# Floor Leveling Mortar Quantity Estimation in High-Rise Buildings

by
Belle Junge Riehemann

A thesis submitted to the Department of Construction Management,
College of Technology
in partial fulfillment of the requirements for the degree of

Master of Science
in
Construction Management

Committee Chair: Dr. Ahmed Senouci
Committee Co-Chair: Dr. Neil Eldin
Committee Member: Dr. Zia Din

University of Houston
May 2022

# DEDICATION/EPIGRAPH

This paper is dedicated to my parents and husband who have been a great support throughout my personal and professional development all these years.

# ACKNOWLEDGMENTS

I would like to thank my advisors Dr. Ahmed Senouci and Dr. Neil Eldin for their support and understanding this past academic year. The journey to a final thesis topic was long and winding and I appreciate the time Dr. Senouci and Dr. Eldin have taken to allow me to pursue this passion.

# ABSTRACT

Concrete floors often present severe surface regularity requirements for flooring installation. Floor regularity is normally an evaluation of the differences between the points' elevation on the real surface with respect to an ideal reference plan.

The surface regularity is defined and controlled regarding two characteristics. The first one, which is called (FF) "floor flatness," evaluates the surface regularity over a short distance. Secondly, (FL) "floor levelness" evaluates the surface regularity over a longer distance. Self-leveling mortars are commonly used to increase the flatness and levelness of concrete floors and improve their surfaces. The American Society for Testing and Materials (ASTM) provides guidelines (i.e., FF and FL limits) for floor leveling. However, these guidelines do not give an estimate for self-leveling mortar needed to achieve an acceptable concrete floor surface. As a result, flooring contractors do not usually provide a cost estimate for floor leveling. This situation places general contractors at a high risk of submitting a lower bid during the bidding process. Therefore, there is a need to develop regression (mathematical) models that could predict, based on FF and FL testing, the number of self-leveling mortar bags needed.

In the proposed work, regression models were developed for the predicting the number of self-leveling mortar bags using FF and FL testing. Limited research is available for using FF and FL testing to predict the amount of floor leveling needed on a project currently. Floor leveling has caused significant budget overruns for general contractors over the years. A multifamily high-rise project was used as a case study to generate the FF and FL testing data for the development of the prediction models.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# CHAPTER 1
# INTRODUCTION

## Problem Statement

Accurately estimating the amount of floor leveling is a common recurring problem in high-rise concrete buildings. The amount of self-leveling mortar is often underestimated. At times, this item is completely overlooked resulting in bubbling or creaking of the finish flooring on the concrete floor.

The burden of determining the necessary floor leveling mortar is frequently placed on the project team prior to awarding the flooring subcontract. Typically, this amount would be–largely determined by the amount of money left in the budget or arbitrarily dictated by the project owner.

Surprisingly, there are not many tools available to accurately estimate the floor leveling mortar in a building. However, many vendors include 'calculators' on their websites for determining floor leveling. But these tools are only useful when the thickness of the leveling (in inches) and the area needing leveling are known. The challenge for an estimator is to determine the thickness of leveling, as the concrete surface varies from one location to another, especially in post tensioned decks.

Additionally, flooring contractors will not provide an estimate based on concrete specifications and will not take on liability for a floor leveling budget cap on the entire project. To complete an estimate, the estimator / contraction is placed with the responsibility of assigning a budget to self-leveling mortar. This can result in floor leveling going over budget or not enough floor leveling being used in the building to stay within budget, leading to flooring problems in the future. This paper proposes that FF and FL testing specifications can be used to develop a budget for self-leveler.

## Problem Significance

Preparing an accurate estimate for self-leveling mortar in concrete buildings is a common problem for general contractors. Flooring contractors are only willing to commit to an allowance (specified by the general contractor) to cover the floor leveling work. They are not willing to commit up front to a binding price. Over the years, flooring contractors have become wary of providing fixed prices because of the wide variations expected in concrete floor slabs (e.g., surface flatness, surface levelness, etc.). As a result, the general contractor may just proceed with a floor leveling allowance equal to the uncommitted amount left in the flooring budget.

## Proposed Solution

There are standard tests that measure floor FF and FL values. This study attempted to use the standard tests to accurately estimate the amount of floor leveling necessary for properly installing floor finishes. A case study was also included to validate the proposed solution.

## Study Beneficiaries

Finding a solution to this problem would be a great benefit to both general contractors and flooring contractors. By being able to accurately estimate how much floor leveling is needed on a project, the general contractor and the flooring contractors can prepare more accurate estimates/prices for the owners while avoiding budget overruns.

# CHAPTER 2
# LITERATURE REVIEW

The literature search has revealed that the research on concrete floor leveling falls under three major areas, namely, self-leveling mortar, leveling devices, and leveling standards. The following sections describe the research conducted in the three areas.

## Self-leveling Mortars

Extensive research work has been conducted on the development of innovative self-leveling mortars to speed up construction processes, increase productivity, improve quality, and reduce costs [1-3]. Self-leveling mortars flow due to gravity without the need for vibration or compaction. They permit a quick filling of large areas with small thickness as shown in Figure 2.1.

