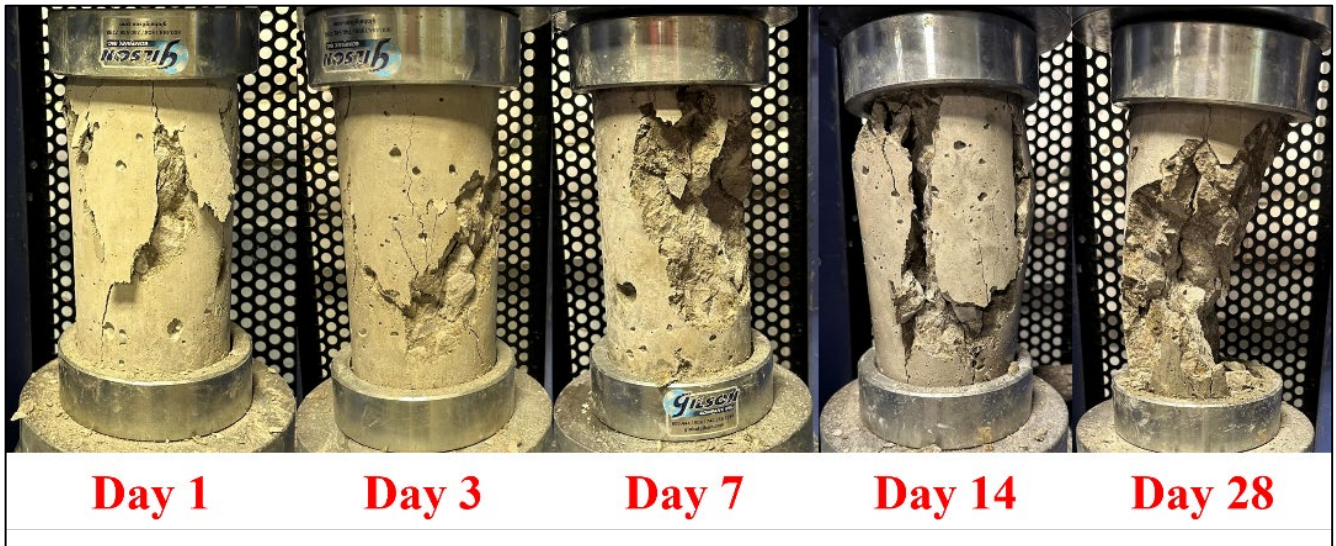


Figure 64. Image. Crushed cylinders for Project 4.

For the flexural strength (M_R), $6 \times 6 \times 21$ in. beams in the lab were broken in accordance with ASTM C78, or the 3-point bending test (Figure 65). The flexural strength in Wavelogix was estimated based on the following ACI 330 equation for normal-weight concrete. (Wavelogix, 2025).

$$M_R = 2.3 \times (f'_c)^{2/3}$$



Figure 65. Image. 6 × 6 × 21 in. beam split during 3-point bending test.

PROJECT 1

The following tables contain the raw data collected from Project 1. Table 7 displays the compressive strength in psi of the laboratory tests (LT), the average of the lab tests, and the recorded strength of each sensor.

Table 7. Compressive Strength in psi (Project 1)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast	Beam Sensor
24	2359	2437	2398	1766	1640	1655	1770	1680	1633
72	3513	3451	3482	2856	2867	2872	2984	2879	2735
168	4327	4224	4276	3888	3987	4073	3967	3914	3763
336	4259	4179	4219	4649	4738	4764	4626	4607	4471
672	4828	5778	5303	5272	5342	5418	5269	5110	5132

Table 8 displays the flexural strength in psi of the laboratory test and the sensor readings at 24 hours.

Table 8. Flexural Strength in psi (Project 1)

Age (hr)	LT	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast	Beam Sensor
24	416	336	320	322	337	325	319

Table 9 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 9. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 1)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast	Beam Sensor
24	2768	2814	2791	2395	2308	2319	2398	2336	2303
72	3378	3348	3363	3046	3052	3055	3114	3058	2981
168	3749	3705	3727	3554	3599	3638	3590	3566	3497
336	3720	3685	3702	3886	3923	3934	3877	3869	3811
672	3961	4333	4147	4139	4166	4196	4138	4075	4083

PROJECT 2

The following tables contain the raw data collected from Project 2. Table 10 displays the compressive strength in psi of the laboratory tests, the average of the lab tests, and the recorded strength of each sensor. Data for the partially cast cylinder at 672 hours were unavailable because the sensor malfunctioned.

Table 10. Compressive Strength in psi (Project 2)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	2311	2289	2300	2131	2070	1856	1967	2000
72	3174	3425	3300	3728	3711	3592	3501	3513
168	4219	4635	4427	4854	4440	4347	4647	4590
336	5095	4606	4851	5516	5153	5096	5386	5540
672	5184	5808	5496	6141	5755	5713	6014	-

Table 11 displays the flexural strength in psi of the laboratory tests, the average of the lab tests, and the sensor readings at 24 hours.

Table 11. Flexural Strength in psi (Project 2)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	389	324	357	381	374	347	361	365

Table 12 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 12. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 2)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	2740	2727	2734	2631	2593	2456	2528	2549
72	3211	3336	3274	3480	3472	3416	3373	3378
168	3702	3881	3791	3971	3798	3758	3886	3862
336	4068	3869	3969	4233	4092	4069	4183	4243
672	4104	4344	4224	4467	4324	4308	4420	-

PROJECT 3

The following tables contain the raw data collected from Project 3. Table 13 displays the compressive strength in psi of the laboratory tests, the average of the lab tests, and the recorded strength of each sensor.

Table 13. Compressive Strength in psi (Project 3)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	2139	2191	2282	2204	1705	1871	1754	1672	1701
72	3866	3746	4002	3871	3043	3382	3264	3070	3062
168	5072	5451	5069	5198	4170	4511	4432	4137	4231
336	6194	6012	6247	6151	5158	5158	5092	4792	4910
672	7121	7132	6943	7065	5500	5736	5681	5402	5523

Table 14 displays the flexural strength in psi of the laboratory tests, the average of the lab tests, and the sensor readings at 24 hours.

Table 14. Flexural Strength in psi (Project 3)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	349	285	317	328	349	335	324	328

Table 15 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 15. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 3)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	2636	2668	2723	2676	2354	2466	2387	2331	2351
72	3544	3489	3606	3546	3144	3315	3256	3158	3154
168	4060	4208	4058	4109	3681	3828	3777	3666	3708
336	4486	4420	4505	4470	3973	4094	4067	3946	3994
672	4810	4814	4750	4791	4227	4317	4296	4189	4236

PROJECT 4

The following tables contain the raw data collected from Project 4. Table 16 displays the compressive strength in psi of the laboratory tests, the average of the lab tests, and the recorded strength of each sensor. Note that this project used a Class PP-1 patching mix.

Table 16. Compressive Strength in psi (Project 4)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	3596	3591	3669	3619	2628	2390	2410	2565	2482
48	—	—	—	—	3078	3472	3472	3640	3622
72	4549	4970	4359	4626	4314	4068	4101	4261	4267
168	5456	5242	5364	5354	5401	5285	5366	5510	5532
336	5155	6181	5668	5668	6199	6084	6213	6306	6361
672	5997	6696	6604	6432	6910	6810	6898	7020	7056

Table 17 displays the flexural strength in psi of the laboratory tests, the average of the lab tests, and the sensor readings at 24 hours.

Table 17. Flexural Strength in psi (Project 4)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	500	506	503	438	411	413	431	422

Table 18 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 18. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 4)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	3418	3416	3453	3429	2922	2787	2798	2887	2840
48	—	—	—	—	3470	3359	3359	3439	3430
72	3845	4019	3763	3875	3744	3636	3650	3721	3723
168	4210	4127	4175	4171	4189	4144	4175	4231	4240
336	4093	4481	4291	4288	4488	4446	4493	4526	4546
672	4414	4664	4632	4570	4738	4704	4734	4776	4788

PROJECT 5

The following tables contain the raw data collected from Project 5. Table 19 displays the compressive strength in psi of the laboratory tests, the average of the lab tests, and the recorded strength of each sensor. Note that this project used a Class PP-2 patching mix.

Table 19. Compressive Strength in psi (Project 5)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	3375	3981	4011	3789	2782	2836	3158	2949	2997
72	4649	4403	4579	4544	4879	5091	5524	5215	5231
168	5282	5350	5305	5312	6102	6176	6645	6418	6458
336	5836	5851	5898	5862	6776	6831	7221	7070	7129
672	5851	6653	5880	6128	7372	7415	7792	7648	7684

Table 20 displays the flexural strength in psi of the laboratory tests, the average of the lab tests, and the sensor readings at 24 hours.

Table 20. Flexural Strength in psi (Project 5)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	593	587	590	455	461	495	473	478

Table 21 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 21. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 5)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Full Cast	Cylinder Half Cast
24	3311	3596	3610	3506	3006	3035	3203	3095	3120
72	3886	3782	3857	3842	3981	4067	4236	4116	4123
168	4142	4169	4152	4154	4453	4479	4646	4566	4581
336	4355	4360	4377	4364	4692	4711	4844	4793	4813
672	4360	4649	4371	4460	4894	4908	5032	4985	4997

PROJECT 6

The following tables contain the raw data collected from Project 6. Table 22 displays the compressive strength in psi of the laboratory tests, the average of the lab tests, and the recorded strength of each sensor.

Table 22. Compressive Strength in psi (Project 6)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Half Cast
24	3027	3061	2940	3009	1601	1625	1716	1612
72	4337	4257	4456	4350	2782	2748	2988	2637
168	5342	5232	5417	5330	3893	3946	4075	3517
336	6206	6229	6022	6152	4617	4666	4783	4242
672	6684	6781	6591	6685	5260	5295	5405	4909

Table 23 displays the flexural strength in psi of the laboratory tests, the average of the lab tests, and the sensor readings at 24 hours.

Table 23. Flexural Strength in psi (Project 6)

Age (hr)	LT 1	LT 2	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Half Cast
24	628	556	592	315	318	330	316

Table 24 displays Young's Modulus in ksi of the laboratory tests, the average of the lab tests, and the sensor readings.

Table 24. Young's Modulus (According to ACI 318 for Normal Weight Concrete) in ksi (Project 6)

Age (hr)	LT 1	LT 2	LT 3	LT Avg	Embed Sensor 1	Embed Sensor 2	Embed Sensor 3	Cylinder Half Cast
24	3136	3153	3090	3127	2281	2298	2361	2289
72	3754	3719	3805	3759	3006	2988	3116	2927
168	4166	4123	4195	4161	3556	3581	3639	3380
336	4490	4498	4423	4471	3873	3894	3942	3712
672	4660	4694	4627	4660	4134	4148	4191	3994

CHAPTER 6: DATA ANALYSIS

OVERVIEW

Several analytical methods were used. The first analyses presented are plots of compressive strength, flexural strength, and Young’s Modulus over time. These plots are followed by linear regression analyses comparing laboratory and sensor data and by Bland–Altman plots.

Additional analyses were conducted using two-sample t-tests that assumed unequal variances. The small number of laboratory specimens limited the reliability of these tests. The small sample sizes made the results sensitive to variability within the data. Larger sample sizes likely would have produced more reliable estimates. Because of these limitations, the t-test results were omitted from this report.

COMPRESSIVE STRENGTH COMPARISON BETWEEN SENSOR AND LAB DATA

The sensor data were plotted continuously, with compressive strength on the y-axis and time on the x-axis. The resulting graph resembles a maturity curve. The sensor range is calculated by taking the maximum sensor data value at a given time and the minimum sensor data value at the same time across all sensors. The maximum and minimum strength values are plotted with their corresponding times in a smooth curve. The area between the two curves was shaded blue to represent the sensor range. The average of the sensor values at the specific time intervals was also calculated and plotted as a smooth line, presented in orange. Finally, the laboratory compressive-strength test results were plotted as red dots. The compressive strength is measured in psi, and the time is measured in hours. Compressive-strength comparisons for all six projects are presented in Figure 66 through Figure 71.

