Tech Brief

U.S. Department of Transportation
Federal Highway Administration

SUMMARY AND DISCLAIMERS

The purpose of this Tech Brief is to present random sampling practices and describe sample security measures for construction materials. The document is intended for highway agency and contractor engineers.

QUALITY ASSURANCE

RANDOM SAMPLING AND SAMPLE SECURITY

INTRODUCTION

State departments of transportation (State DOTs) and other transportation agencies often demonstrate responsible stewardship of public funds by ensuring pavements and other infrastructure reach their expected service lives. Variability in construction materials and the products produced with them should be accounted for in acceptance approaches. Consistent materials and construction can increase long-term project performance. Acceptance plans are a defined process for evaluating the acceptability of a lot of material (TRB 2018). Specifications and acceptance plans rely on random sampling and sample security to provide confidence in the test measurements and their evaluation.

The objective of this technical brief is to present effective practices and procedures for random sampling and sample security for construction materials used in Federal-aid highway infrastructure projects. Effective practices described in this technical brief can be applied to:

- Soils
- Base materials (including aggregate, stabilized base, and lean concrete)
- Materials used to construct flexible pavements (including liquid asphalt cement, aggregates)
- Materials used to construct rigid pavements (including cement, supplementary cementitious materials, aggregates)
- Constructed asphalt and concrete pavements
- Structural concrete and constructed bridge decks

Examples of implementation of these practices by State DOTs are also presented.

QUALITY ASSURANCE PROGRAM ELEMENTS

The requirements for State DOTs and contractors to implement quality assurance (QA) for Federal-aid projects on the National Highway System are detailed in 23 CFR Part 637 Subpart B – Quality Assurance Procedures for Construction (23 CFR 637). The requirements in 23 CFR 637 allow for different implementation approaches and as a result QA programs vary by agency. A QA program can be described in six elements:

- Agency acceptance
- Contractor quality control (QC)
- Independent assurance (IA)
- Technician qualification and certification
- Laboratory qualification and accreditation
- Materials testing dispute resolution

These elements are shown in Figure 1.

Figure 1. Core elements of a Quality Assurance program. Source: FHWA

Of the six elements in a QA program, four directly support reducing variability: IA sampling and testing, technician qualification and certification, laboratory qualification and accreditation, and materials testing dispute resolution (Dvorak 2019). Contractors may perform additional process control activities, beyond required QC, to ensure their processes are in control and to guide the contractor's corrective actions. If the contractor's QC test results are used in the acceptance decision, samples and tests must be performed by qualified or certified technicians (23 CFR 637.209(b)) in qualified or accredited laboratories (23 CFR 637.209(a)). QC sampling and testing must be performed independently from agency acceptance testing (23 CFR 637.205(d) and 23 CFR 637.207(a)(1)(ii)(B)), and QC sampling and testing must have been evaluated by an IA program (23 CFR 637.207(a)(1)(ii)(C)).

SPECIFICATIONS AND QUALITY CHARACTERISTICS

A quality characteristic is the characteristic of a unit or product that is measured to determine conformance with a given requirement (TRB 2018). State DOT material specifications provide limiting value(s) on quality characteristics, and often reference standards and guidance documents prepared as consensus documents by various organizations. These organizations could be a State DOT, the American Association of State Highway and Transportation Officials (AASHTO) or the ASTM International. Use of these standards is not a Federal requirement.

Materials quality specifications are a set of various constituent characteristics for a specific product, such as aggregates, asphalt mixtures, or portland cement. Quality specifications give limits for technical criteria such as asphalt content (AASHTO T 308), portland cement concrete compressive strength, and other quality requirements designated by the State DOT.

Acceptance testing is used to verify if the product is in compliance with State DOT specific requirements. Agencies must be able to provide evidence to support proper pavement consistent with the applicable Federal-aid project requirements. Many agencies have specific acceptance criteria for contract materials based on one or more quality characteristics.