Figure 2.1. (a) Traditional semi-dry cementitious screed (b) Self-leveling mortar [1]

Self-leveling mortars must have adequate performance in the fresh state and must meet the requirements of strength and surface properties in the hardened state (i.e., an abrasion-resistant surface without cracks, undulations, or stains). Their required properties include thickness range, self-flowing, release, and self-drying times, strength development, and maximum length change. ASTM C1708/C1708M-19 describes the test methods for self-leveling methods to evaluate flowability, workability time, and the physical properties such as setting time, compressive and flexural strength, and length change. It classifies hydraulic binder-based self-leveling mortars into two types depending on each application: self-leveling underlayment (SLU) that receives top coatings such as ceramic tiles, laminate, vinyl, textiles, wood, resin-coated, or raised flooring [2]; and self-leveling overlayment (SLO), which is used as a wear surface, without the need of a protective layer. Both types are used for surface regularization with thicknesses of 1 to 10 mm [3].

## Leveling Devices

Flatness is an important quality evaluation parameter for concrete floors. Floor flatness inspection methods can be divided into contact and non-contact types [4]. The contact type methods involve an instrument that directly contacts the floor to collect relevant data. This includes the following methods: straightedge [5], leveling method [6], and profiler method [7–9]. The straightedge method, which uses a feeler gauge to measure the gap width between the straightedge and the floor, is widely used because it is easy to understand and inexpensive. However, its efficiency is low and only suitable for sparse point sampling inspection. Moreover, there is no specification on how to locate the straightedge on the surface, which results in low accuracy when the inspection is repeated. The leveling method uses a leveling gauge to measure the floor relative height. It is easy to conduct, but the degree of automation is low, which makes the method unsuitable for a large floor. The profiler is a measuring instrument with two feet at the bottom that walks along the planned route. It has the advantages of high repeatability and automation. However, only the overall flatness of the floor can be evaluated.

The non-contact type flatness inspection methods refer to measurement through technology such as photogrammetry [10-11], three-dimensional laser scanning [12–17], etc. Photogrammetry uses a camera to capture the target from different perspectives and calculates the three-dimensional coordinates of the target with high accuracy. The vertical and horizontal accuracy can reach up to one tenth of a millimeter [11]. However, this method requires cooperating markers set on the ground. This step is very time-consuming for super-large floors and will have a certain impact on the construction. LiDAR (Light Detection and Ranging) is a common instrument for intensive and accurate three-dimensional shape scanning. There are existing flatness quality evaluation methods for cast-in-place ground and prefabricated components [12]. It can be integrated with BIM (Building Information Modeling) with high accuracy and large data volume [15]. LiDAR is more suitable for small areas and rooms.

A large-scale floor flatness inspection method was proposed based on wheeled robot with aided INS (Inertial Navigation System) [18]. It aims at a rapid and high-precision flatness inspection of large indoor floors. The wheeled robot integrates high-precision INS, odometers, and prism, and an automatic tracking total station is used to track the prism on the robot to obtain its planar position at the same time. This method can provide support for the quality inspection of larger floors and guide the adjustment of flatness.

## Leveling Standards

Currently, the flatness and levelness of concrete surfaces are determined by the floor flatness (FF) test and floor levelness (FL) tests. The development of these two tests is attributed to Allen Face, a naval architect and marine engineer. He saw the need for more reliable tests after witnessing a warehouse with deviations in concrete exceeding ¾" over a four-foot span [19]. These two tests were quickly adopted in the following years by the American Society for Testing and Materials (ASTM), and the American Concrete Institute (ACI). The standard associated with FF and FL testing is ASTM E1155-20 (Standard Test Method for Determining FF Floor Flatness and FL Floor Levelness Numbers). The following presents a brief description of the ASTM and the ACI standard tests.

ASTM E1155-20 is the standard that outlines the test method for determining FF and FL. It begins with an explanation of tools needed to perform the test. There are two types of apparatuses that are used to complete the test. Type I apparatus includes leveled straightedges, optical levels, laser levels, taut level wires, floor profilers, and laser imaging devices. Type II apparatus consists of inclinometers and longitudinal differential floor profilometers. The main qualification of an apparatus to perform the testing is that it is "capable of measuring the elevations of a series of points spaced at regular 12 in. intervals along a straight line on the floor surface" [7]. The agency performing the inspection may choose between a Type I or Type II apparatus. Type I apparatus requires at least 12 sequential point elevation measurements whereas Type II apparatus requires 11. In addition to an apparatus, ASTM E1155-20 calls for a measuring tape, chalk lines and means by which to record the data.

The following steps describe the procedure for measuring FF and FL outlined in ASTM E1155-20:

1. Record the following information: name and location of the building being tested along with installation date of the floor, the FF and FL values specified, the make, model, and serial number of the test apparatus, the date of testing, and the name of the person performing the test.
2. Lay out the test surface according to ASTM requirements. The measurement lines, also called runs, should be diagonal across the surface and not parallel to each other. The party performing the test will use chalk lines to lay out the runs for the testing.
3. Collect the test samples accordingly with the apparatus type chosen. Figure 2.2 (left) shows a dipstick floor leveler, a type I apparatus. This is a common apparatus used to perform FF and FL testing. Figure 2.2 (right) pictures a man walking the dipstick along the chalk line to take measurements. The dipstick records the distance and elevation as it is walked along the runs.
4. Perform calculations using the test data. The dipstick floor profiler completes this step for the party performing the test by providing the profile shown in Figure 2.3. The dipstick plots the elevation on the Y-axis and the length (in feet) on the X-axis and shows the FF and FL number for the individual runs.

