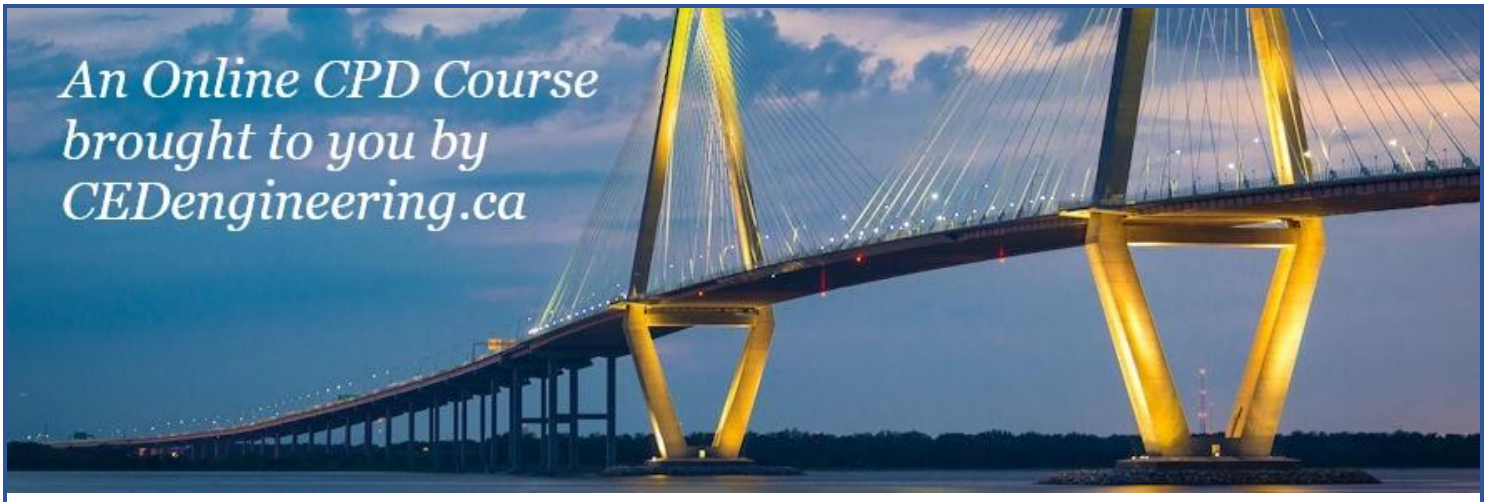


Machine Learning For Construction Material Quality Testing

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Module 1: Introduction to ML-Based Material Testing

Construction material quality testing forms the foundation of structural safety and building performance. Traditional testing methods, while proven and reliable, often require significant time, are destructive in nature, and provide results only after materials have been installed. Machine learning technologies are transforming this landscape by enabling predictive quality assessment, real-time monitoring, and non-destructive evaluation that can identify potential issues before they compromise building integrity.

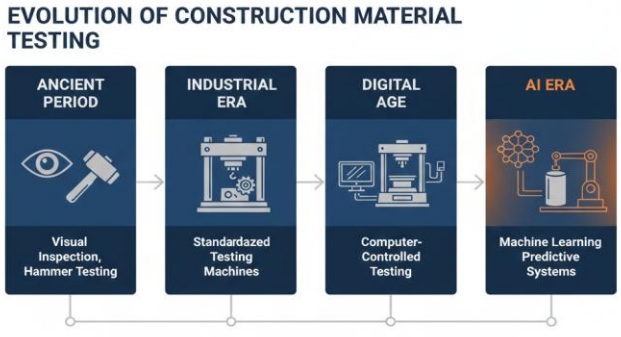
This chapter introduces the fundamental concepts of machine learning as applied to construction material testing. We explore how traditional testing methodologies have evolved, examine the core principles of machine learning that enable intelligent quality assessment, and consider the transformative potential of data-driven approaches for ensuring material performance throughout the construction lifecycle.