VARIABILITY

Variability is present in all products and processes, including those used in highway construction. It is important for both contractor and agency personnel to understand what is being measured and recognize the influence of different sources of variability on the measurement.

When variability is low, a process is "in control" and the contractor is capable of producing a quality end product. If variability is high, issues can arise that cause a product not to meet specifications or result in an inconsistent product being constructed. Construction and materials variability can be grouped into four categories: materials, production, sampling, and testing (Cavalline et al. 2021a). These sources of variability combine to form the composite variability for a construction process (Figure 2).

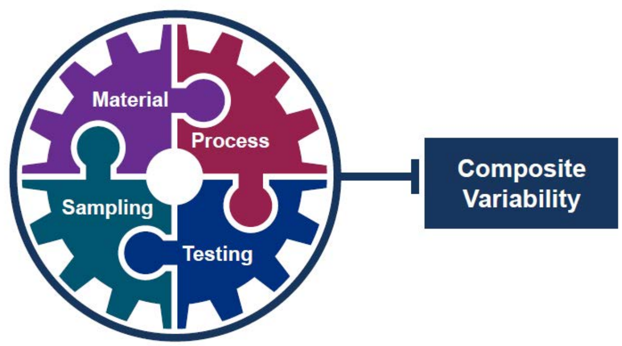

Figure 2: Sources of construction variability. Source: FHWA

Material variability is a result of variations in the raw materials, due to differences in their composition and properties such as strength, porosity, moisture content and other characteristics.

Process variability is incurred due to variation in equipment, operators, and the environment in which the work is performed.

Sampling and testing variabilities are influenced by a number of factors, including operators performing the sampling and testing, environmental conditions under which these activities are performed, and equipment used for sampling and testing.

Variability can be assessed using statistical methods, such as sample means, standard deviations, and confidence intervals. Steps can be taken to reduce variability in a process, including:

- Limiting changes in equipment, operators, and testing technicians
- Ensuring equipment is in good working order and/or calibrated
- Training personnel
- Using qualified or certified technicians
- Using qualified or accredited laboratories

SAMPLING PLAN

Agencies are required to have a QA program approved by FHWA (23 CFR 637.205(a) that includes a frequency guide schedule (23 CFR 637.207(a)(1)(i)(A). The frequency guide schedule can also be called a sampling plan. For each quality characteristic included in a QA program or a QC plan, a sampling plan should be developed to guide the process to obtain measurements (Burati et al. 2003). Often the minimum requirements for QC testing are specified by an agency. However, to maintain process control, contractors may need to perform testing in addition to the frequency required to be able to statistically characterize the material in production (Cavalline et al. 2021b).

When developing a sampling plan, many factors should be considered. Factors include the construction material or process of interest, the experience of personnel performing the sampling, safety, risk tolerance, and the potential for the process to change. To support statistical approaches, a sampling plan should be useful and comprehensive, provide reliable results, include activities that can be readily performed safely and efficiently, provide results that are accurately interpreted and used (Deming 1950). Sampling plans typically rely upon procedures including (but not limited to) those listed in Table 1.

The quantity and frequency of the material sampled for acceptance is generally based on requirements established by the State DOT. Intervals such as the number of hours of production, the quantity of material produced, the number of loads of material, production or delivery, or the order of arrival at the project site can be used to establish the number and timing (frequency) of sampling and testing.

Specifications typically require that work be divided into lots and sublots. Lots are a quantity of material to be accepted statistically. A stratified process is used to ensure random sampling locations are distributed throughout the lot which is important for large lot sizes. A selected number of sublots, such as four to five, can be statistically analyzed to determine quality and payment. Lot size, sublot size, and procedures for partial lots should be clearly addressed in agency specifications. The maximum number of samples or sublots per lot is determined by the agency and published in the specifications or contract requirements.