5. Issue a report listing the calculation results for each run and the calculated overall FF and FL numbers. The overall FF and FL numbers are taken by completing an area-weighted average of the test area's runs.

Figure 2.2. Dipstick Floor Profiler Used to Collect Data [20]

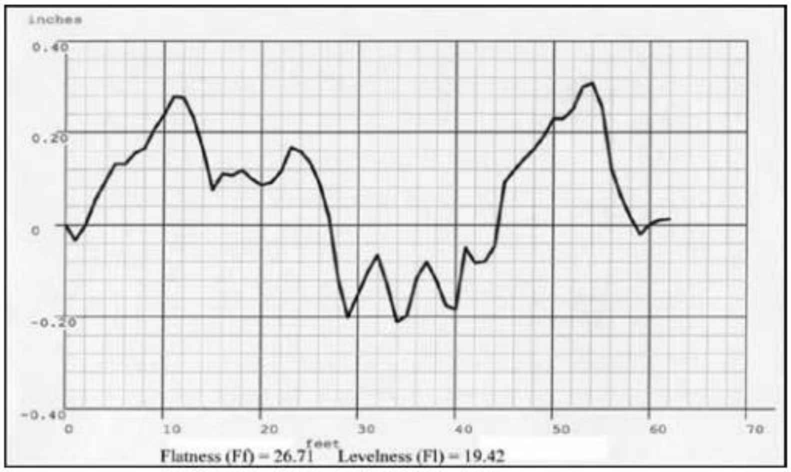


Figure 2.3. Test Run Profile [20]

ASTM F2873-13 is the standard practice for the installation of self-leveling underlayment and the preparation of surface to receive resilient flooring [21]. It consists of general guidelines and information concerning how self-leveling underlayment should be installed. This standard provides a procedure for the install floor levelers, described in the following steps.

1. The design loads for the surface receiving floor leveling must be verified to ensure the subfloor can support the floor leveling.
2. The subfloor should be cleaned and clear of any trash or debris in accordance with the floor leveler's manufacturer instructions.
3. The concrete leveler is installed according to manufacturer instructions.

ASTM F2873-13 plays a role in calculating floor leveling, as the second step may require attention from the concrete contractor if excessive concrete debris or inconsistencies are found. This standard also notes minimum thickness of floor leveling if not otherwise defined by the manufacturer.

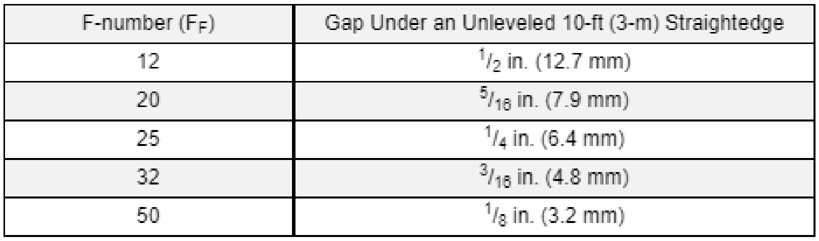
ACI 117-10 includes the specification for tolerances for concrete construction and materials. It provides general guidelines for concrete construction according to the application of concrete. However, this specification defers to ASTM E1155-20 regarding flatness and levelness. The commentary from the ACI Committee notes that a remedy for non-compliance should be outlined in the design specifications, but this appears to be uncommon in practice. Rather, as alluded in ASTM F2873-13, defects of significant magnitude should be remediated, such as excess concrete left on the surface of a floor. ACI defines an overall FF value of 25 and FL value of 20 as a 'moderately flat' floor. ASTM and ACI standards provide recommendations for FF and FL testing, concrete state prior to floor leveling, and how to level floors. However, they do not provide information on how much floor leveling will be needed for the tested surface.

## Current State of The Art

Following the testing method outlined in ASTM E1155-20, the provided FF and FL numbers are compared to the design specifications. The FF and FL tests simply provide a means to prove compliance with the flatness and levelness specified for the concrete surface. There is no known procedure that explains how to use the FF and FL tests to estimate the quantity of floor leveling needed for a project.

However, ASTM F710-21 (Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring) correlates the FF and FL testing to the traditional straightedge method [22]. It provides a table labeled "Rough Correlations Between F-Numbers and Straightedge Tolerances," shown below in Table 2.1. An FF number of 25 is compared to a ¼" gap under a 10-foot straightedge.

Table 2.1. ASTM F710-21 "Rough Correlations Between F-Numbers and Straightedge Tolerances" [22]



| F-number ($F_F$) | Gap Under an Unleveled 10-ft (3-m) Straightedge |
|---|---|
| 12 | $^1/_2$ in. (12.7 mm) |
| 20 | $^5/_{16}$ in. (7.9 mm) |
| 25 | $^1/_4$ in. (6.4 mm) |
| 32 | $^3/_{16}$ in. (4.8 mm) |
| 50 | $^1/_8$ in. (3.2 mm) |

While this table suggests that the two methods are correlated, there is no call for remediation if the concrete surface meets the FF testing requirements but not the straightedge tolerances. The FF testing requirement is the sole obligation outlined in the specification. When met, there is no work made to meet a straightedge tolerance. This study attempted to use the FF and FL tests to estimate the floor leveling quantities.