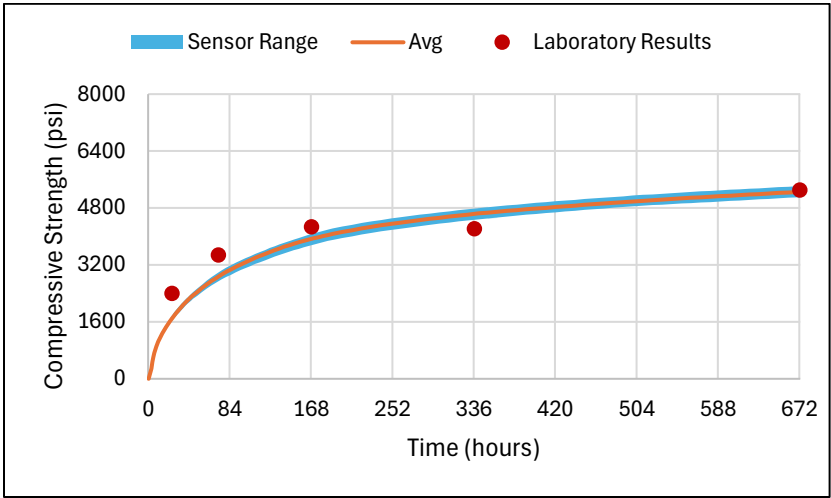


Figure 66. Graph. Project 1 compressive-strength comparison.

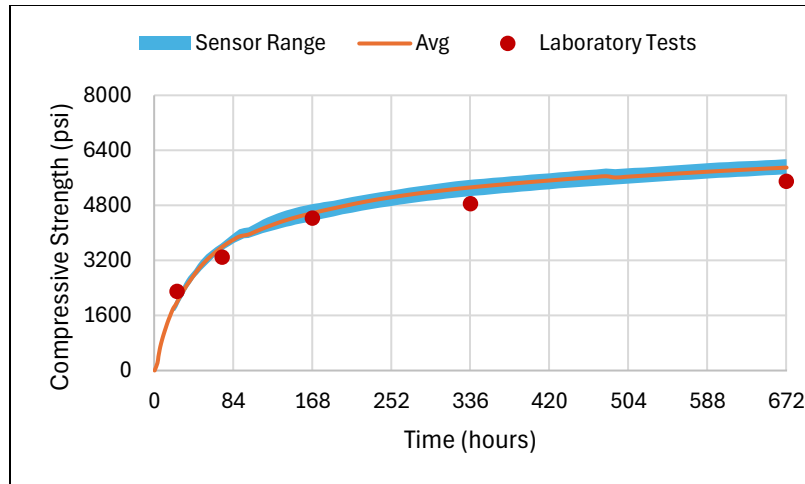


Figure 67. Graph. Project 2 compressive-strength comparison.

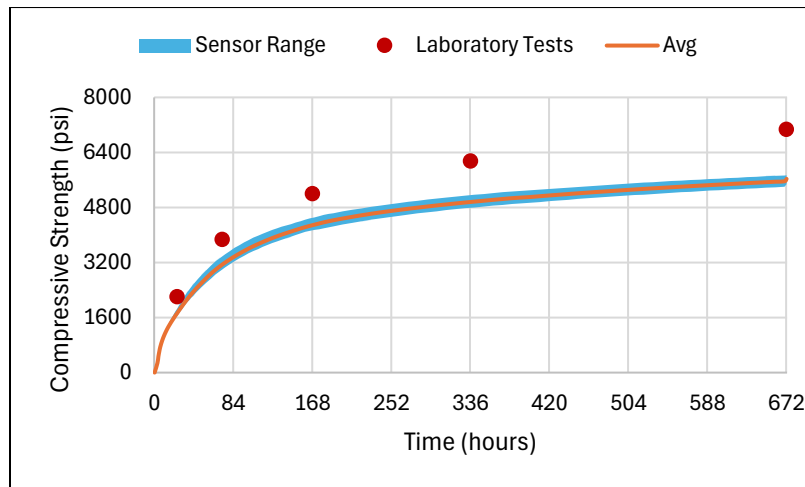


Figure 68. Graph. Project 3 compressive-strength comparison.

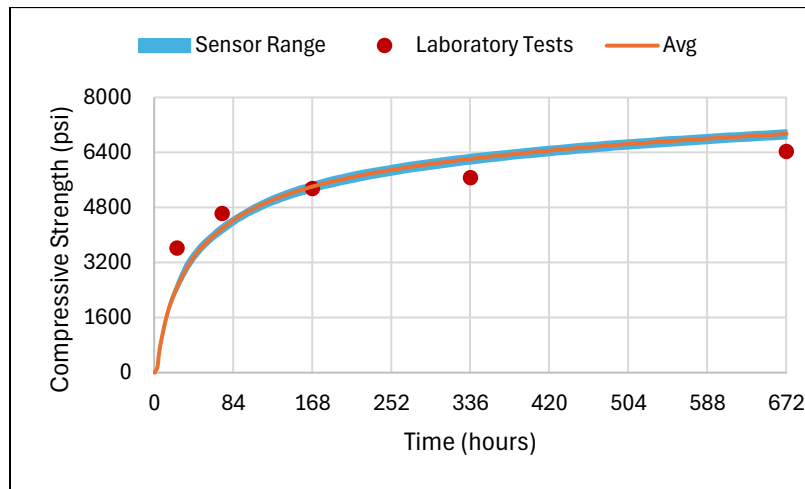


Figure 69. Graph. Project 4 compressive-strength comparison.

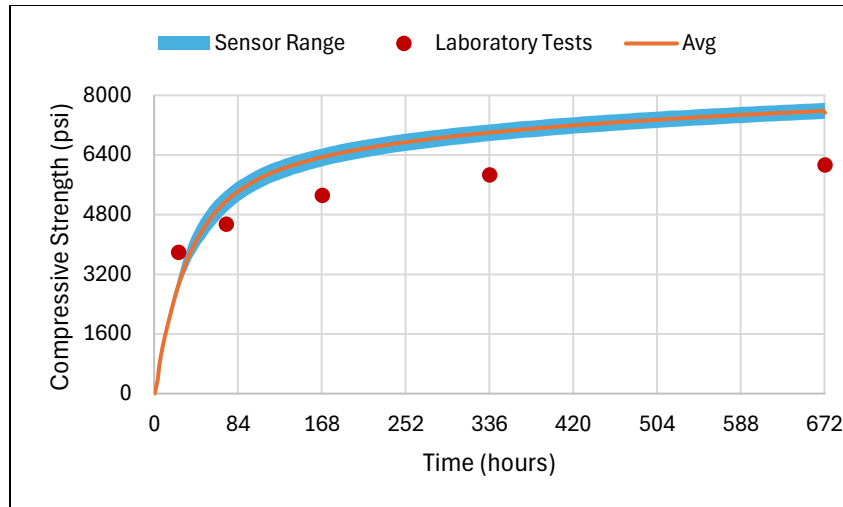


Figure 70. Graph. Project 5 compressive-strength comparison.

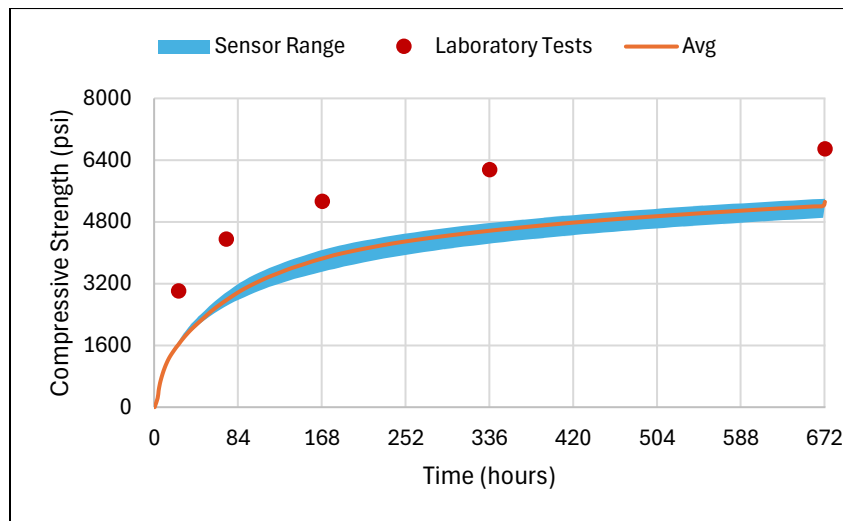


Figure 71. Graph. Project 6 compressive-strength comparison.

For projects 1, 2, and 4, the laboratory-tested data generally follows the sensor-measured maturity curve; however, for projects 3 and 6, the sensor-measured strength underpredicts, and for project 5, the sensor-measured strength overpredicts the maturity curve.

FLEXURAL STRENGTH COMPARISON BETWEEN SENSOR AND LAB DATA

The flexural graphs were prepared in the same manner as the compressive-strength graphs. Flexural strength in psi is on the y-axis, and time in hours is on the x-axis. There are only laboratory results for 1-day (24-hour) beam tests. The sensor range was shaded blue, the sensor average is plotted as an orange line, and the lab result is presented as a red dot. Flexural-strength comparisons for all six projects can be found in Figure 72 through Figure 77.

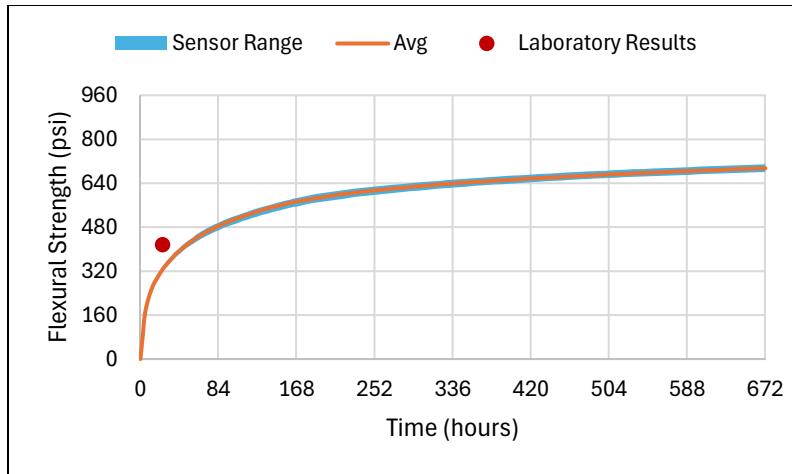


Figure 72. Graph. Project 1 flexural-strength comparison.

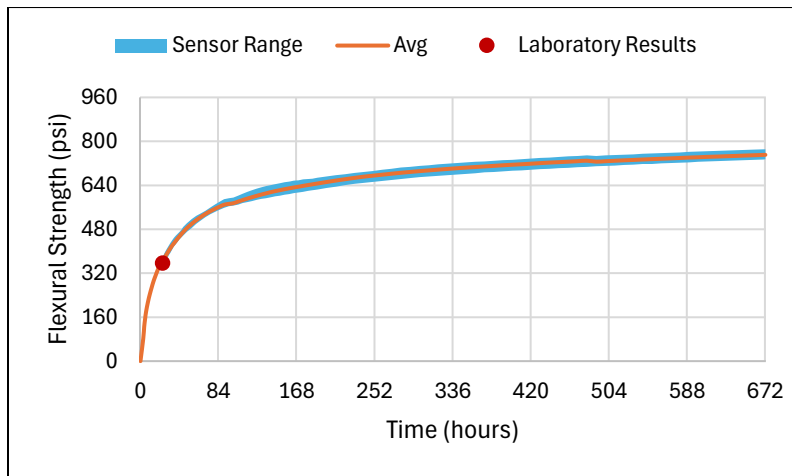


Figure 73. Graph. Project 2 flexural-strength comparison.