Once sampling and testing frequencies are established, the location or point of acceptance typically are determined by the specifying agency. For many materials and products constructed with them, agencies specify where samples are taken and how they should be taken. Samples can be obtained in a variety of locations:

- The production facility or plant (from stockpiles, belts, or flowing streams of material)
- At pits or quarries (for earthen materials)
- Vehicles or haul units
- At the point of placement (either before or after paving for roadway projects)

Table 1: Specifications commonly used for sampling and acceptance

Material or Need	Standard(s)
Aggregates	AASHTO R 90, “Standard Practice for Sampling Aggregate Products (AASHTO 2018)” ASTM D75, “Standard Practice for Sampling Aggregates (ASTM 2019)”
Hydraulic Cement	ASTM C183, “Standard Practice for Sampling and the Amount of Testing of Hydraulic Cement (ASTM 2022)”
Fresh Concrete	AASHTO R 60, “Standard Practice for Sampling Freshly Mixed Concrete (AASHTO 2012)” ASTM C172, “Standard Practice for Sampling Freshly Mixed Concrete (ASTM 2017)”
Bituminous Materials	AASHTO R 66, “Standard Practice for Sampling Asphalt Materials (AASHTO 2016)” ASTM D140, “Standard Practice for Sampling Asphalt Materials (ASTM 2016)”
Bituminous Paving Mixtures	AASHTO R 97, “Standard Practice for Sampling Asphalt Mixtures (AASHTO 2019)” ASTM D979, “Standard Practice for Sampling Asphalt Mixtures (ASTM 2022)”
Compacted Bituminous Materials	ASTM D5361, “Standard Practice for Sampling Compacted Asphalt Mixtures for Laboratory Testing (ASTM 2022)”
Probability Sampling of Materials	ASTM E105, “Standard Guide for Probability Sampling of Materials (ASTM 2021)”
Sample Size	ASTM E122, “Standard Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process (ASTM 2022)”
Acceptance	ASTM E141, “Standard Practice for Acceptance of Evidence Based on the Results of Probability Sampling (ASTM 2018)”

Note: Each standard listed in Table 1 is voluntary, and their use is not a Federal Requirement.

Upon establishing the point of acceptance, the standard practice for sampling should be determined.

SAMPLING APPROACHES

Several approaches exist for acquiring both QC and acceptance samples. Approaches can generally be categorized into random sampling and biased or selective sampling. Random sampling can also be called period-in-time sampling or population sampling. Biased or selective sampling can also be called time-order sampling, instant-in-time sampling, or process sampling (Cavalline et al. 2021a).

Random sampling must be performed when characterizing a population of material for use in the agency's acceptance decision (23 CFR 637.205(e)). In random sampling approaches, the random sample represents the entire output over a defined lot or sublot, and each portion of material or constructed product has an equal probability of being selected for sampling and testing. Simple random sampling approaches (Figure 3a) can result in samples being taken from a certain area of a lot, which may not represent the entire output.