## Current Practice

When estimating floor leveling, it is common practice to include an allowance to cover the amount of floor leveling. The finalization of such a budget is then left to the contractor's project management team. Budget finalization usually takes place during the phase of awarding subcontracts on the floor finishes. The budget for the floor leveling is usually subjectively determined by the contractor following a guideline of leveling 25% of the eligible flooring area. This percentage is provided by the contractor’s estimating team and the amount is typically equivalent to some or all of the assigned budget allocated for the floor finishes.

# CHAPTER 3
# MODEL DEVELOPMENT AND TESTING

## Methodology

This study presents a procedure that uses the flatness and levelness standard test results to accurately estimate the amount of floor self-leveling mortar bags that are necessary for installing floor finishes. Actual project data was used to develop a mathematical model that relates the number of self-leveling mortar bags to concrete floor flatness and levelness results.

The following procedure, which will be explained further in the next chapter, was used for the development of the models:

1. As noted in the ASTM E1155-20 testing procedure, the profilometer or dipstick presents the FF and FL data on an X and Y graph. The X and Y coordinates are in feet and inches, respectively.
2. The collected data is used to determine maximum Y values and average elevations for each run.
3. Regression models that relate the actual floor leveling mortar bags to average elevations, are developed using Microsoft Excel.
4. The models' coefficients are multiplied by the elevation to yield the predicted number of mortar bags per square foot.
5. The calculated number of bags per square foot is then multiplied by the leveled area to predict the number of floor leveling mortar bags.
6. The leveling budget is obtained by multiplying the predicted number of mortar bags by their unit cost.

### Model Development

Data from a total of 82 runs spanning over eight floors was compiled for the model development. It was randomly divided in training and testing sets. The training set, which included 80% of the total data, was used for model development. On the other hand, the testing set, which included 20% of the total data, was used for model testing. Each measurement line or run spanned 31 to 53 feet long, as shown in Figure 3.1. Reports were provided by the testing agency. Each report covered half of the building floor plan, or around 5000 square feet, which is outlined in red in Figure 3.1. Each report consisted of 6 to 8 runs, or 12 to 16 runs per floor. Each arrow in the figure indicates the location of a run.

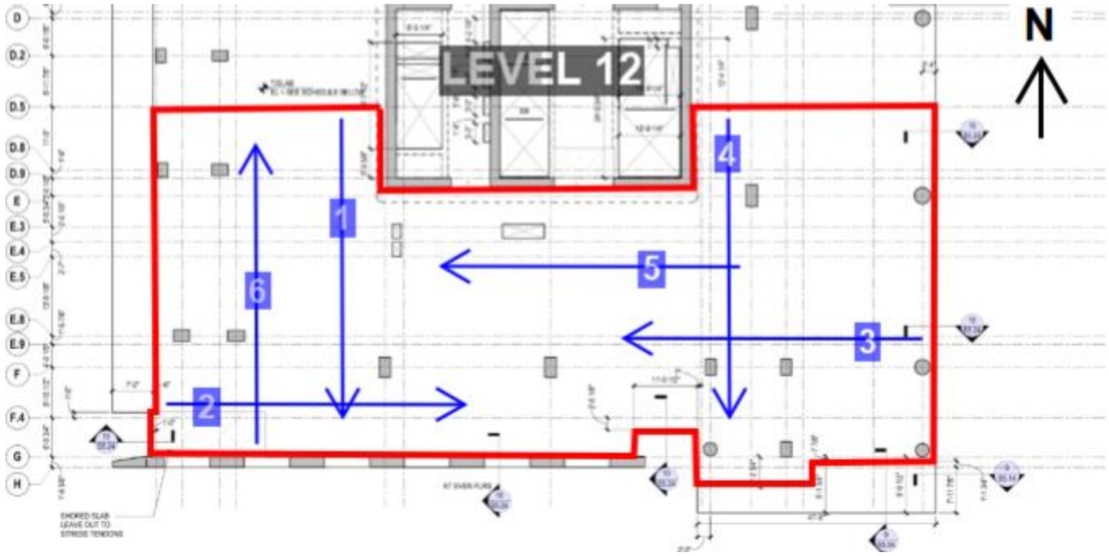


Figure 3.1 – Case Study 12th Floor Testing Report Runs

The elevation was measured at each foot of the run using a dipstick. The dipstick plotted the data on a graph with feet and inches in the X and Y axes, respectively as shown in Figure 3.2.