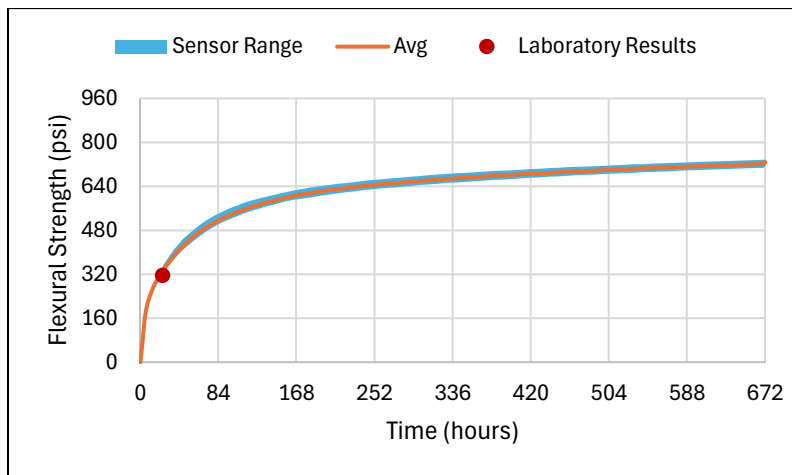


Figure 74. Graph. Project 3 flexural-strength comparison.

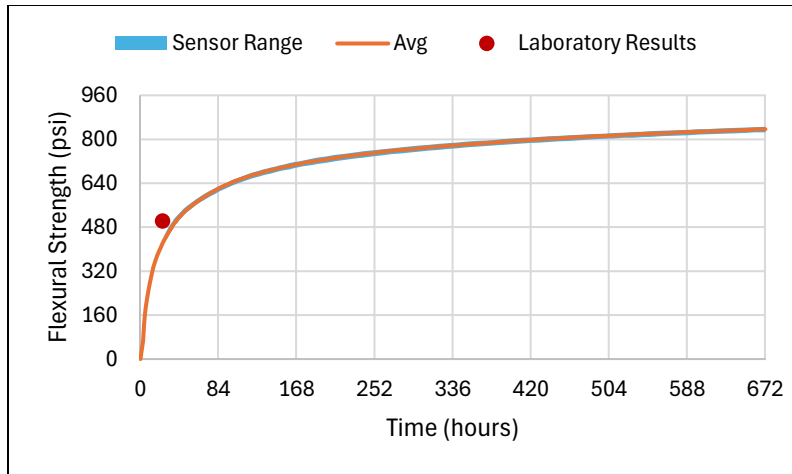


Figure 75. Graph. Project 4 flexural-strength comparison.

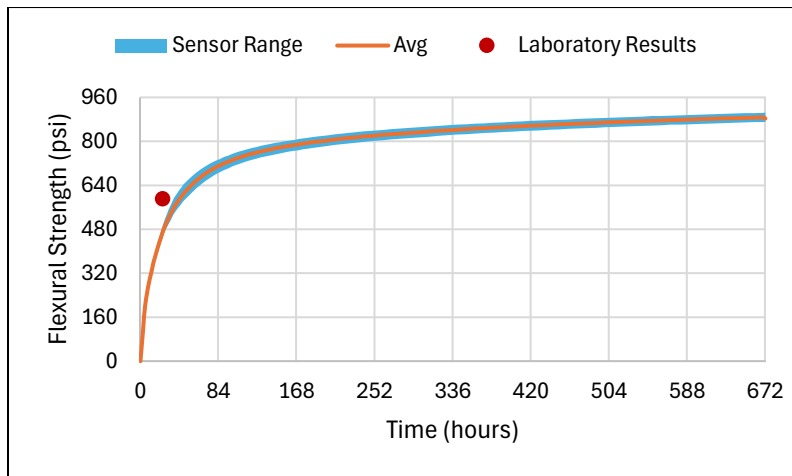


Figure 76. Graph. Project 5 flexural-strength comparison.

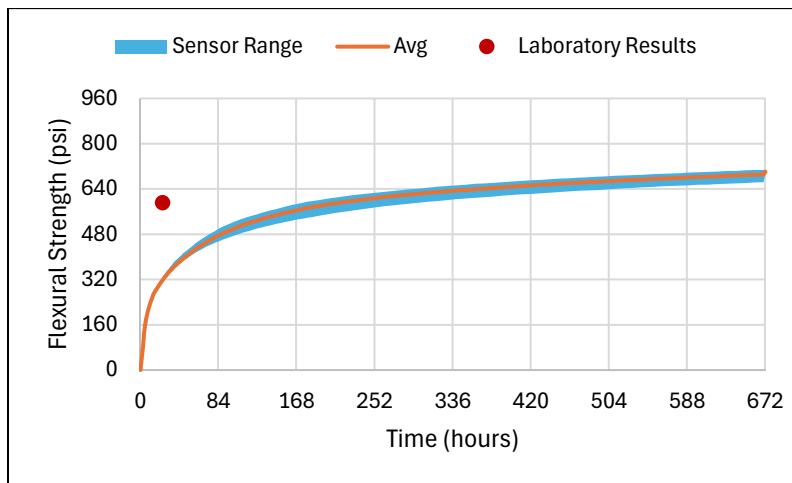


Figure 77. Graph. Project 6 flexural-strength comparison.

The laboratory results fell within the sensor range in Projects 2 and 3 and exceeded the sensor readings in Projects 1, 4, 5, and 6.

YOUNG’S MODULUS COMPARISON BETWEEN SENSOR AND LAB DATA

The graphs for Young’s Modulus were also plotted in a manner similar to the compressive-strength graphs. Young’s Modulus is presented on the y-axis in psi, and time is on the x-axis in hours. The sensor range is shaded in blue, the sensor average is an orange line, and the lab data is plotted as red circular dots. Young’s Modulus comparisons for all six projects can be found in Figure 78 through Figure 83.

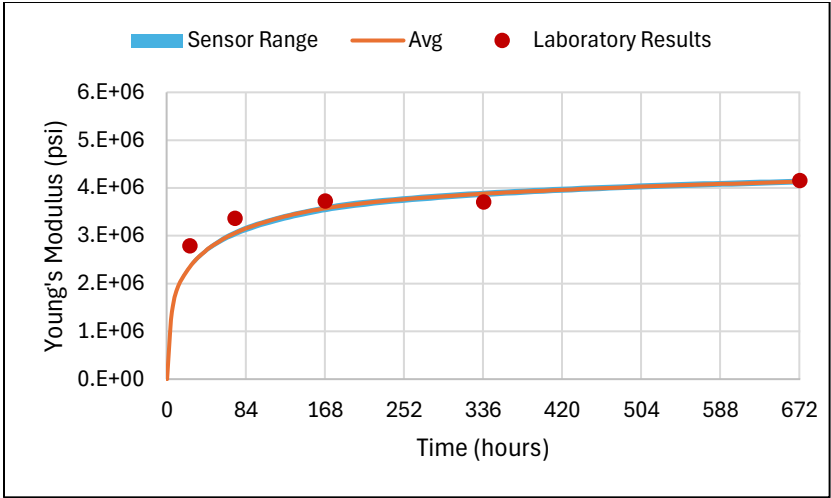


Figure 78. Graph. Project 1 Young’s Modulus comparison.

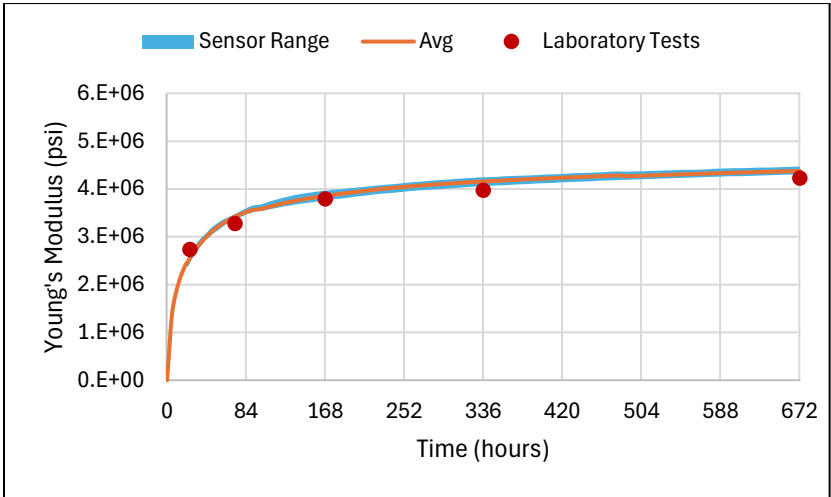


Figure 79. Graph. Project 2 Young’s Modulus comparison.

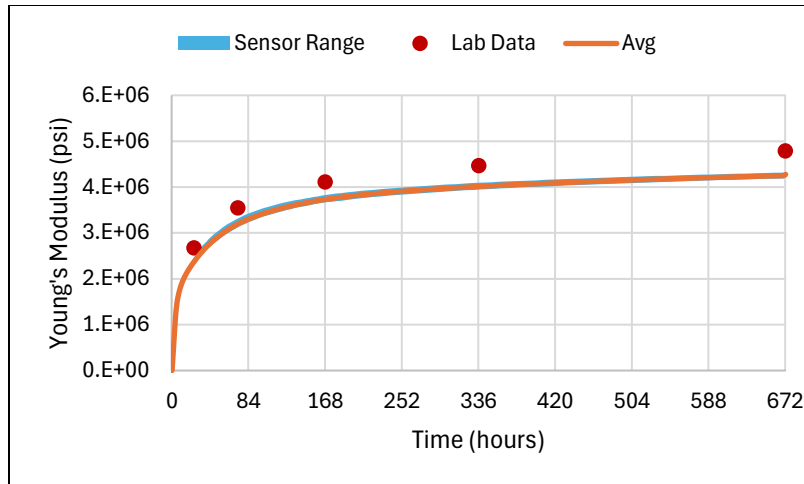


Figure 80. Graph. Project 3 Young's Modulus comparison.

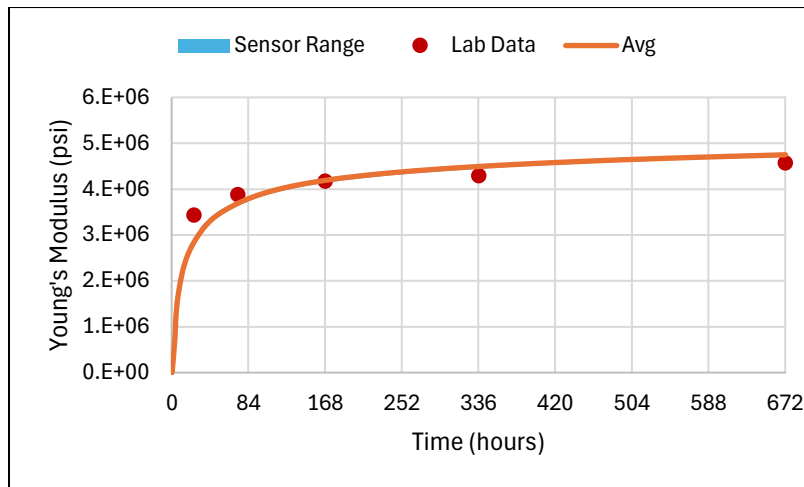


Figure 81. Graph. Project 4 Young's Modulus comparison.