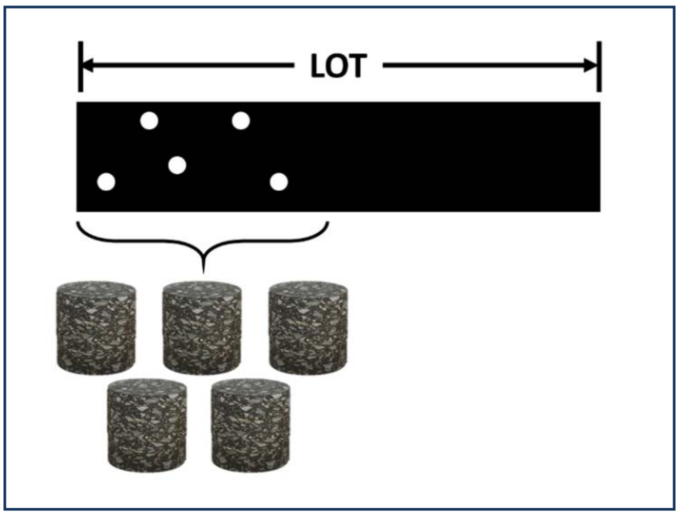

Figure 3a. Simple random sampling. Source: FHWA

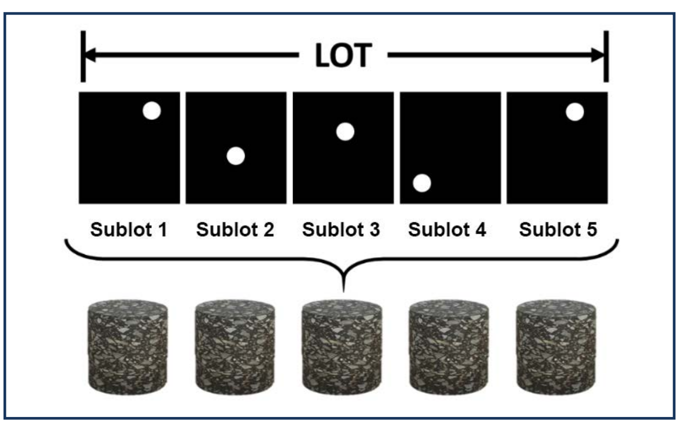

Figure 3b. Stratified random sampling. Source: FHWA

In stratified random sampling approaches (Figure 3b), lot(s) are divided into sublots, and sample location(s) are then randomly determined within each sublot. The incremental process of stratified random sampling is ongoing throughout the production or delivery process to properly represent the material and capture material and process variability discussed earlier.

Independent samples are selected without consideration of previous samples from the same lot and reflect all sources of variability associated with a material (FHWA 2004). 23 CFR 637.207(a)(1)(ii)(B) requires that independent samples be used for verification sampling and testing. Agency samples are always independent of contractor samples.

For both QC and acceptance samples, random sampling is critical to ensuring the integrity of the acceptance decision. Using separate random numbers to identify the locations of both QC and acceptance samples keeps them independent (Dvorak 2019). This approach ensures that these samples are taken independently and ultimately supports acceptance of a quality project that meets agency requirements. Samples for dispute resolution are normally split samples of the original samples, but otherwise follow the same practices and procedures as QC and agency acceptance samples.

When first examining what is to be sampled, a key decision should be made regarding variables (or axes) of interest. For example, there can be a single ("x") variable of interest or a two-variable ("x and y") situation. Sampling ready-mixed concrete from a truck is an example of a case where only a single variable of interest exists. In this case, only one random number is required to be generated to support identification of a sampling from the truck. Alternatively, sampling across a paved area (with both x and y axes) requires generation of two random numbers, which identify the station and offset at which the sample is taken.

Random number selection can be used to generate sublot sampling quantities if those quantities are required. Sublots are typically set at a common frequency such as every 10, 100, 500, 1000, 2000, or 4000 units of measurement.

Random number generation can often use tables, a software program's random number generation feature, or an online random number generator. Some agencies use procedures found in ASTM D3665, "Standard Practice for Random Sampling of Construction Materials (ASTM 2017)." Random numbers have also been shared from agency to contractor before sampling, which increases the risk of fraud and abuse. Agencies should ensure the integrity of random number generation and use. If changes are made to random numbers for any reason, the changes should be documented along with the reason for the change(s).

Biased or selective sampling can be useful in process control and production monitoring. While biased or selective sampling can be very useful for instances such as monitoring the startup of a process, it is not appropriate for many agency purposes such as acceptance.

EXAMPLES OF RANDOM SAMPLING PROCEDURES

A few approaches illustrating methods used by State DOTs to comply with 23 CFR 637 are provided below.