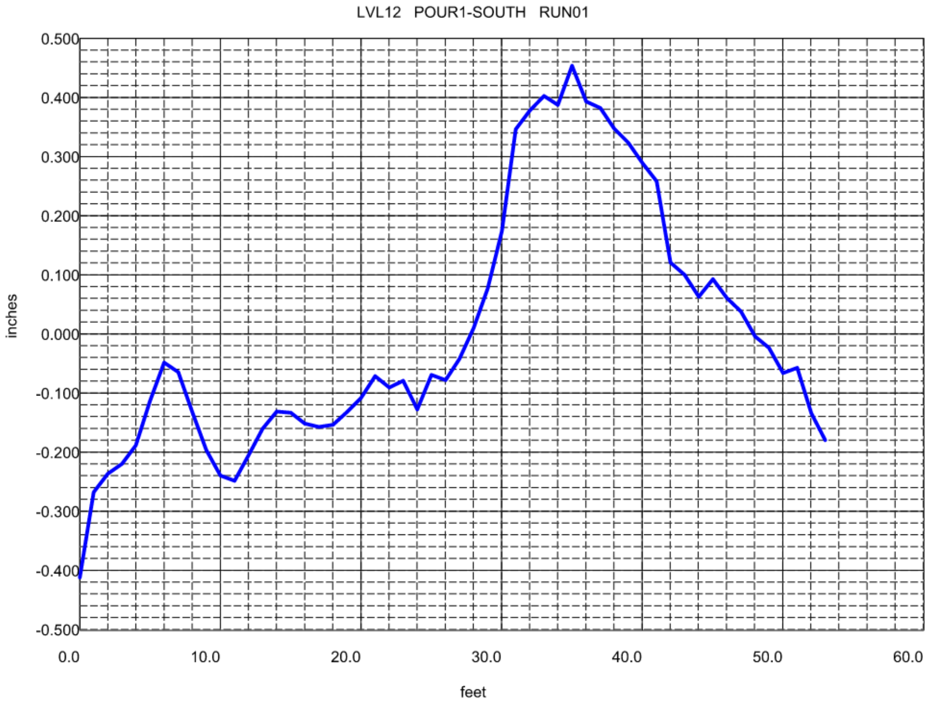


Figure 3.2. Case Study 12th Floor Individual Run Data

The following steps summarize the model development procedure:

1. The data from each run was broken down into X and Y coordinates, as the dipstick only provides a graphical representation of the data and not the individual data points.
2. The maximum elevation, $Y_{max,}$ on the Y-axis for each run was determined using the following equation:

$$Y_{max} = Max\left(Y_1, Y_{2,}Y_3, \ldots, Y_n\right)\ (n = number\ of\ data\ points)$$

3. The elevation, $Elev_x$, was calculated for each individual run by multiplying the distance of each interval (in feet) by the average slab deviation (in inches) and dividing by the total distance of the run (in feet). This is represented by the following equation:

$$Elev_x = \frac{\left[\frac{Abs(Y_{max}-Y_1)+Abs(Y_{max}-Y_2)}{2}\right]*[X_2-X_1]+\cdots\ldots\ldots+\left[\frac{Abs(Y_{max}-Y_8)+abs(Y_{max}-Y_9)}{2}\right]*[X_n-X_{n-1}]}{[X_n-X_1]}$$

4. The run area was determined by adding the area of laminate flooring in each apartment (unit) that the run crossed. Some runs only went through one unit, while others involved multiple units. Figure 3.3 shows examples of the runs shown on a floor plan. The light gray lines denote demising walls between apartments. For example, run 4 crosses units 1 and 2, therefore the area of run four would include the areas of units 1 and 2 added together.

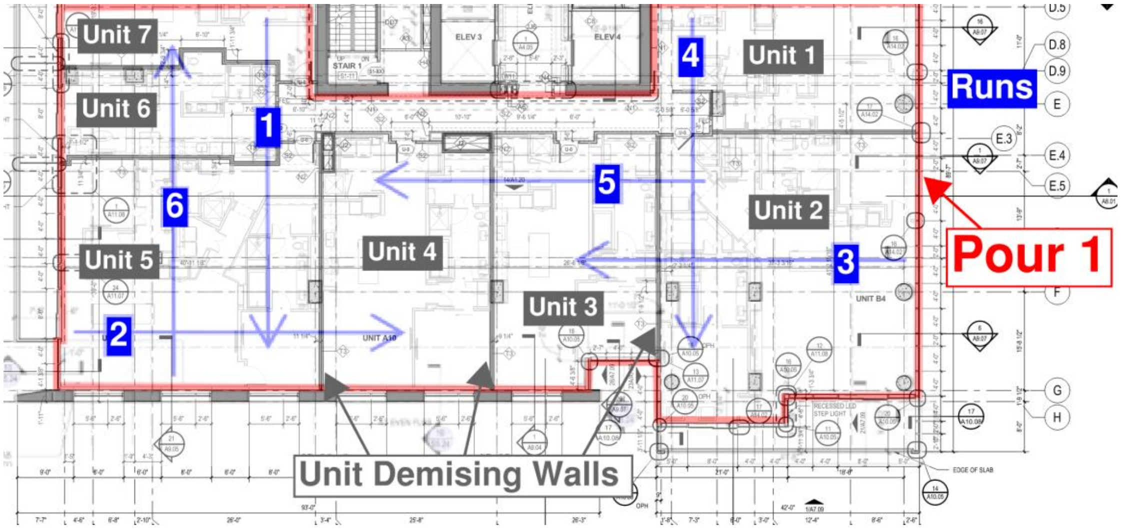


Figure 3.3. Case Study 12th Floor Overlay

5. The number of mortar bags used per run was then determined. This was calculated by adding the actual number of floor leveling mortar bags by unit using actual project data from the case study. Therefore, like in step 4, the number of bags associated with run 4 was determined by adding the bags used in units 1 and 2.
6. Table 3.1 summarizes the data collected from level 12.
7. The number of bags per square foot was determined by dividing the number of bags by the area for each run.
8. The training data set was used to develop regression models that correlate the computed average floor elevations to the number of self-leveling mortar bags used per square foot. However, the scatter plot of the training data set, which is shown in Figure 3.4, shows a weak correlation between floor elevations and the number of self-leveling bags used per square foot.