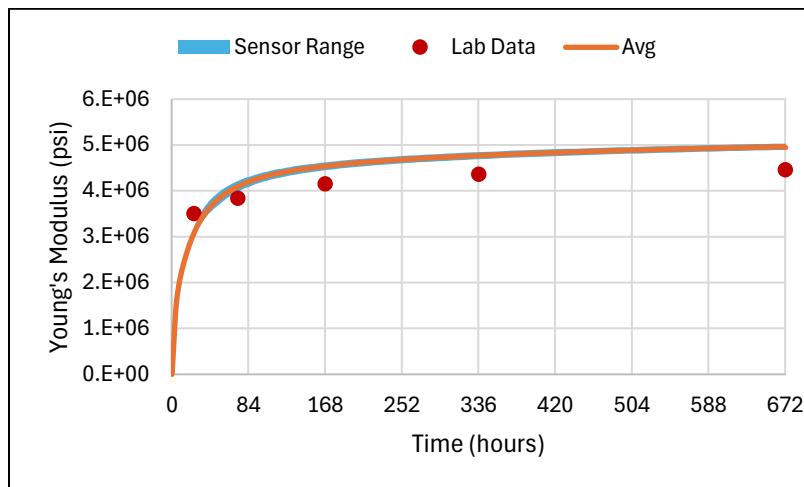


Figure 82. Graph. Project 5 Young's Modulus comparison.

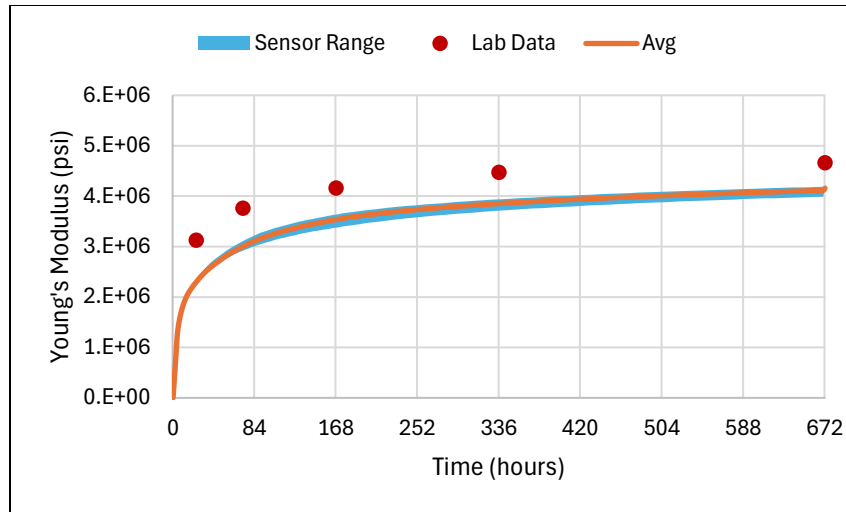


Figure 83. Graph. Project 6 Young's Modulus comparison.

Young's Modulus is determined from the compressive strength, so similar trends would be expected. In Projects 3 and 6, the lab data exceeds the sensor range, and in Project 5, the sensor data exceeds the lab data after 24 hours. The lab data in the other three projects—1, 2, and 4—fall within or near the sensor range, with some points above and some below.

LINEAR REGRESSION OF LAB DATA AVERAGE VS SENSOR AVERAGE

To compare the laboratory and sensor data, linear regression analyses were performed. The x-axis has the laboratory data, and the y-axis has the sensor data. For example, the average laboratory compressive strength at 24 hours was plotted against the average sensor-reported data at 24 hours as an (x-y) coordinate pair. This procedure was repeated at each time interval, and a dashed red linear trendline was fitted to the resulting data points. This trendline can be compared to a straight 1:1 line ($y = x$), which is graphed in blue in Figure 84 through Figure 89.

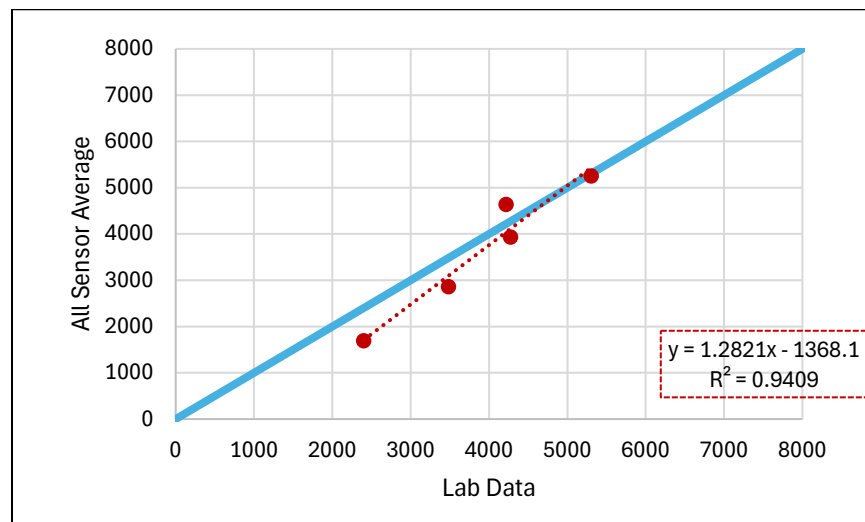


Figure 84. Graph. Project 1 linear regression of average laboratory and sensor data.

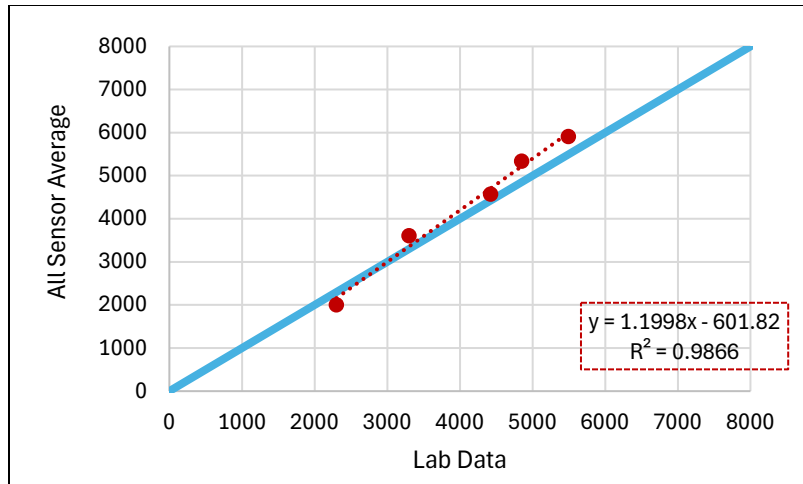


Figure 85. Graph. Project 2 linear regression of average laboratory and sensor data.

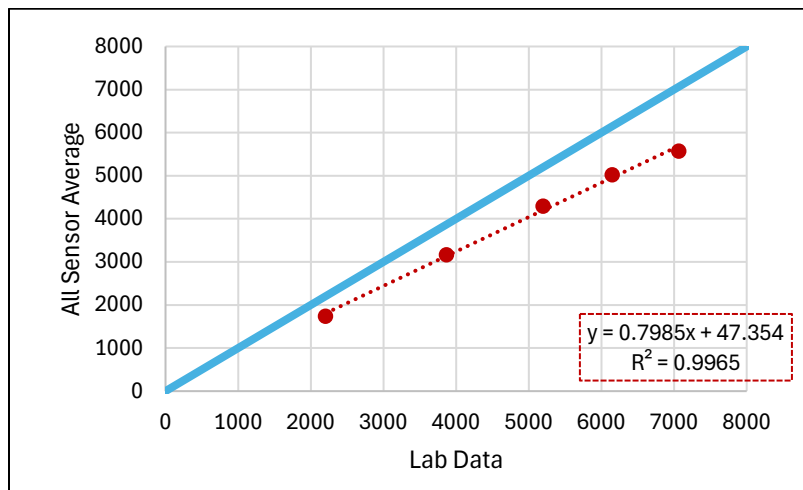


Figure 86. Graph. Project 3 linear regression of average laboratory and sensor data.

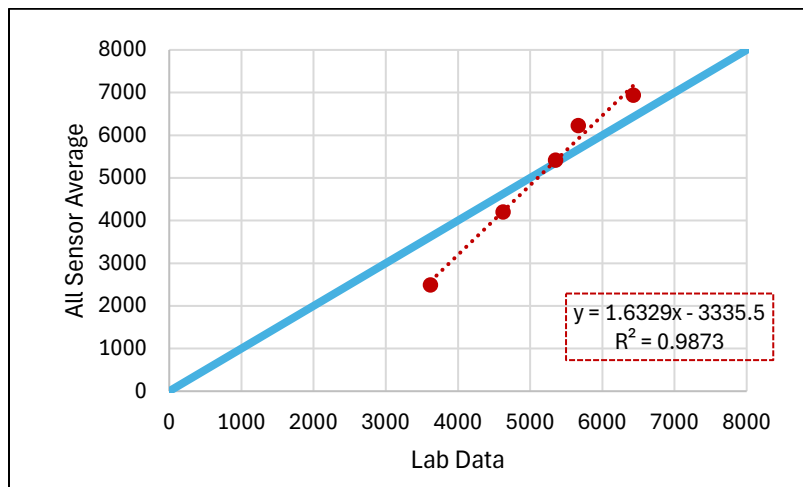


Figure 87. Graph. Project 4 linear regression of average laboratory and sensor data.

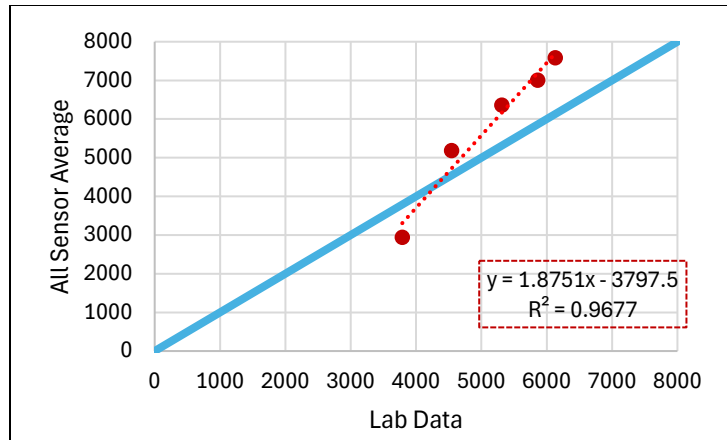


Figure 88. Graph. Project 5 linear regression of average laboratory and sensor data.

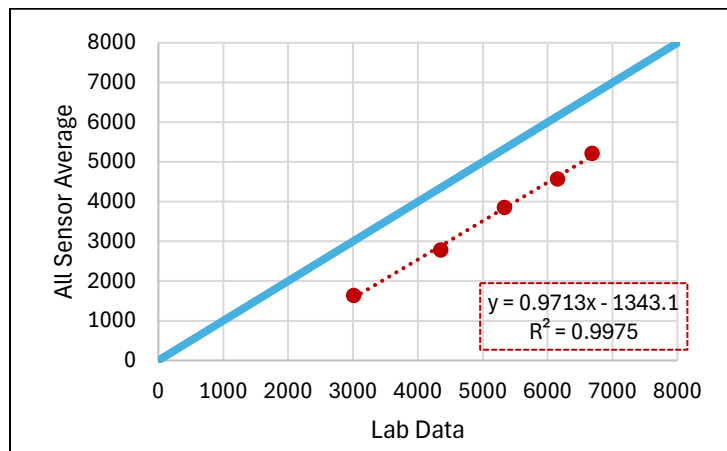


Figure 89. Graph. Project 6 linear regression of average laboratory and sensor data.

Table 25. Linear Analysis Summary

Statistical Parameter	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Average Strength Ratio	0.91	1.03	0.81	0.96	1.11	0.69
Standard Deviation	0.15	0.09	0.02	0.17	0.19	0.09
COV	0.17	0.09	0.02	0.17	0.17	0.14
R-Squared	0.94	0.99	1.00	0.99	0.97	1.00
Linear Slope	1.28	1.20	0.80	1.63	1.88	0.97

These graphs display a good linear fit between lab and sensor data, with all R-squared values above 0.9 and most above 0.95. The regression slopes ranged from 0.8 to 1.9. The closer the slopes are to 1.0, the greater the direct correlation between sensors and lab results. Projects 1, 2, 3, and 6 have a slope of 1 ± 0.3 , indicating a good correlation. The slope in Project 4 is 1.6, and the slope in Project 5 is 1.9. The linear regression analysis shows that the strength of concrete between the laboratory-cured samples and the field concrete is proportional; however, the 1:1 correlation in these projects is not as good, indicating greater inconsistency across projects.