1.1 Evolution of Material Testing in Construction

Material testing has been fundamental to construction practice since ancient civilizations first sought to ensure building durability and safety. Early builders relied on empirical knowledge, selecting stones, timber, and clay based on observable characteristics and accumulated experience. The standardization of material testing began in earnest during the Industrial Revolution, when the rapid expansion of infrastructure demanded consistent quality assurance methods.

The twentieth century brought significant advancement to material testing practice. The introduction of standardized testing protocols by organizations such as ASTM International and the American Concrete Institute established uniform procedures for evaluating material properties. These standards enabled consistent quality assessment across projects and jurisdictions, supporting the growth of modern construction practices.

Traditional material testing relies heavily on destructive methods that require physical samples to be tested to failure. Concrete compression testing, for example, requires casting and curing test cylinders that are subsequently crushed to determine compressive strength. Steel tensile testing involves pulling specimens until fracture. While these methods provide accurate measurements of material properties, they are time-consuming, require laboratory facilities, and typically provide results 28 days or more after material placement.



Non-destructive testing methods emerged to address some limitations of traditional approaches. Ultrasonic pulse velocity testing can assess concrete quality without sample destruction. Rebound hammer tests provide rapid estimates of surface hardness. Radiographic inspection reveals internal defects in welds and castings. However, these methods often require expert interpretation and may provide less definitive results than destructive testing.

The integration of digital sensors and data acquisition systems in the late twentieth century enabled continuous monitoring of material properties during production and placement. Temperature sensors embedded in concrete elements track hydration processes. Strain gauges measure deformations under load. These monitoring systems generate vast datasets that, until recently, exceeded human capacity to analyze comprehensively.

1.2 Fundamentals of Machine Learning for Quality Testing

Machine learning represents a branch of artificial intelligence that enables computer systems to learn from data and improve their performance without being explicitly programmed for every scenario. Unlike traditional software that follows predetermined rules, machine learning algorithms identify patterns in training data and apply those patterns to make predictions about new, unseen data.

Three primary categories of machine learning apply to construction material testing. Supervised learning algorithms train on labeled datasets where both inputs and correct outputs are known. For material testing, this might involve training a model on concrete mix proportions and corresponding compressive strength results. Once trained, the model can predict strength for new mix designs. Unsupervised learning algorithms identify patterns in data without labeled outputs, useful for anomaly detection and clustering similar material behaviors. Reinforcement learning enables systems to learn optimal actions through trial and error, applicable to automated material handling and testing procedures.

Neural networks, inspired by biological brain structure, have proven particularly effective for material property prediction. These models consist of interconnected nodes organized in layers that process information sequentially. Deep neural networks with multiple hidden layers can capture complex, nonlinear relationships between input variables and material properties that traditional statistical methods struggle to model.

Random forests and gradient boosting algorithms represent ensemble methods that combine multiple decision trees to improve prediction accuracy and reduce overfitting. These methods have demonstrated strong performance for predicting concrete strength and durability properties from mix design parameters and curing conditions.

Computer vision algorithms enable automated visual inspection of construction materials. Convolutional neural networks can analyze images of concrete surfaces to detect cracks, honeycombing, and other defects. These systems can process images from construction sites in real-time, identifying quality issues that might

be missed in manual inspections. Research has demonstrated that deep learning-based defect detection can achieve accuracy rates exceeding 90 percent for common concrete defects.

Transfer learning enables models trained on large datasets to be adapted for specialized construction applications with limited training data. A model trained on millions of general images can be fine-tuned with hundreds of construction-specific examples, dramatically reducing the data requirements for developing effective quality assessment systems.