Table 3.1. 12th Floor Data Summary

| **Level-Pour** | **Run** | **Elevation** | **Area** | **Bags Used** | **Bags/SF** |
|---|---|---|---|---|---|
| 12-P1 | 1 | 0.450 | 1969.38 | 64 | 0.032 |
| 12-P1 | 2 | 0.415 | 1861.72 | 60 | 0.032 |
| 12-P1 | 3 | 0.414 | 2080.06 | 68 | 0.033 |
| 12-P1 | 4 | 0.394 | 2689.19 | 113 | 0.042 |
| 12-P1 | 5 | 0.307 | 2893.89 | 92 | 0.032 |
| 12-P1 | 6 | 0.190 | 1969.38 | 64 | 0.032 |
| 12-P2 | 1 | 0.179 | 2005.31 | 49 | 0.024 |
| 12-P2 | 2 | 0.386 | 1616.72 | 45 | 0.028 |
| 12-P2 | 3 | 0.157 | 1616.72 | 45 | 0.028 |
| 12-P2 | 4 | 0.142 | 702.98 | 22 | 0.031 |
| 12-P2 | 5 | 0.335 | 755.83 | 20 | 0.026 |
| 12-P2 | 6 | 0.270 | 1856.8 | 54 | 0.029 |
| 12-P2 | 7 | 0.295 | 1856.8 | 54 | 0.029 |
| 12-P2 | 8 | 0.463 | 2494.01 | 103 | 0.041 |

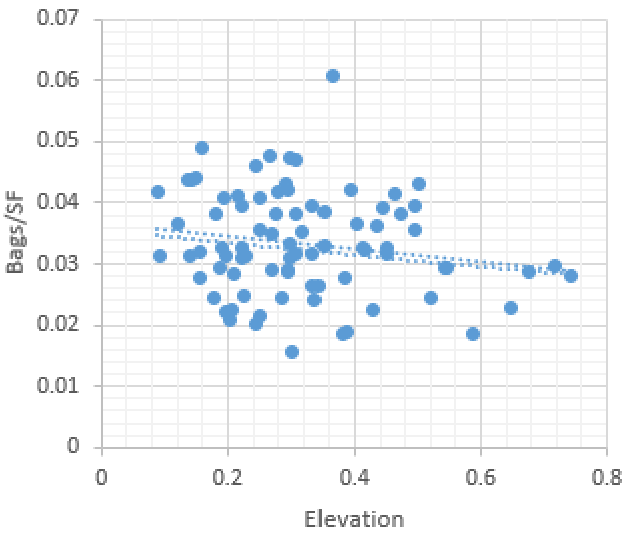
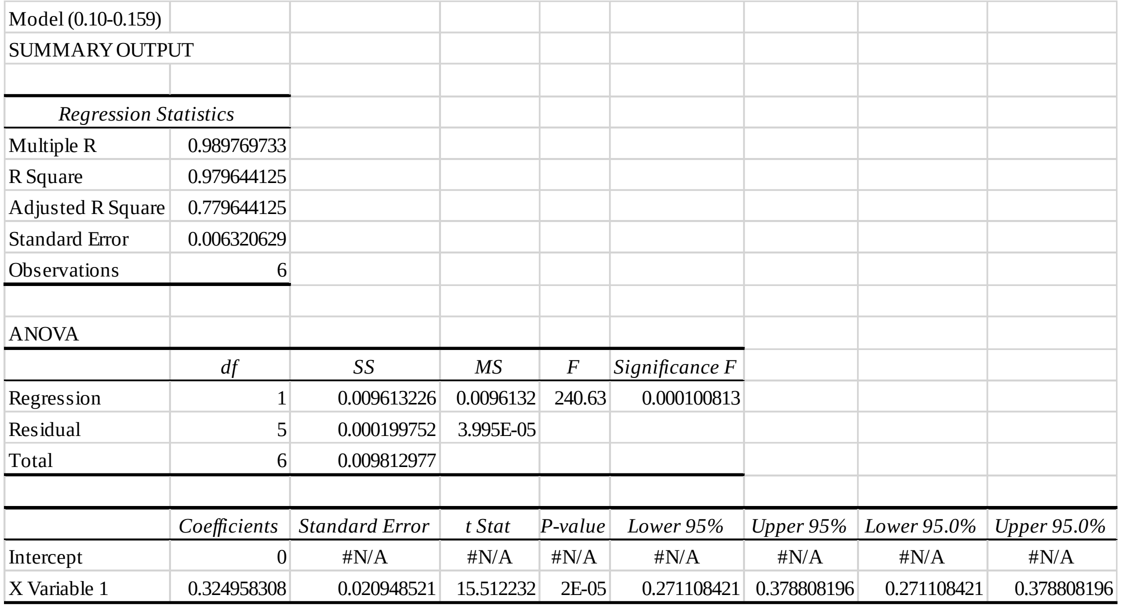