BLAND–ALTMAN PLOT

Bland–Altman Overview

Linear regression is used to find correlation in data to see if two sets of data are related; however, this does not tell the whole story. Bland–Altman plot analysis compares differences between two data sets to determine whether there is bias. There are three scenarios on which the Bland–Altman analysis was performed for this report: per project, per day, and all data from the six projects combined.

Normally Distributed Data

One assumption for a Bland–Altman analysis is that the differences between the data sets are normally distributed (Giavarina, 2015). Therefore, before performing the Bland–Altman analysis, the differences must be tested for normality. The differences between all six projects combined contain the largest number of data points and therefore would provide the best visual representation of how this could be tested. This is displayed in Figure 90 where the differences are plotted as a histogram with a normal distribution curve overlaid.

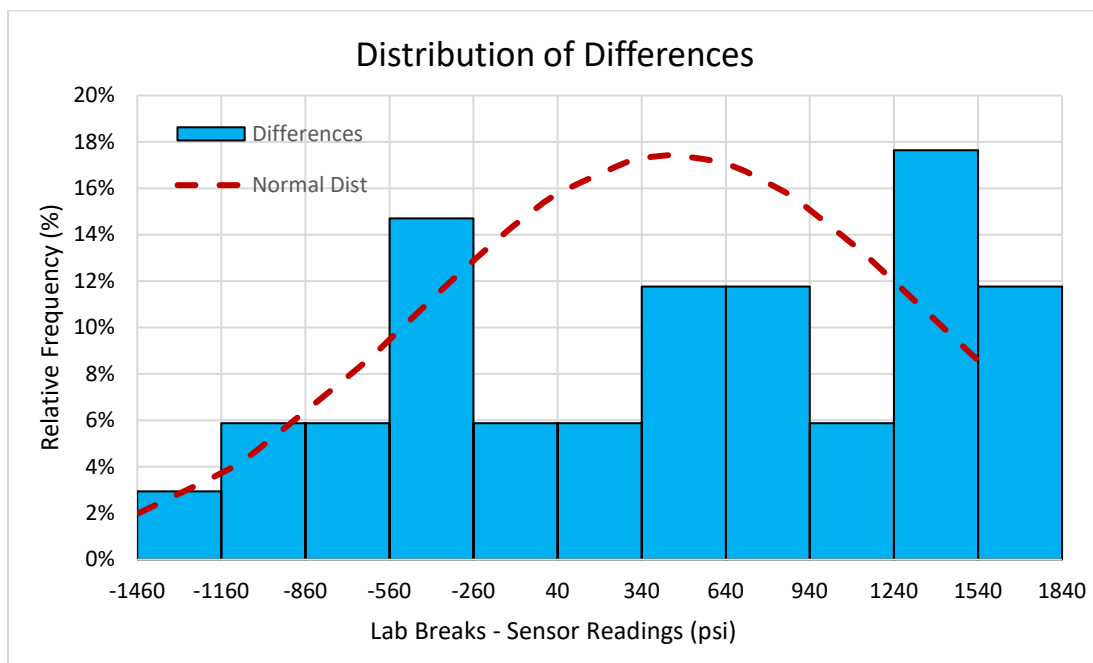


Figure 90. Graph. Distribution of differences of all six projects.

Additionally, to test normality numerically, one way is to perform a Shapiro-Wilk test. The test procedure and calculation are detailed in Appendices A, B, and C for each scenario, respectively. (Shapiro & Wilk, 1965). The results indicate that for individual projects and individual days, the data are normally distributed. However, when all six projects are combined, the data are not normally distributed. As such, a Bland–Altman plot analysis cannot be performed with accurate limits of agreement for this scenario; therefore, the plot is omitted from the body of this report, but can be found in Appendix D. The plots for the data per project and per day are displayed below.

Bland–Altman Analysis per Project

The first step in creating a Bland–Altman plot is to find the average lab and sensor data for each measured time interval. The average of the lab and sensor data was calculated and plotted along the x-axis in psi. The difference between the average lab data and the average sensor data was then calculated for each time interval and plotted on the y-axis. The bias was calculated as the average of the differences and plotted as a solid orange line. The standard deviation of the differences was also calculated and used to find the upper and lower limits of agreement. These limits were calculated as the bias plus or minus 1.96 times the standard deviation, which is the typical statistical number for 95% confidence of a normally distributed data set. These limits were also plotted as solid lines, this time in red. The data points are x-y pairs of the average of the lab and sensor data vs the difference between the two at the five different time intervals, which is why there are five data points per plot. Bland–Altman plots for each of the six projects can be found in Figure 91 though Figure 96. Looking at the data on a project-by-project basis allows differences in project type or mix design to potentially stand out.

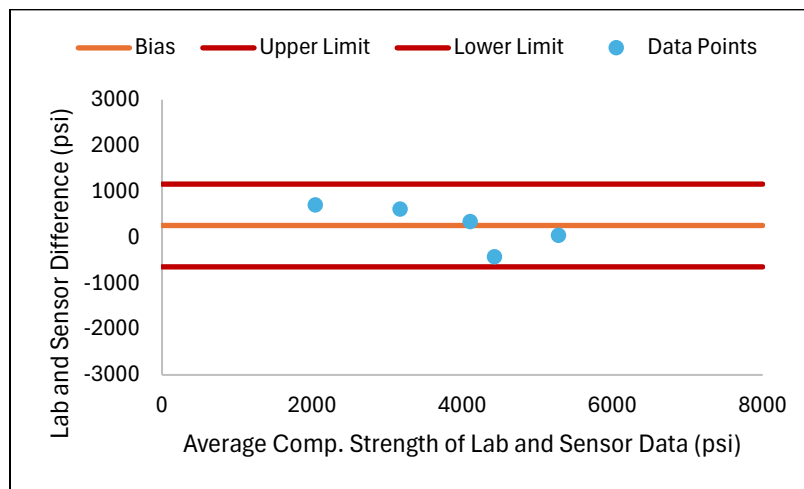


Figure 91. Graph. Project 1 Bland–Altman plot.

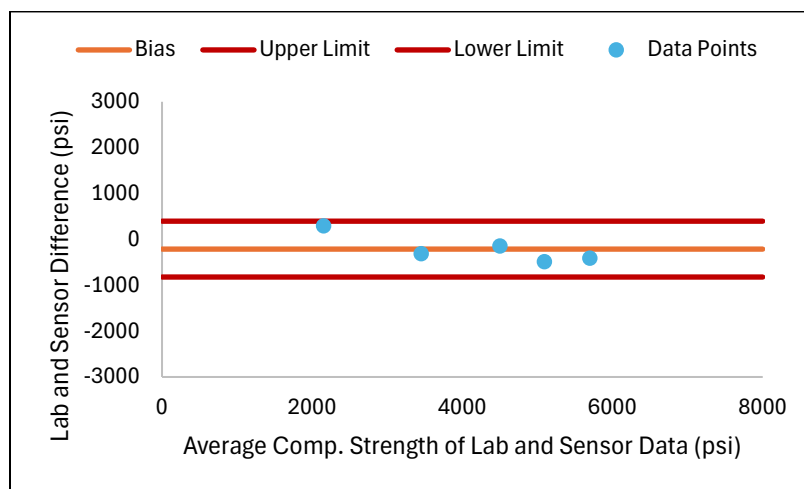


Figure 92. Graph. Project 2 Bland–Altman plot.

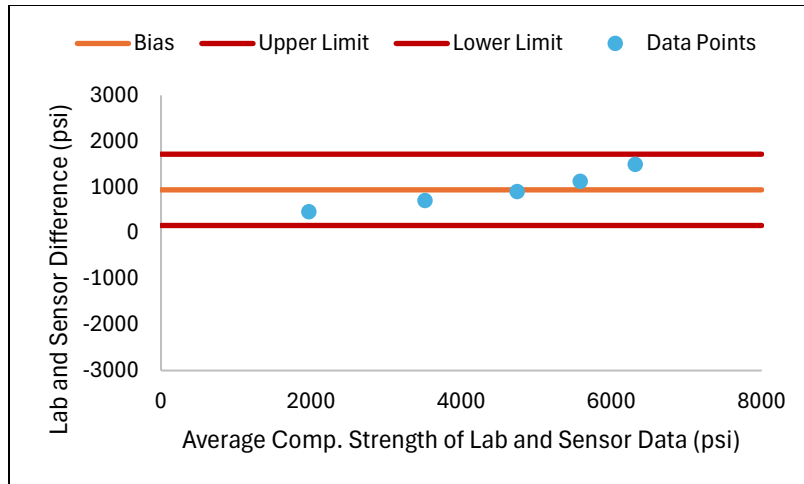


Figure 93. Graph. Project 3 Bland–Altman plot.

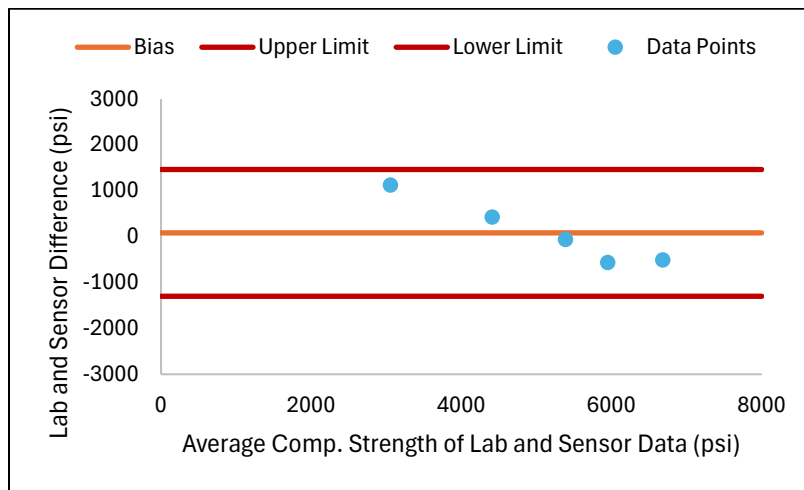


Figure 94. Graph. Project 4 Bland–Altman plot.

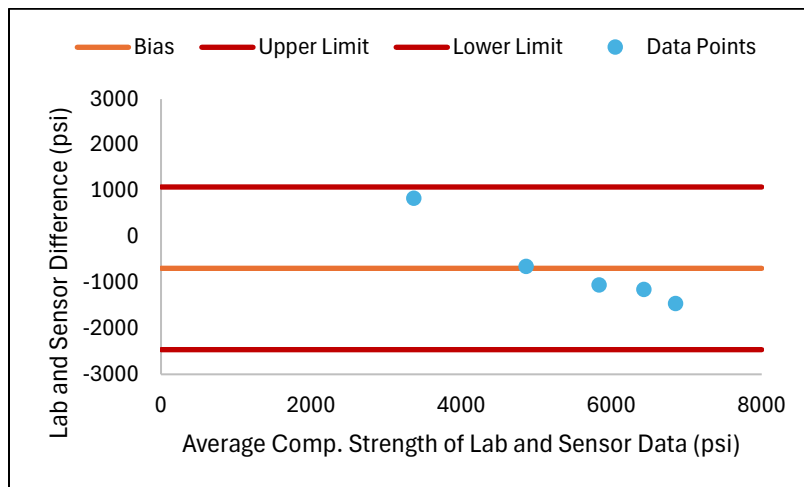


Figure 95. Graph. Project 5 Bland–Altman plot.