1.3 Industry Adoption and Benefits

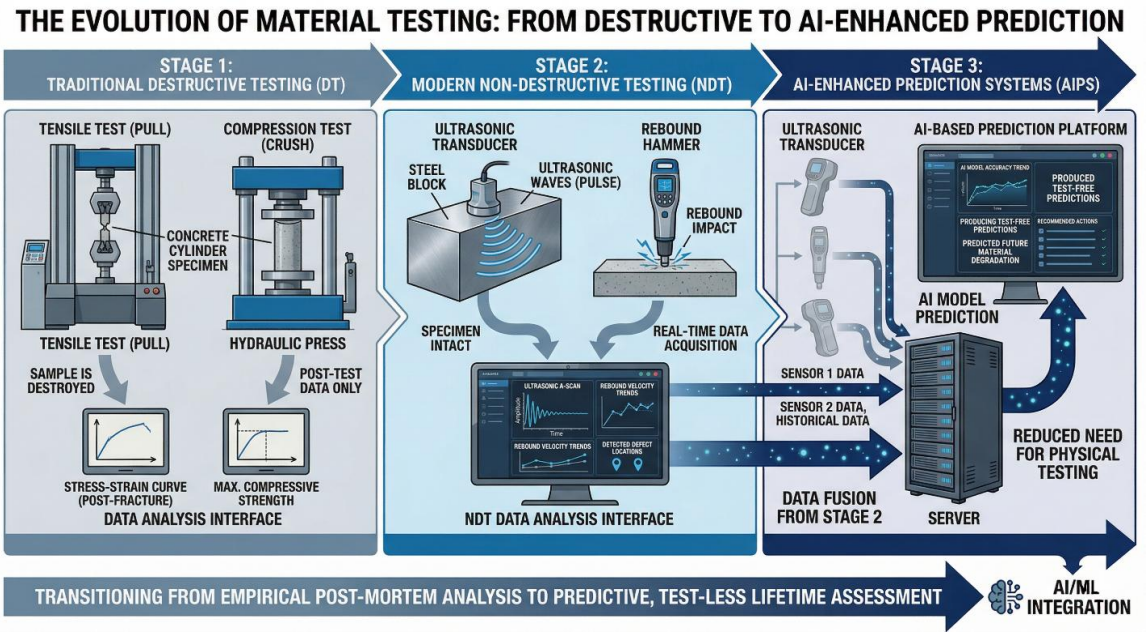
The construction industry has begun embracing machine learning for material quality testing, driven by demonstrated benefits including reduced testing time, improved prediction accuracy, and early identification of potential quality issues. According to a McKinsey Global Institute analysis, AI and machine learning technologies could generate 1.2 trillion dollars in annual value for the engineering and construction sector through productivity improvements and quality enhancements.

Research by the Construction Industry Institute indicates that material-related defects account for approximately 20 percent of construction rework costs. Machine learning systems that predict material performance before placement can significantly reduce this waste by identifying problematic materials before they are incorporated into structures. Studies have shown that predictive quality systems can reduce material-related rework by 30 to 45 percent.

Time savings represent another significant benefit. Traditional concrete strength testing requires 28 days for standard cylinder tests. Machine learning models trained on early-age strength data and mix parameters can predict 28-day strength with accuracy exceeding 95 percent within the first 7 days. This acceleration enables faster project progression and earlier detection of strength deficiencies.

Quality consistency improves through machine learning applications that optimize material production processes. Real-time monitoring systems can detect deviations from target properties and recommend adjustments before out-of-specification materials are produced. Concrete batch plant operators using ML-based guidance systems have reported reduction in batch rejection rates by 25 to 40 percent.

Safety implications are substantial. Machine learning systems can identify materials with potentially inadequate properties before they are placed in critical structural elements. This predictive capability complements rather than replaces traditional testing, providing an additional layer of quality assurance that enhances overall construction safety.