- The Kansas DOT (2022) Construction Manual provides procedures for securing random samples from a lot by use of random numbers obtained from tables or generated by other methods. A table of random numbers is provided, along with guidance on its use. Use of calculators and spreadsheets for producing random numbers is also described. Examples illustrating the use of random numbers in different types of sampling are presented, and are summarized below:
    - *Determining When to Sample* describes the use of the random number to identify a number of trucks, tons of production, or other unit, rounding up to the nearest whole number when a decimal value is obtained. It also describes how to use a random number to select a time of day or day of the week for sampling.
    - *Determining a Location for Sampling* describes the use of random numbers selected as “x” and “y” variables, and the process for converting these random numbers into the selected sample point station coordinates by directly multiplying the random number by the lot dimensions.
- Washington State DOT (WSDOT) Test Method T 716, “Method of Random Sampling for Locations of Testing and Sampling Sites” outlines the procedure for selecting sampling and testing sites in accordance with accepted “stratified” random sampling techniques (WSDOT 2017). The methodologies summarized below provide WSDOT’s sequences or criteria to sample randomly for several different conditions:
    - *Random Locations by Area (Method A) for asphalt pavement density* is designed for an “x and y” variable random number system generation. The “x” variable deals with the length of the sublot. The “y” variable deals with the width of the sublot. This example could apply to sampling and testing such as asphalt core locations or concrete pavement thickness measurement.
    - *Random Location by Weight/Tonnage (Method B) for HMA mixture or aggregate properties* is an “x” variable process that moves progressively forward through each sublot once the next sampling threshold is reached. Then the “x” variable is determined through the generation process and the process is repeated for each sublot. This approach uses a two-step process, using a random number to enter a number table to obtain another random number, which is then used to determine the weight or tonnage of material to be sampled.
    - *Random Sample by Truck/Hauling Vehicle (Method C) Cement Concrete (Structural)* is designed for placements of greater than 100 yd3 and is very similar to Method B. It considers the number of trucks used to place the concrete so one can choose a truck to sample from, rather than identify a sample based on a certain number of cubic yards of concrete delivered.

SAMPLE SECURITY

Sample security practices are essential to ensure that fraud, abuse, and/or negligence do not jeopardize an agency’s ability to procure materials and construct products that meet specifications.

The integrity of a sample should be maintained during collection, storage, and transport to ensure it is representative of the quality of the material on the project. The agency needs to take the sample or witness the sample being taken and then take possession of the sample or some alternative sample security procedures can be used as described in this section.

The adherence by all parties to appropriate storage practices (including curing and other environmental conditioning) and appropriate transport provisions is important to maintain sample integrity. If a sample is not cured properly or is damaged in transit due to carelessness, it could result in a payment determination that does not represent the actual quality of material on the project. The need for investigations on low-strength tests is reduced if proper curing and transport of concrete cylinders is ensured (Obla et al. 2018).

If agency personnel are in possession of acceptance samples from the point of sampling to delivery to the agency’s laboratory, the chance of tampering is minimized. However, this direct method of transport may not be possible in some situations. For example, if projects are in remote areas, or agency resources are limited, delays may occur between the time of sampling and pickup and delivery to the laboratory, and the potential for fraud or abuse of the samples exists. Non-agency personnel such as contractors and couriers may be involved in transporting samples, causing concern that samples may be mishandled or tampered (Bradbury 2019).

Figure 4. Security tape used by Maine DOT for asphalt mix samples. Source: Maine DOT