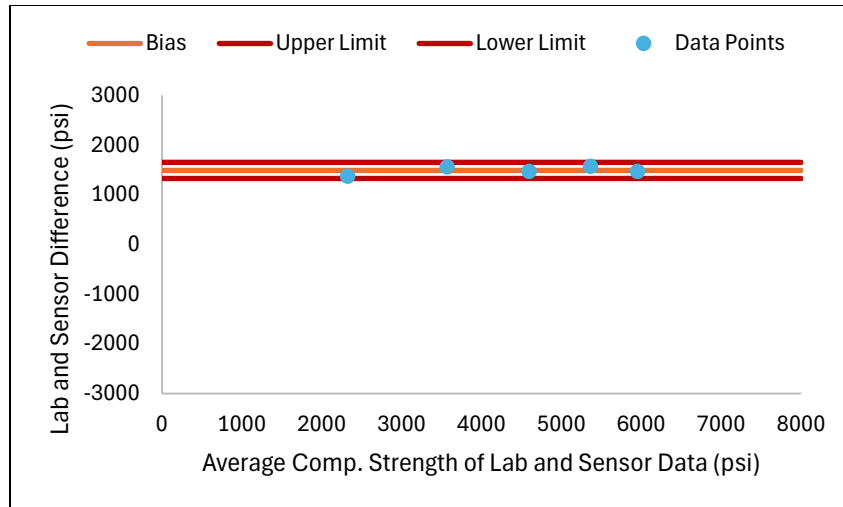


Figure 96. Graph. Project 6 Bland–Altman plot.

All data points fell within the upper and lower limits, indicating there are no outliers in the data. This is more significant in some projects compared to others. For example, the distance between the upper and lower limits of agreement, or the range, was 324.5 psi for Project 6 and 3,546 psi for Project 5, as shown in Table 26. Thus, the limits for Project 6 were approximately 11 times narrower, indicating less variability in the laboratory–sensor differences for Project 6. The farther the limits are from the bias line, the less accurate the graph.

Table 26. Bland–Altman Data Per Project

Project	Upper Limit	Lower Limit	Mean Difference (Bias)	Standard Deviation	Range
1	1160.0	-644.09	257.9	460.2	1804.0
2	396.7	-820.9	-212.1	310.6	1218.0
3	1716.0	162.3	939.4	396.5	1554.0
4	1464.0	-1300.0	82.3	705.1	2764.0
5	1084.0	-2462.0	-689.1	904.7	3546.0
6	1652.0	1327.0	1490.0	82.79	324.5

In the plots for Projects 4 and 5, there appears to be an inverse relationship between compressive strength and the number of data points. This can be compared with Project 3, where there appears to be a proportional trend in the data points. These differing patterns suggest that the data does not universally skew in either direction.

Bland–Altman Analysis per Day

The Bland–Altman plots per day were created in the same manner as those per project. These plots are displayed in Figure 97 through Figure 101. Looking at the data on a day-by-day basis allows differences in concrete age/strength and accuracy of sensors over time to be examined.

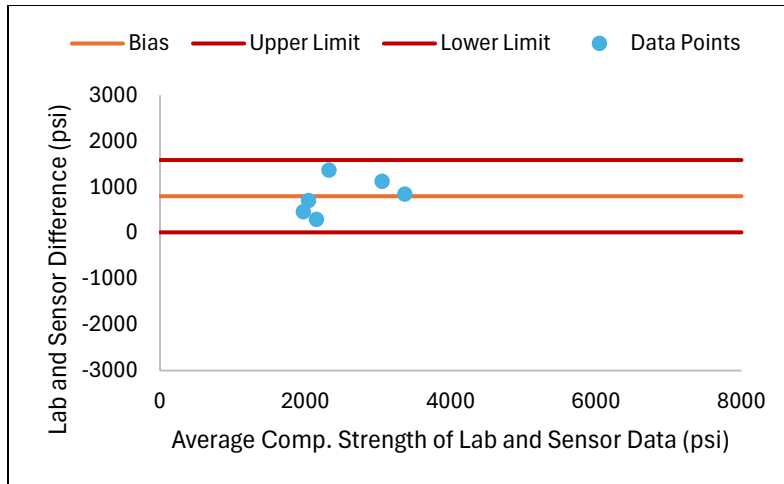


Figure 97. Graph. Day 1 Bland-Altman plot.

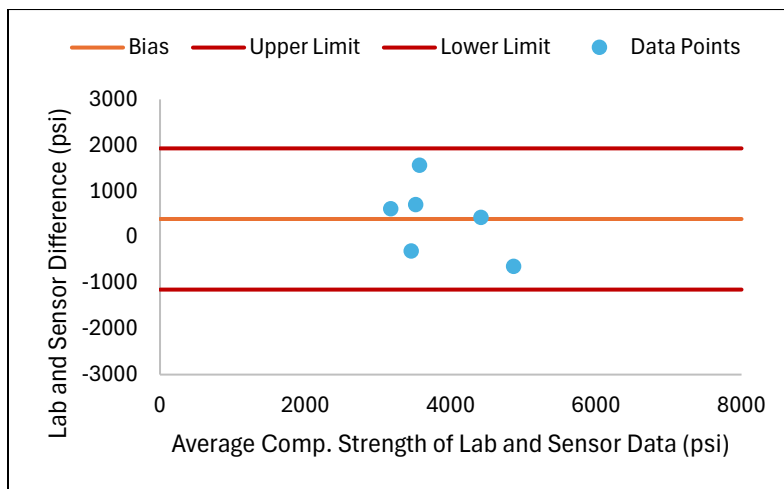


Figure 98. Graph. Day 3 Bland-Altman plot.

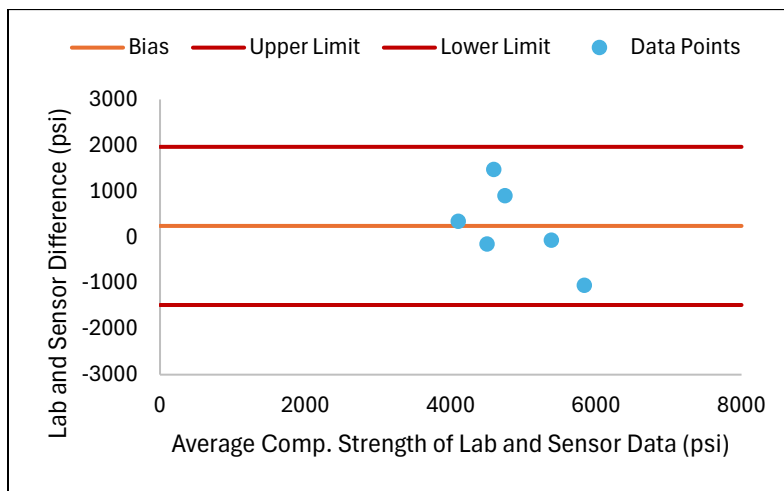


Figure 99. Graph. Day 7 Bland-Altman plot.

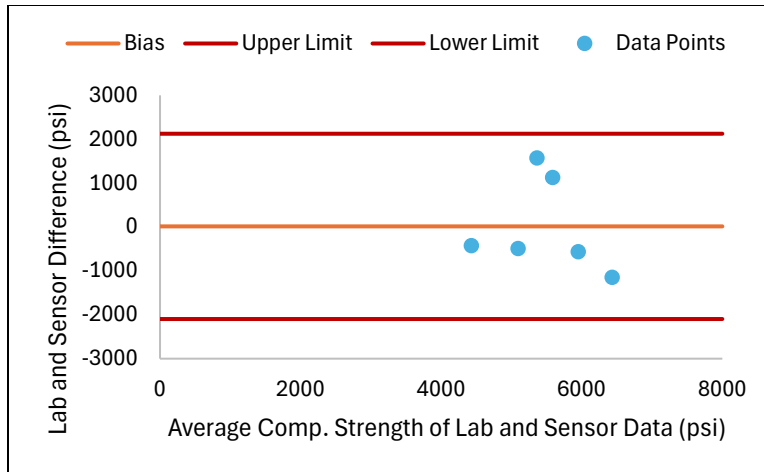


Figure 100. Graph. Day 14 Bland-Altman plot.

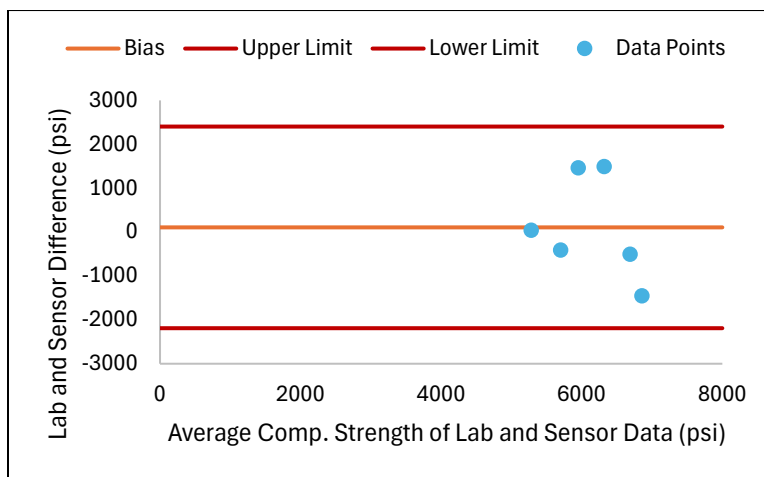


Figure 101. Graph. Day 28 Bland-Altman plot.

There are no outliers in these graphs, as all data points fall within the upper and lower limits of agreement. Additionally, there appears to be a relationship between time and the range between the upper and lower limits. These limits are shown in Table 27, and as time increases, so does the range. To determine the type of relationship between these variables, they can be plotted on an x-y graph as shown in Figure 102. In this graph, a logarithmic trendline is drawn based on the data points and has an R^2 value of 0.9675. As with linear regression, the closer the R^2 value is to 1.0, the better the fit of the graph. Therefore, the range vs time graph displays a good logarithmic fit to the data.

Another graph that may look similar to the logarithmic graph is the compressive strength vs time curve. The average compressive strength of the lab samples is plotted versus time in Figure 103 with logarithmic trendlines to compare with the range vs time graph. All of these graphs display a good logarithmic fit to the data, indicating a similar relationship.

It can be concluded that as time increases, so does the variability, or the range. This variability changes in a logarithmic fashion, as does compressive strength.