THE EVOLUTION OF MATERIAL TESTING: FROM DESTRUCTIVE TO AI-ENHANCED PREDICTION
STAGE 1:
TRADITIONAL DESTRUCTIVE TESTING (DT)
STAGE 2:
MODERN NON-DESTRUCTIVE TESTING (NDT)
STAGE 3:
AI-ENHANCED PREDICTION SYSTEMS (AIPS)
TENSILE TEST (PULL)
COMPRESSION TEST (CRUSH)
CONCRETE CYLINDER SPECIMEN
TENSILE TEST (PULL)
HYDRAULIC PRESS
SAMPLE IS DESTROYED
POST-TEST DATA ONLY
STRESS-STRAIN CURVE (POST-FRACTURE)
MAX. COMPRESSIVE STRENGTH
DATA ANALYSIS INTERFACE
ULTRASONIC TRANSDUCER
REBOUND HAMMER
STEEL BLOCK
ULTRASONIC WAVES (PULSE)
REBOUND IMPACT
SPECIMEN INTACT
REAL-TIME DATA ACQUISITION
NDT DATA ANALYSIS INTERFACE
ULTRASONIC TRANSDUCER
AI-BASED PREDICTION PLATFORM
AI MODEL PREDICTION
SENSOR 1 DATA
SENSOR 2 DATA, HISTORICAL DATA
REDUCED NEED FOR PHYSICAL TESTING
DATA FUSION FROM STAGE 2
SERVER
TRANSITIONING FROM EMPIRICAL POST-MORTEM ANALYSIS TO PREDICTIVE, TEST-LESS LIFETIME ASSESSMENT
AI/ML INTEGRATION

Module 2: Machine Learning for Concrete Quality Testing

Concrete is the most widely used construction material globally, with over 10 billion tons produced annually. Ensuring concrete quality is essential for structural safety, durability, and building performance. This chapter examines how machine learning transforms concrete quality testing, from strength prediction to durability assessment and mix design optimization.

2.1 Predicting Concrete Compressive Strength

Compressive strength represents the primary quality indicator for structural concrete. Traditional testing requires casting standardized cylinders or cubes, curing for specified periods, and testing to failure in compression machines. Machine learning approaches can predict this fundamental property from mix design parameters, constituent material properties, and curing conditions.

The input variables for concrete strength prediction typically include cement content, water-to-cement ratio, aggregate proportions and properties, admixture dosages, and curing temperature and humidity. Neural networks trained on databases of mix designs and corresponding test results learn complex relationships between these variables and resulting strength. Research published in the Journal of Materials in Civil Engineering has demonstrated prediction accuracy with mean absolute percentage errors below 5 percent for models trained on comprehensive datasets.

Early-age strength prediction enables faster project progression. Models trained on relationships between 3-day or 7-day strength and 28-day strength can provide reliable predictions weeks before traditional testing would yield results. This capability is particularly valuable for fast-track construction where waiting for 28-day results would delay critical path activities.

Sensor-based strength monitoring represents an emerging application. Temperature sensors embedded in concrete elements track hydration heat development, which correlates with strength gain. Machine learning models trained on temperature histories and corresponding strength measurements can estimate in-place strength in real-time. The maturity method, enhanced by machine learning calibration, can predict concrete strength with accuracy suitable for determining safe formwork removal times.

Quality control applications extend beyond prediction. Machine learning can identify anomalous test results that may indicate testing errors or specimen damage. Statistical process control enhanced by ML algorithms detects trends and shifts in production quality before they result in out-of-specification concrete. These capabilities support continuous improvement in concrete production processes.

2.2 Durability Assessment and Service Life Prediction

Concrete durability determines long-term structural performance and maintenance requirements. Traditional durability assessment relies on accelerated laboratory tests that may not accurately represent field exposure conditions. Machine learning enables more nuanced durability prediction by analyzing multiple factors including material properties, environmental exposure, and historical performance data.

Chloride-induced corrosion of reinforcing steel represents a primary concrete durability concern, particularly for bridges and marine structures. Machine learning models trained on chloride penetration test data and long-term exposure studies can predict time to corrosion initiation more accurately than traditional diffusion-based models. These predictions consider the complex interactions between concrete permeability, environmental chloride concentration, temperature variations, and cracking that affect actual field performance.

Carbonation depth prediction benefits similarly from machine learning approaches. Neural networks trained on accelerated carbonation test data and field measurements learn relationships between concrete composition, curing conditions, environmental CO2 concentration, and carbonation progression. Studies have shown that ML models can reduce prediction errors by 30 to 40 percent compared to empirical carbonation models.

Freeze-thaw durability assessment presents particular challenges due to the complex physics of ice formation in concrete pore structures. Machine learning models trained on freeze-thaw test results, pore structure characterization, and air void parameters can predict durability factors and scaling resistance. These predictions help specify appropriate air entrainment for cold climate applications.