Figure 3.4. Floors 11 to 18 Data Scatter Plot

9. Because of its weak correlation, the data was divided into smaller sets of elevations (i.e., elevations between 0.100-0.149, 0.150-0.199, 0.200-0.249, 0.250-0.299, 0.300-0.349, 0.350-0.399, 0.400-0.449, 0.450-0.499, 0.500-0.599, 0.600-0.699, and ≥0.700). Eleven regression models were developed using the training data set (i.e., one model for each small data set). Table 3.2 summarizes the developed models (i.e., model number, floor elevation range, model coefficient, and R value). The model number represents the model developed from the elevation ranges. The coefficient and multiple R value, or correlation, are pulled from the model's statistical results, an example of which is shown in Figure 3.5.

Table 3.2. Linear Regression Model Results

| Models | Elevation | Coefficient | Multiple R |
|---|---|---|---|
| 1 | 0.100-0.149 | 0.325 | 0.9898 |
| 2 | 0.150-0.199 | 0.213 | 0.9728 |
| 3 | 0.200-0.249 | 0.141 | 0.9718 |
| 4 | 0.250-0.299 | 0.122 | 0.9771 |
| 5 | 0.300-0.349 | 0.102 | 0.9572 |
| 6 | 0.350-0.399 | 0.091 | 0.9224 |
| 7 | 0.400-0.449 | 0.078 | 0.9875 |
| 8 | 0.450-0.499 | 0.077 | 0.9964 |
| 9 | 0.500-0.599 | 0.053 | 0.9497 |
| 10 | 0.600-0.699 | 0.039 | 0.9958 |
| 11 | >=0.700 | 0.039 | 0.9987 |



Model (0.10-0.159)

SUMMARY OUTPUT

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.989769733 |
| R Square | 0.979644125 |
| Adjusted R Square | 0.779644125 |
| Standard Error | 0.006320629 |
| Observations | 6 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 0.009613226 | 0.0096132 | 240.63 | 0.000100813 |
| Residual | 5 | 0.000199752 | 3.995E-05 | | |
| Total | 6 | 0.009812977 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | 0 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| X Variable 1 | 0.324958308 | 0.020948521 | 15.512232 | 2E-05 | 0.271108421 | 0.378808196 | 0.271108421 | 0.378808196 |

Figure 3.5. Model 1 Statistical Results

## Model Validation

The developed models were validated using the testing data set (i.e., 20% of total data set). The data taken from levels 20 and 22 of the building totaling 16 runs and 19.2% of the total data was used to test the developed models. The calculated number of self-leveling bags were compared to the actual number of bags used on the project to determine if the models were accurate in predicting the amount of self-leveling mortar needed.

The validation included the following computational steps:

1. The predicted number of self-leveling mortar bags per square foot were obtained using the developed linear regression models. For example, the predicted number of self-leveling mortar bags per square foot for model 1, which is equal to 0.427, was obtained by multiplying model 1 coefficient (i.e., 0.325) by the average floor elevation (i.e., 0.131).
2. The total number of self-leveling mortar bags was obtained by multiplying the number of bags per square foot by the total run (floor) area, $A$.
3. The predicted total number of bags was compared to the actual number of bags used, as shown in the next section.

Table 3.3 summarizes the model testing results, which show that the percent difference between the predicted and actual numbers of self-leveling mortar bags had average value of 0.21 and a standard deviation of 0.14. This is an indication that the developed models were able to predict the number of self-leveling mortar bags with a reasonable accuracy. However, it is worth noting that more data from other projects is needed to be able to fully validate the developed models.

Table 3.3. Model Testing Results

| Elevation | Bags/SF | Coefficient | # of bags/ft2 | Area | Bags Calculated | Actual Bags Used | % Difference |
|---|---|---|---|---|---|---|---|
| 0.131 | 0.050 | 0.325 | 0.042659 | 1393.04 | 59 | 70 | 0.15 |
| 0.148 | 0.047 | 0.325 | 0.048224 | 2372.55 | 114 | 112 | 0.02 |
| 0.159 | 0.058 | 0.325 | 0.051606 | 1616.72 | 83 | 93 | 0.10 |
| 0.193 | 0.037 | 0.213 | 0.041012 | 2005.31 | 82 | 75 | 0.10 |
| 0.222 | 0.055 | 0.141 | 0.0313 | 702.98 | 22 | 39 | 0.44 |
| 0.229 | 0.048 | 0.141 | 0.032258 | 1616.72 | 52 | 78 | 0.33 |
| 0.239 | 0.048 | 0.141 | 0.033712 | 702.98 | 24 | 34 | 0.30 |
| 0.264 | 0.050 | 0.122 | 0.0322 | 2494.01 | 80 | 125 | 0.36 |
| 0.276 | 0.042 | 0.122 | 0.033661 | 1475.04 | 50 | 62 | 0.20 |
| 0.295 | 0.054 | 0.122 | 0.036025 | 755.83 | 27 | 41 | 0.34 |
| 0.305 | 0.032 | 0.102 | 0.031222 | 1856.8 | 58 | 60 | 0.03 |
| 0.317 | 0.045 | 0.102 | 0.032425 | 755.83 | 25 | 34 | 0.28 |
| 0.320 | 0.031 | 0.102 | 0.032729 | 2494.01 | 82 | 77 | 0.06 |
| 0.336 | 0.032 | 0.102 | 0.034372 | 1856.8 | 64 | 60 | 0.06 |
| 0.371 | 0.058 | 0.091 | 0.033668 | 1616.72 | 54 | 93 | 0.41 |
| 0.469 | 0.048 | 0.077 | 0.036186 | 2559.78 | 93 | 123 | 0.25 |
|  |  |  |  |  |  | **Average % Difference** | **0.21** |
|  |  |  |  |  |  | **STD** | **0.14** |