Table 27. Bland–Altman Data Per Day

Day	Upper Limit	Lower Limit	Mean Difference (Bias)	Standard Deviation	Range
1	1589.0	12.2	800.8	402.3	1577.0
3	1932.0	-1147.0	392.5	785.3	3078.0
7	1967.0	-1481.0	242.7	879.6	3448.0
14	2125.0	-2097.0	14.1	1077.0	4222.0
28	2404.0	-2190.0	106.6	1172.0	4594.0

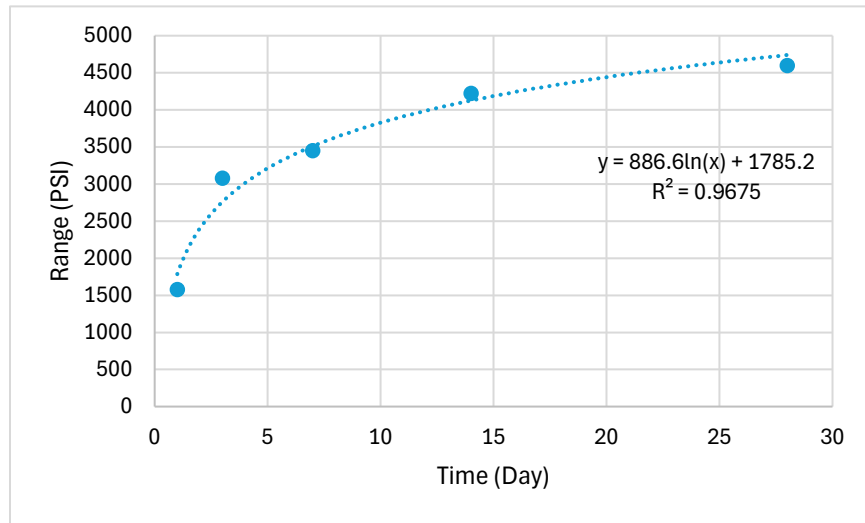


Figure 102. Graph. Range vs Time

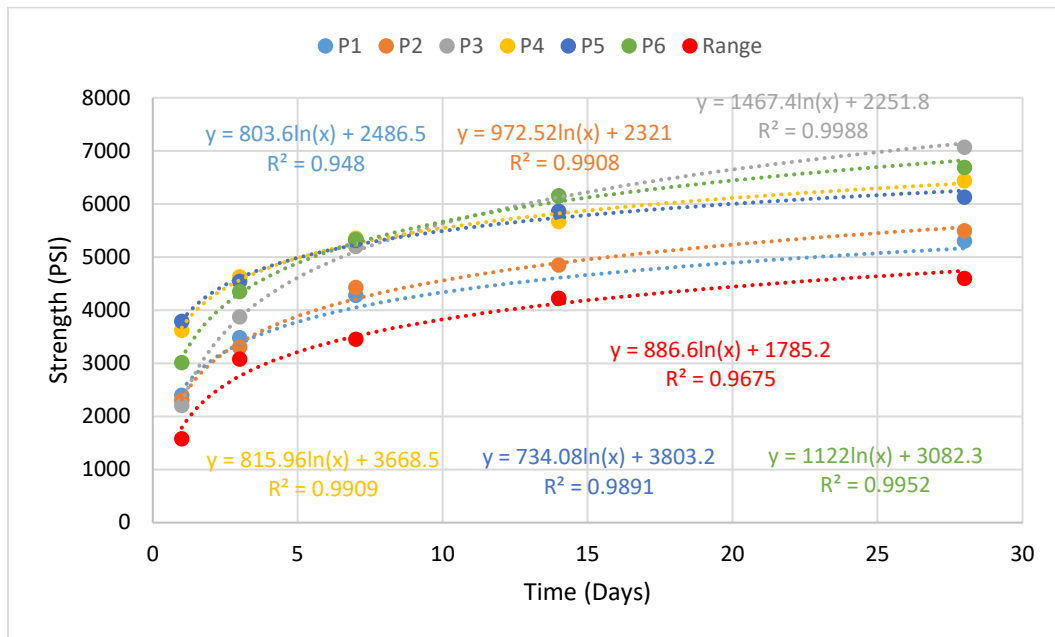


Figure 103. Graph. Logarithmic trendlines on compressive strength data.

Bland–Altman Analysis Limitations

One limitation of the graphs is that only five or six data points are compared in each project. To increase the number of data points, it was attempted to compare all data on a single graph. However, as the data is not normally distributed, this would not be an accurate comparison and is omitted.

Comparison of Test Results to Literature

Comparing the test results of the six projects with those reported in the literature has revealed some similarities. Other research evaluating the REBEL sensor performance in various projects across the U.S. showed similar trends to those observed in our projects (Kong and Lu, 2024; Kong, 2020). Projects within these articles included patching and paving projects and involved three sensors being deployed within the pavement itself and additional sensors within test cylinders and beams for comparison. In most of these deployments, the sensors in the test specimens yielded readings closer to the cylinder break results than those in the pavement. This was noted to be correlated with the temperature profile of the specimens; the test specimens had a consistent temperature reading after the first day of curing, like our test specimens for the six projects. The similarity in readings from this fact is attributed to the curing conditions, as these test specimens were cured in a laboratory setting. When comparing the pavement readings from research literature to the readings from our project, a similarity in strength development is noted due to the temperature profile of the sensor and the mix design of the project. Research has shown that admixtures can have an impact on sensor readings as well as drastic temperature profiles. While keeping a consistent ambient temperature is not probable, drastic temperature shifts were shown to have an impact on the sensor's performance, as well as mixes containing admixtures that impact the concrete's strength development or homogeneity.

MIX DESIGN COMPARISON

The six projects used mix designs with both shared and differing components as shown in Table 28. All six projects use varying quantities of Type IL cement and similar quantities of water. The aggregate quantities varied among projects, as did the types of coarse aggregate used. Projects 2 and 5 included slag, with Project 2 containing the greater quantity. All projects except Project 1 included an air entrainer and water reducer in varying amounts. Unlike the air entrainer and water reducer, only three projects use a retarder in their mix in varying quantities; and one project used a strength enhancer. All projects had a similar slump, air content and target w/c ratio. The certification strengths of the projects were similar to each other. Projects 1 and 6, 2 and 3, and 4 and 5 have the same certifications. One notable difference can be found within the admixtures of Project 5, the quantities used for the air entrainer, water reducer and retarder are in dosage units of ounces per 100 lb. The other projects used ounces per cubic yard, which are used for yield units. This is a notable difference because the dosage units relate to weight whereas the yield units relate to volume, which made comparing Project 5 to the others difficult. Therefore, Project 5 admixture dosages were not compared directly with those of the other projects.

Table 28. Combined Mix Design Summary

Ingredient/Characteristic	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Cement (Type IL)	475 lb/cy	463 lb/cy	490 lb/cy	535 lb/cy	625 lb/cy	435 lb/cy
Water	32 gal/cy	30.2 gal/cy	30.3 gal/cy	32.6 gal/cy	31 gal/cy	29.2 gal/cy
Coarse Aggregate (Unspecified)	1742 lb/cy			1791 lb/cy		
Coarse Aggregate (CA-16)		1422 lb/cy				
Coarse Aggregate (CA-111)			1328 lb/cy			
Coarse Aggregate (CA-161)			493 lb/cy			
Coarse Aggregate (CA-11)						1821 lb/cy
Coarse Aggregate (CM11 R-T)					1782 lb/cy	
Fine Aggregate (Unspecified)	1200 lb/cy			1121 lb/cy		
Fine Aggregate (FA-01)		1233.3 lb/cy	1245 lb/cy			1271 lb/cy
Fine Aggregate (FM02 F-S)					1116 lb/cy	
Fly Ash (Unspecified)	160 lb/cy			180 lb/cy		
Fly Ash (Class C)			125 lb/cy			145 lb/cy
Slag		154.4 lb/cy			110 lb/cy	
Air Entrainment (Unspecified)		2.8 oz/cy			0.6 oz/cwt	
Air Entrainment (DRAVAIR140)			0.85 oz/cy	0.85 oz/cy		
Air Entrainment (AEA 14 Sika)						1.1 oz/cy
Water Reducer (High-Range)		28.3 oz/cy			5 oz/cwt	
Water Reducer (High-Range; Superplasticizer)		1.8 oz/cy		153 oz/cy		
Water Reducer (Mid-Range; MIRA 95)			4.5 oz/cy			
Water Reducer (Low-Range)						4 oz/cy

Ingredient/Characteristic	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Water Reducer (Low-Range; ZYLA630)				225 oz/cy		
Retarder (Unspecified)		24.4 oz/cy				
Retarder (SikaTard 10)					1 oz/cwt	
Retarder (SikaTard 440)						2 oz/cy
Slump	4 in.	5 in.	5.5 in.	4 in.	4 in.	5.5 in.
Air Content	6.10%	6.70%	6.10%	5.50%	6%	6%
Target w/c Ratio	0.42	0.40	0.41	0.33	0.352	0.419
Certification Strength	3500 psi @ 14 d	4000 psi @ 14 d	4000 psi @ 14 d	3200 psi @ 48 hrs	3200 psi @ 24 hrs	3500 psi @ 14 d

One factor that contributes to the concrete curing is the condition it cures in. In the first 24 hours, the cast samples were stored in various field conditions depending on the project location. Projects in IDOT District 5 stored the cylinders in an insulated box for the first 24 hours, which provides some temperature regulation. This can be compared to projects in other districts; for example, in Project 5 in District 2, the cylinders were stored in cardboard boxes for the first day. Additionally, in all of the projects, the beam samples were kept outside and covered with a moist towel. After the first 24 hours, the samples were brought to the lab, where they were kept in a temperature-controlled water tank until breaking. The temperature was kept at 71±3°F. These lab conditions can be compared with field conditions. The average of the three embedded sensors' recorded ambient temperatures for each project is shown in Table 29. These projects took place in the winter and spring months, when outside temperatures were colder than the lab temperature and sometimes dropped below freezing.

Table 29. Embedded Sensors Recorded Average Ambient Temperature

Project No.	Sensor Deployment Date	Temperature (°F)				
		24 Hr.	72 Hr.	168 Hr.	336 Hr.	672 Hr.
1	11/24/2025	51	38	32	61	41
2	2/27/2026	54	35	69	49	42
3	4/7/2026	52	48	78	74	53
4	5/4/2026	51	56	65	64	80
5	5/14/2026	65	75	63	80	72
6	5/27/2026	69	70	56	77	81

CHAPTER 7: CONCLUSION AND FUTURE STUDIES

This study evaluated the use of REBEL embedded sensors for monitoring in-place concrete strength in transportation construction applications. Sensor-based strength estimates were compared with results obtained from conventional laboratory testing methods to assess the degree of agreement between the two approaches under field and laboratory conditions.

The findings indicate that REBEL sensors were generally capable of tracking trends in concrete strength development over time. However, the level of agreement between sensor predictions and conventional test results varied depending on the concrete mixture, curing conditions, and stage of strength development. While correlations were observed in several applications, differences between predicted and measured strengths highlight the need for careful evaluation of sensor performance before relying on the technology for quality assurance decisions.

Based on the results obtained in this investigation, REBEL sensors show potential as a supplementary tool for monitoring concrete strength development and providing continuous information on in-place concrete behavior. However, the data collected in this study do not support replacing established acceptance and quality control procedures without additional validation. Further evaluation across a broader range of concrete mixtures, environmental conditions, and construction scenarios would help clarify the applicability and limitations of the technology.

Overall, the research provides an assessment of the performance of embedded resonance-based sensing technology under Illinois transportation construction conditions. The results contribute to the understanding of its capabilities and limitations and provide information that may be considered in future evaluations of sensor-based approaches for concrete strength monitoring.

PROJECT AVAILABILITY

One limitation of this study was the availability of construction projects. The study began in the fall/winter, when most construction projects had wrapped up for the year, which resulted in a very limited project selection. Additionally, there was too much variation in the projects' mix designs to compare apples to apples. Therefore, it would be beneficial to conduct another analysis to better compare the differences among these mix designs.

This analysis would be best to perform during the main summer construction season. Not only would this open up a wider range of project selection, but it would also occur during the typical outdoor weather conditions of construction. The current study spanned from fall to spring, which does not accurately reflect when most roadway projects are constructed.

TECHNICAL IMPROVEMENTS

There are several ways this study could be improved in the future. The first suggestion for improvement is to cross-check laboratory data. The lab data in this study were collected from break results in Bradley University's concrete lab. It would be beneficial to compare these results with the certification strength tests performed by IDOT or a contractor on-site to ensure consistency. Although

the contractor/consultant/IDOT QA/QC teams prepared samples at the same time the research team did, the limited scope of this study meant we did not use QA/QC sample test results.

Another idea for improvement was inspired by a malfunctioning sensor. When the data analysis was performed, the sensor readings used at the specified time intervals did not correspond to the exact times of the concrete breaks. Data were collected from a reading taken close to break time, generally within a few hours of it. It would be very beneficial if users of the Wavelogix platform could manually trigger a sensor reading to collect data at times that are important to them, as when a malfunctioning sensor had to be manually triggered in Project 2. There are several situations in which this would be helpful. First is the data analysis scenario mentioned above. A second instance where it would have been nice to trigger a reading was at the end of the project, so that the data loggers could be picked up from the site. Since the data is collected less frequently after the initial stages of the project, it took a day or two for the final data reading to come in and the data loggers to be collected. In situations where data loggers need to be moved from one project to another quickly, this would create a delay. The final situation may be the most practical in a construction project. In a patching job, there is pressure to open the road as quickly as possible. With an instant reading at the click of a button, strength can be monitored more closely, especially as it approaches the opening strength.