Service life modeling integrates multiple degradation mechanisms to predict overall structural performance. Physics-informed neural networks combine machine learning with fundamental deterioration mechanisms, providing predictions that respect underlying physical constraints while capturing complex interactions that purely mechanistic models may miss. This approach is particularly valuable for infrastructure management, where accurate service life predictions support maintenance planning and capital investment decisions.

2.3 Mix Design Optimization

Concrete mix design involves balancing multiple objectives including strength, workability, durability, sustainability, and cost. Traditional mix design follows established procedures that may not fully optimize across all criteria. Machine learning enables multi-objective optimization that identifies mix proportions achieving desired performance while minimizing cost and environmental impact.

Genetic algorithms combined with machine learning prediction models can explore vast design spaces to identify optimal mix proportions. These approaches have demonstrated ability to reduce cement content by 10 to 15 percent while maintaining required strength and durability performance. Given that cement production accounts for approximately 8 percent of global CO2 emissions, such optimization has significant environmental implications.

Supplementary cementitious materials including fly ash, slag, and silica fume affect concrete properties in complex ways that machine learning captures effectively. Models trained on databases incorporating various SCM combinations predict how different replacement levels affect strength development, durability, and workability. This capability supports increased use of industrial byproducts in concrete, enhancing sustainability.

Real-time mix adjustment systems use machine learning to compensate for variability in constituent materials. Aggregate moisture content, cement batch variations, and temperature changes all affect fresh and hardened concrete properties. ML-based systems monitor incoming materials, predict effects on concrete performance, and recommend mix adjustments to maintain consistent quality.

Module 3: Steel and Metal Quality Assessment

Steel and other metals serve critical structural functions in construction, where material defects can have catastrophic consequences. Machine learning transforms metal quality assessment through automated defect detection, weld quality evaluation, and predictive corrosion modeling that enhance safety while improving inspection efficiency.

3.1 Defect Detection in Steel Components

Steel manufacturing and fabrication can introduce defects including surface cracks, inclusions, laminations, and dimensional variations that affect structural performance. Traditional inspection relies on visual examination and periodic non-destructive testing, which may miss defects or detect them only after components are installed. Machine learning enables automated, continuous inspection that improves detection rates while reducing inspection costs.

Computer vision systems using convolutional neural networks analyze images of steel surfaces captured by automated inspection cameras. These systems can detect surface defects with accuracy exceeding 95 percent, significantly outperforming human visual inspection for consistent defect identification. Production line implementation enables 100 percent inspection rather than statistical sampling, ensuring that defective products are identified before shipment.

Ultrasonic testing data analysis benefits significantly from machine learning interpretation. Traditional ultrasonic inspection requires skilled technicians to interpret complex signal patterns indicating internal defects. Neural networks trained on ultrasonic scan data and corresponding defect characterizations can automatically classify defect types, sizes, and locations with accuracy comparable to expert inspectors. This automation addresses the shortage of qualified NDE technicians while maintaining inspection quality.

Magnetic flux leakage testing for steel wire ropes and cables generates data patterns that machine learning excels at analyzing. Algorithms trained on MFL signals and corresponding wire rope conditions can predict remaining strength capacity, supporting replacement decisions before critical degradation occurs. Studies have demonstrated that ML-based analysis can extend inspection intervals while improving safety margins.

3.2 Weld Quality Evaluation

Welded connections are critical elements in steel construction where defects can significantly reduce joint capacity. Traditional weld inspection through radiography, ultrasonic testing, or magnetic particle examination requires skilled interpretation of test results. Machine learning enhances weld quality evaluation through automated image analysis and real-time monitoring of welding processes.

Radiographic weld inspection interpretation has been transformed by deep learning algorithms trained on thousands of radiographic images and corresponding defect assessments. These systems can identify porosity, slag inclusions, lack of fusion, and cracks with accuracy exceeding that of certified radiographic interpreters.

Automated radiographic interpretation reduces evaluation time from hours to minutes while providing consistent, objective assessments.