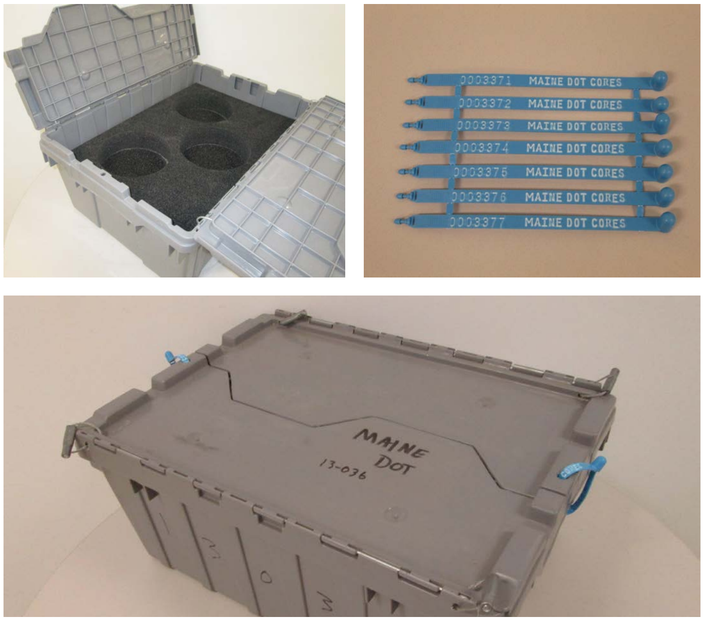

Figure 5. Tamper-resistant security tags on asphalt pavement core sample cases used by Maine DOT. Source: Maine DOT

Figure 6. Bar code labels used with tamper-evident tape by Iowa DOT. Source: Iowa DOT

Figure 7. Bar code tags used with tamper-resistant bag tags by Iowa DOT. Source: Iowa DOT

To ensure the integrity of the sampling program, security measures should be used to secure samples and prevent tampering. Appropriate forms and procedures to track the chain of custody and transfer information between parties should also be implemented. These measures provide confidence to the agency that the samples are secure while allowing personnel such as contractors to deliver acceptance and verification samples to agency or partner laboratories in a timely manner. Tamper-evident devices include security tape with a unique number every 12 inches so that the number is included in sample documentation (Figure 4) and security seals (e.g., numbered zip-tie locks) on specimen transport cases (Figure 5).

Security devices can be paired with technologies such as bar codes and other means to transfer documentation. As an example, Iowa DOT uses bar codes in conjunction with tamper-evident tape (Figure 6) and tamper-resistant bag tags (Figure 7). The security number on the bar code tape is also recorded on the appropriate forms required for submittal of the sample to the DOT laboratory (Iowa DOT 2020). Lab staff should check the documentation, comparing to the security device to verify compliance.

For concrete cylinders, controlling moisture loss and maintaining appropriate temperature control is critical during early stages to ensure concrete cylinder strength test results reflect the appropriate strength.

Appropriate curing containers should be used, and provisions implemented to maintain appropriate temperatures, particularly in hot or cold weather (Figure 8). To prevent tampering and theft, on-site curing containers should be clearly marked and secured. (Obla et al. 2018). On-site curing containers should also be secured so that specimens cannot be switched.

Figure 8. Use of beverage cooler for curing concrete cylinder specimen. A thermometer is placed in the curing container which is locked and clearly marked. Source: Michigan Concrete Association.

CLOSING

Consistent materials and construction can increase long-term project performance. Variability is inherent in all construction materials and products produced using these materials, and agency QA programs contain elements that support understanding and reducing variability. Agencies can use specifications that encourage and reward the contractor for providing a consistent product.

Quality characteristics are specified and measured to determine conformance with a given State DOT requirement. For each quality characteristic, a sampling plan is used to support quality control and acceptance. Sampling and testing aids agencies and contractors in understanding variability in materials and products and provides information to support quality control and the acceptance decision. Random sampling and sample security are important aspects of ensuring that the sampling and testing results accurately represent the materials on each project. Random sampling is crucial to safeguarding the value of data obtained as part of QA programs. Published standards exist to support sampling approaches for a variety of materials, as well as for sampling probability, calculating sample sizes, and acceptance based on sampling probability.

Biased (or selective) sampling can be used to support process control, but is not appropriate for most agency purposes, including acceptance.

It is imperative that the State DOT takes possession of samples immediately after they are obtained. If this is not feasible, qualified personnel must use appropriate sample security measures to deliver the sample. Security practices for samples implemented by agencies should eliminate fraud, abuse, or negligence from impacting the integrity of the acceptance decision.

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