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APPENDIX A: NORMALITY TEST PER PROJECT

PROJECT 1

A Shapiro-Wilk Test is used to determine whether or not data is normally distributed. The steps to perform this test are shown below (Shapiro & Wilk 1965).

First, the data is displayed in Table 30, ordered from smallest to largest (y_i). The average or mean ($\bar{y}$) is found to be about 450.6 psi. This average can be used to find an S^2 value, which is calculated using the equation below.

$$S^2 = \sum_{i=1}^n (y_i - \bar{y})^2$$

Table 30. Data for Project 1 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-424	-681	464351
2	46	-212	44986
3	344	86	7322
4	617	359	128570
5	707	449	201960
		Σ	847190

Now that the S^2 value is determined, the next step is to find a b value. To do this, a table must be utilized from Shapiro and Wilk (1965). This table has a_{n-i+1} coefficients used to find b , as the equation for b is shown below. The coefficients used for a_{n-i+1} are shown in Table 31.

$$b = \sum_{i=1}^k a_{n-i+1} (y_{n-i+1} - y_i)$$

Where, for even values of n , $n=2k$; for odd values of n , $n=2k + 1$.

Table 31. Coefficients and Data for Calculation of b in Project 1

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	707	-424	752
0.2413	617	46	138
0.0000	344	344	0
		Σ	889.6

Once b is known, the W statistic can be calculated using the equation below. This W value is then compared to another table in Shapiro and Wilk (1965) to determine if the data is distributed normally. If this W value is small, then the data is not normally distributed.

$$W = \frac{b^2}{S^2}$$

The calculated value is $W = 0.9334$. When comparing this value to the table, the W value falls between levels 0.50 and 0.90, indicating a large number. Therefore, it is determined that the data is normally distributed.

The following projects are calculated in a similar manner.

PROJECT 2

The calculated value is $W = 0.8818$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 32. Data for Project 2 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-488	-276	75966
2	-410	-198	39153
3	-309	-97	9461
4	-149	63	4030
5	295	507	257333
		Σ	385943

Table 33. Coefficients and Data for Calculation of b in Project 2

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	295	-488	520
0.2413	-149	-410	63
0.0000	-309	-309	0
		Σ	583

PROJECT 3

The calculated value is $W = 0.9893$. When comparing this value to the table, the W value falls between levels 0.98 and 0.99, indicating a large number. Therefore, the data is normally distributed.

Table 34. Data for Project 3 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	463	-476	226798
2	707	-232	54010
3	901	-38	1452
4	1129	189	35872
5	1497	557	310620
		Σ	628752

Table 35. Coefficients and Data for Calculation of b in Project 3

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	1497	463	687
0.2413	1129	707	102
0.0000	901	901	0
		Σ	789

PROJECT 4

The calculated value is $W = 0.9121$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 36. Data for Project 4 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-565	-647	418807
2	-507	-589	346748
3	-65	-147	21654
4	424	342	116677
5	1124	1042	1084889
		Σ	1988776

Table 37. Coefficients and Data for Calculation of b in Project 4

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	1124	-565	1122
0.2413	424	-507	225
0.0000	-65	-65	0
		Σ	1347

PROJECT 5

The calculated value is $W = 0.8297$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 38. Data for Project 5 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-1454	-765	585378
2	-1144	-455	206691
3	-1047	-358	128427
4	-644	45	1998
5	844	1533	2351316
		Σ	3273810

Table 39. Coefficients and Data for Calculation of b in Project 5

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	844	-1454	1528
0.2413	-644	-1144	120
0.0000	-1047	-1047	0
		Σ	1648

PROJECT 6

The calculated value is $W = 0.9181$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 40. Data for Project 6 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	1371	-119	14141
2	1468	-22	472
3	1473	-17	287
4	1561	72	5141
5	1575	86	7376
		Σ	27417

Table 41. Coefficients and Data for Calculation of b in Project 6

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6646	1575	1371	136
0.2413	1561	1468	23
0.0000	1473	1473	0
		Σ	159

APPENDIX B: NORMALITY TEST PER DAY

The calculations in the following tables used the same method as in Appendix A.

DAY 1

The calculated value is $W = 0.9765$. When comparing this value to the table, the W value falls between levels 0.90 and 0.95, indicating a large number. Therefore, the data is normally distributed.

Table 42. Data for Day 1 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	295	-506	255581
2	463	-338	113963
3	707	-93	8727
4	844	44	1897
5	1124	323	104426
6	1371	570	324729
		Σ	809322

Table 43. Coefficients and Data for Calculation of b in Day 1

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6431	1371	295	692
0.2806	1124	463	185
0.0875	844	707	12
0.0000	707	844	0
		Σ	889

DAY 3

The calculated value is $W = 0.9599$. When comparing this value to the table, the W value falls between levels 0.50 and 0.90, indicating a large number. Therefore, the data is normally distributed.

Table 44. Data for Day 3 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-644	-1037	1075116
2	-309	-702	492562
3	424	31	987
4	617	224	50186
5	707	315	98924
6	1561	1169	1365951
		Σ	3083726

Table 45. Coefficients and Data for Calculation of b in Day 3

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6431	1561	-644	1418
0.2806	707	-309	285
0.0875	617	424	17
0.0000	424	617	0
		Σ	1720

DAY 7

The calculated value is $W = 0.9839$. When comparing this value to the table, the W value falls between levels 0.95 and 0.98, indicating a large number. Therefore, the data is normally distributed.

Table 46. Data for Day 7 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-1047	-1290	1664652
2	-149	-391	153153
3	-65	-308	94606
4	344	101	10151
5	901	659	433692
6	1473	1230	1512497
		Σ	3868750

Table 47. Coefficients and Data for Calculation of b in Day 7

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6431	1473	-1047	1621
0.2806	901	-149	295
0.0875	344	-65	36
0.0000	-65	344	0
		Σ	1951

DAY 14

The calculated value is $W = 0.8571$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 48. Data for Day 14 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-1144	-1158	1340514
2	-565	-579	335132
3	-488	-502	251775
4	-424	-438	191469
5	1129	1115	1242618
6	1575	1561	2437744
		Σ	5799253

Table 49. Coefficients and Data for Calculation of b in Day 14

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6431	1575	-1144	1749
0.2806	1129	-565	475
0.0875	-424	-488	6
0.0000	-488	-424	0
		Σ	2230

DAY 28

The calculated value is $W = 0.9039$. When comparing this value to the table, the W value falls between levels 0.10 and 0.50, indicating a large number. Therefore, the data is normally distributed.

Table 50. Data for Day 28 Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-1454	-1561	2436131
2	-507	-613	375946
3	-410	-517	266835
4	46	-61	3694
5	1468	1361	1852790
6	1497	1390	1932440
		Σ	6867836

Table 51. Coefficients and Data for Calculation of b in Day 28

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.6431	1497	-1454	1898
0.2806	1468	-507	554
0.0875	46	-410	40
0.0000	-410	46	0
		Σ	2492

APPENDIX C: NORMALITY TEST FOR SIX COMBINED PROJECTS

A Shapiro-Wilk Test is used to determine whether data is normally distributed. The steps to perform this test are shown below (Shapiro & Wilk 1965). First, the data is displayed in Table 52, ordered from smallest to largest (y_i). The average or mean ($\bar{y}$) is found to be about 450.6 psi. This average can be used to find an S^2 value, which is calculated using the equation below.

$$S^2 = \sum_{i=1}^n (y_i - \bar{y})^2$$

Table 52. Data for Shapiro-Wilk Test

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
1	-1454	-1905	3628190
2	-1144	-1594	2541838
3	-1047	-1498	2244146
4	-644	-1095	1198983
5	-565	-1015	1031066
6	-507	-957	916068
7	-488	-938	880371
8	-424	-874	764017
9	-410	-861	740513
10	-309	-760	577495
11	-149	-599	359018
12	-65	-515	265652
13	46	-405	163821
14	295	-155	24143
15	344	-107	11466
16	424	-27	712
17	463	13	158
18	617	166	27529
19	707	256	65751
20	707	257	65922
21	844	394	155015
22	901	451	203148
23	1124	673	453359
24	1129	678	459981
25	1371	920	846435
26	1371	920	846435
27	1468	1017	1034701
28	1473	1022	1044489
29	1473	1022	1044489

i	y_i	$y_i - \bar{y}$	$(y_i - \bar{y})^2$
30	1497	1046	1094435
31	1561	1111	1233512
32	1561	1111	1233512
33	1575	1125	1265218
34	1575	1125	1265218
		Σ	27686806

Now that the S^2 value is determined, the next step is to find a b value. To do this, a table must be utilized from Shapiro and Wilk (1965). This table has a_{n-i+1} coefficients used to find b , as the equation for b is shown below. The coefficients used for a_{n-i+1} are shown in Table 53.

$$b = \sum_{i=1}^k a_{n-i+1}(y_{n-i+1} - y_i)$$

Where, for even values of n , $n = 2k$; for odd values of n , $n = 2k + 1$.

Table 53. Coefficients and Data for Calculation of b

a_{n-i+1}	y_{n-i+1}	y_i	$a_{n-i+1}(y_{n-i+1} - y_i)$
0.4127	1575	-1454	1250
0.2854	1575	-1144	776
0.2439	1561	-1047	636
0.2132	1561	-644	470
0.1882	1497	-565	388
0.1667	1473	-507	330
0.1475	1473	-488	289
0.1301	1468	-424	246
0.114	1371	-410	203
0.0988	1371	-309	166
0.0844	1129	-149	108
0.0706	1124	-65	84
0.0572	901	46	49
0.0441	844	295	24
0.0314	707	344	11
0.0187	707	424	5
0.0062	617	463	1
0.0000	463	617	0
		Σ	5037

Once b is known, the W statistic can be calculated using the equation below. This W value is then compared to another table in Shapiro and Wilk (1965) to determine if the data is distributed normally. If this W value is small, then the data is not normally distributed.

$$W = \frac{b^2}{S^2}$$

The calculated value is $W = 0.9165$. When comparing this value to the table, the W value falls between levels 0.01 and 0.02, indicating a small number. Therefore, the data is not normally distributed.

APPENDIX D: BLAND–ALTMAN PLOT WITH ALL DATA

The Bland–Altman plot of all six projects combined can be found in Figure 104.

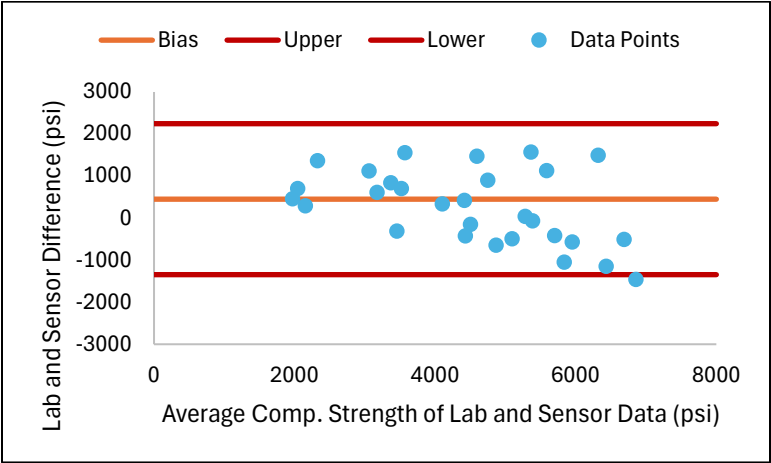


Figure 104. Graph. Combined Bland–Altman plot for all projects.



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