Real-time weld monitoring systems analyze current, voltage, and arc stability parameters during welding to predict weld quality before post-weld inspection. Machine learning models trained on welding process data and corresponding quality assessments learn relationships between process signatures and defect formation. These systems can alert welders to developing quality issues, enabling immediate correction rather than costly post-weld repairs.

Phased array ultrasonic testing data contains rich information about weld geometry and defects that machine learning effectively extracts. Deep learning models trained on phased array datasets can perform automated defect detection, sizing, and characterization. These capabilities support risk-based inspection approaches where resources focus on welds with higher probability of defects based on historical data and current test results.

3.3 Corrosion Prediction and Assessment

Corrosion represents a primary cause of steel structural deterioration, with annual costs estimated at over 2.5 trillion dollars globally according to NACE International. Machine learning enables more accurate corrosion prediction and assessment by analyzing environmental exposure data, material properties, and historical inspection results.

Atmospheric corrosion rate prediction traditionally relies on empirical models based on environmental classifications. Machine learning approaches incorporating detailed environmental monitoring data including temperature, humidity, chloride deposition, and pollutant concentrations provide more accurate location-specific predictions. Studies have shown that neural network models can reduce corrosion rate prediction errors by 40 to 50 percent compared to classification-based approaches.

Image-based corrosion assessment uses computer vision to quantify corrosion extent and type from photographs. Deep learning models trained on corrosion images with corresponding condition ratings can automatically evaluate structural steel condition from drone or inspection photographs. This capability enables more frequent, lower-cost condition assessment of structures in difficult-to-access locations.

Remaining service life prediction integrates corrosion models with structural capacity calculations. Physics-informed neural networks combine fundamental corrosion mechanisms with machine learning flexibility, predicting section loss progression and corresponding strength reduction. These predictions support maintenance planning and capital investment decisions for aging infrastructure.

Module 4: Soil and Geotechnical Material Analysis

Geotechnical engineering relies on accurate characterization of soil properties that exhibit significant natural variability. Machine learning addresses this variability by extracting patterns from extensive testing databases and site investigation data, enabling more reliable predictions of soil behavior under construction loading conditions.

4.1 Soil Classification Using Machine Learning

Soil classification provides the foundation for geotechnical design by categorizing soils based on physical properties and expected engineering behavior. Traditional classification systems such as the Unified Soil Classification System rely on grain size distribution and Atterberg limits, requiring laboratory testing of multiple samples. Machine learning enables rapid classification from field observations and limited test data.

Image-based soil classification uses computer vision to analyze photographs of soil samples. Deep learning models trained on soil images with corresponding laboratory classifications can identify soil types with accuracy exceeding 85 percent from visual inspection alone. This capability supports rapid field classification during site investigations, enabling more efficient sampling strategies.

Cone penetration test data provides continuous profiles of soil resistance that machine learning interprets for soil type identification. Neural networks trained on CPT data and corresponding boring logs learn relationships between tip resistance, sleeve friction, and pore pressure that indicate soil type. These models can classify soil layers with accuracy approaching that of experienced geotechnical engineers while providing consistent interpretation across different sites.

Geophysical data integration enhances soil characterization by combining multiple data types. Machine learning algorithms fuse seismic, electrical resistivity, and ground-penetrating radar data with boring and testing information to develop three-dimensional soil property models. This integration provides more complete site characterization than any single investigation method alone.

4.2 Compaction Quality Control

Earthwork compaction quality directly affects foundation performance and pavement durability. Traditional compaction testing through nuclear density gauges or sand cone tests provides point measurements that may not capture spatial variability across large earthwork areas. Machine learning enables continuous compaction monitoring and predictive quality assessment that improves both efficiency and reliability.

Intelligent compaction systems equipped with accelerometers measure roller drum vibration response during compaction. Machine learning algorithms correlate these measurements with conventional density test results, enabling continuous mapping of compaction quality across entire work areas. Research has demonstrated that IC systems can reduce density testing requirements by 60 to 80 percent while improving overall compaction uniformity.



Predictive compaction modeling uses machine learning to forecast the number of roller passes required to achieve target density based on soil properties and moisture content. These predictions enable more efficient compaction operations by avoiding both insufficient compaction and over-compaction that can damage some soil types. Field studies have shown that predictive guidance can reduce fuel consumption by 15 to 25 percent while achieving more consistent compaction results.

Moisture-density relationship prediction supports optimal moisture content targeting for compaction. Machine learning models trained on Proctor test results learn relationships between soil index properties and compaction characteristics. These predictions reduce laboratory testing requirements while ensuring moisture content during construction remains within optimal ranges.

4.3 Bearing Capacity Prediction

Bearing capacity determination governs foundation sizing for structures of all types. Traditional bearing capacity calculations rely on simplified analytical methods that may not fully capture soil variability and complex loading conditions. Machine learning enables more nuanced predictions incorporating extensive site investigation data and historical performance records.

Neural networks trained on databases of load tests and corresponding soil properties can predict bearing capacity with accuracy exceeding that of conventional methods for complex soil conditions. Studies

comparing ML predictions with load test results have shown mean prediction errors below 15 percent, compared to 25 to 40 percent for traditional methods in variable soil profiles.

Settlement prediction benefits significantly from machine learning approaches that capture complex soil-structure interaction effects. Models trained on monitored settlement data learn relationships between foundation geometry, loading conditions, and soil properties that affect settlement magnitude and distribution. This capability supports performance-based foundation design.

Pile capacity prediction from installation monitoring represents an emerging ML application. Machine learning models analyzing driving resistance during pile installation can predict ultimate capacity with accuracy sufficient to optimize pile lengths and reduce expensive load testing requirements. Some transportation agencies have begun accepting ML-based capacity verification for routine pile installations.

Module 5: Implementation and Future Directions

Successful implementation of machine learning for material testing requires careful attention to data quality, system integration, and professional standards. This chapter examines practical implementation considerations, data management requirements, and emerging technologies that will shape the future of ML-based quality assessment in construction.

5.1 Implementing ML-Based Testing Systems

Implementation of machine learning systems for material testing begins with identifying appropriate applications where ML provides clear value over traditional methods. Priority applications typically include those with large historical datasets, complex multi-variable relationships, or requirements for rapid, continuous assessment. Starting with focused pilot projects allows organizations to build expertise before broader deployment.

System architecture decisions affect both performance and maintainability. Cloud-based solutions offer scalability and reduced infrastructure requirements but require reliable connectivity and may raise data security concerns for sensitive projects. Edge computing deployments process data locally, supporting real-time applications and offline operation but requiring more local computing resources. Hybrid architectures combining local processing with cloud-based model training often provide optimal balance.

Integration with existing workflows requires attention to user experience and change management. Systems that augment rather than replace familiar processes typically achieve higher adoption rates. Visualization of ML predictions alongside traditional test results helps users develop appropriate trust in ML capabilities. Training programs that demonstrate ML accuracy and limitations enable informed use of these tools.

Validation and verification protocols ensure ML systems perform as expected under production conditions. Initial validation against held-out test data demonstrates model accuracy. Ongoing monitoring compares ML predictions with actual test results to detect model degradation or drift. Periodic recalibration with new data maintains prediction accuracy as material sources and production methods evolve.

5.2 Data Management and Quality Assurance

Data quality fundamentally determines ML system performance. The principle of garbage in, garbage out applies particularly to machine learning, where models trained on low-quality data will produce unreliable predictions. Implementing robust data quality assurance processes is essential for successful ML deployment.

Data standardization addresses the challenge of integrating information from multiple sources with different formats, units, and precision levels. Common data schemas for material testing enable aggregation of results across projects and organizations. Industry initiatives including buildingSMART's IFC and the Open Data Construction Alliance are developing standards that support ML applications.

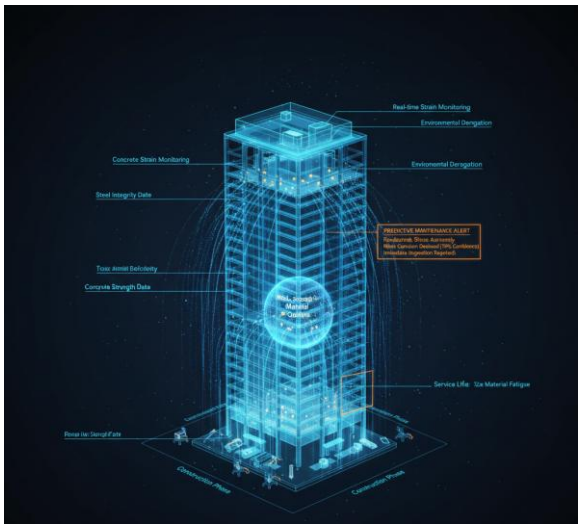
Historical data preparation often requires significant effort before ML training. Missing values, outliers, and inconsistent recording practices in legacy databases must be addressed. Feature engineering transforms raw test data into formats suitable for ML algorithms. Domain expertise is essential for these preparation activities to ensure that data transformations preserve meaningful information.

Ongoing data governance maintains quality as systems operate in production. Automated data validation checks identify anomalous inputs before they affect predictions. Audit trails document data provenance and processing history. Access controls protect sensitive information while enabling authorized use for model training and improvement.

5.3 Emerging Technologies and Industry Standards

The rapid evolution of machine learning technologies continues to expand capabilities for material testing applications. Large language models are enabling natural language interfaces for quality documentation and specification interpretation. Multimodal AI systems that integrate visual, textual, and numerical data promise more comprehensive quality assessment. Edge AI hardware advances are making sophisticated models practical for field deployment.

Digital twin integration connects ML-based material testing with broader building lifecycle management. Material quality data flows into digital twins that track building condition throughout service life. This integration supports predictive maintenance by connecting original construction quality with observed performance and deterioration.



Industry standards for ML applications in construction are emerging. ASTM International has established committees examining AI and machine learning standards for material testing. Professional engineering societies are developing guidelines for appropriate use of ML predictions in engineering decisions. These standards will provide frameworks ensuring that ML technologies are applied responsibly while enabling their benefits.

Regulatory acceptance of ML-based testing is progressing. Building codes increasingly reference performance-based approaches that ML supports. Transportation agencies are piloting acceptance of ML predictions for routine quality verification. As track records demonstrate ML reliability, regulatory frameworks will likely evolve to accommodate these technologies while maintaining safety standards.

The role of construction professionals evolves alongside ML adoption. Rather than replacing human expertise, ML systems augment professional capabilities by processing data at scales beyond human capacity and identifying patterns that might otherwise go unnoticed. Engineers and technicians who understand both traditional testing methods and ML capabilities will be positioned to leverage these tools effectively while maintaining the professional judgment essential for construction quality assurance.

Conclusion

Machine learning is transforming construction material quality testing from reactive sampling to predictive, continuous assessment. From concrete strength prediction that accelerates project schedules to automated defect detection that improves steel fabrication quality, these technologies enhance both safety and efficiency across the construction industry.

The applications examined in this course demonstrate the breadth of ML impact on material testing practice. Neural networks predict concrete properties from mix design parameters with accuracy exceeding 95 percent. Computer vision systems detect steel defects more consistently than human inspectors. Intelligent compaction monitoring ensures earthwork quality across entire construction sites rather than isolated test points.

However, successful implementation requires more than technology adoption. Data quality fundamentally determines ML system performance. Integration with existing workflows affects user acceptance. Professional standards are evolving to address appropriate use of ML predictions in engineering decisions. Organizations that address these implementation factors while building technical capabilities will realize the greatest benefits from ML-based quality testing.

As artificial intelligence continues advancing and as construction industry adoption accelerates, the integration of machine learning into material testing practice will deepen. Professionals who understand these technologies and their appropriate applications will be positioned to deliver higher quality construction while improving the efficiency of quality assurance processes. The built environment will benefit from materials that are better characterized, better predicted, and better controlled throughout the construction lifecycle.

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