# CHAPTER 4
# MODEL SIGNIFICANCE ANALYSIS

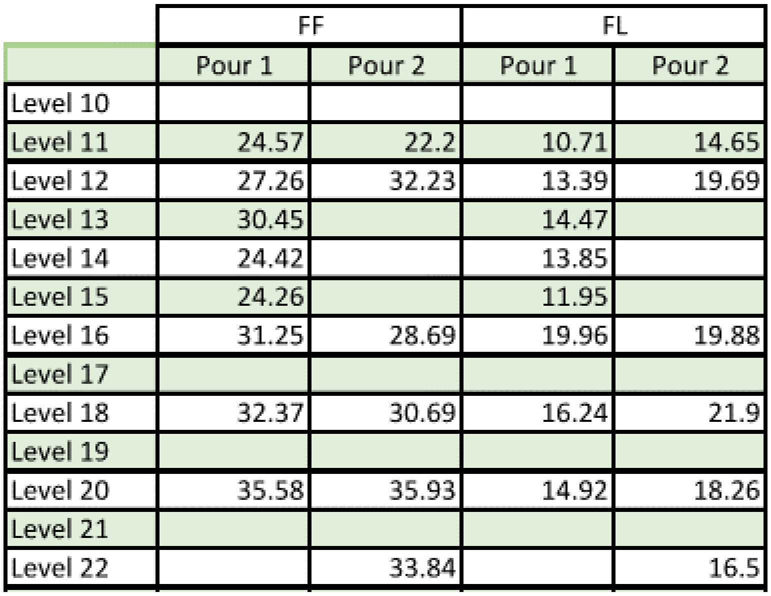
## Case Study

As previously discussed, a data set from a 40-story multifamily high-rise was used to develop and test the prediction models for estimating the number of self-leveling mortar bags needed for floor leveling. The flooring subcontractor did not include floor leveling cost in the bid because of the lack of reliable estimates for the number of self-leveling mortar bags. As a result, the project team budgeted an allowance equal to 25% of the total square footage for laminate flooring multiplied by $2.25/SF to cover the cost of floor leveling. This allowance was based on two assumptions:1) tile and carpeted surfaces do not need floor leveling, and 2) only 25% of the area eligible for receiving leveling would need to be leveled. As such, the project team allocated about $170,000 for the floor leveling allowance. The general contractor was comfortable with such an allowance based on past projects. The project team realized the inaccuracy of the allowance budget when the cost of leveling averaged over $10,000 per floor. It soon became obvious that the $170,000 budget for floor leveling was significantly inadequate.

In search for an explanation of the underestimating of the floor leveling budget, the project team turned to the specifications. The concrete specifications called for measurements to be taken and reported prior to removal of shoring but not later than 72 hours of concrete placement, which aligns with the ACI 117-10 requirements. The FF requirement for the building defined in the project specifications was 25, or a 'moderately flat' slab. Because the project had elevated cambered slabs, the specifications had no FL testing requirement, however the measurements were still taken by the testing agency. The FF measurements ranged from 22.2 to 36.59, with most of the measurements meeting or exceeding the FF requirement of 25, shown below in Table 4.1. As a result, no further action was taken apart from the concrete team on the project providing minor floor grinding on levels that were out of compliance.

Without much assistance from the concrete team, the need for proper estimating of floor leveling is crucial for the general contractor to stay on budget. As mentioned above, the original estimate for the case study project was $170,000.

Table 4.1. Floor FF and FL Test Results



| | FF | | FL | |
|---|---|---|---|---|
| | Pour 1 | Pour 2 | Pour 1 | Pour 2 |
| Level 10 | | | | |
| Level 11 | 24.57 | 22.2 | 10.71 | 14.65 |
| Level 12 | 27.26 | 32.23 | 13.39 | 19.69 |
| Level 13 | 30.45 | | 14.47 | |
| Level 14 | 24.42 | | 13.85 | |
| Level 15 | 24.26 | | 11.95 | |
| Level 16 | 31.25 | 28.69 | 19.96 | 19.88 |
| Level 17 | | | | |
| Level 18 | 32.37 | 30.69 | 16.24 | 21.9 |
| Level 19 | | | | |
| Level 20 | 35.58 | 35.93 | 14.92 | 18.26 |
| Level 21 | | | | |
| Level 22 | | 33.84 | | 16.5 |

## Prediction Models' Performance

Based on the developed models' prediction of the number of self-leveling mortar bags (Table 3.3), the project budget would be closer to $500,000, or 74% of the total area needing floor leveling. This adjusted budget was calculated as follows.

1. The project's total leveling area (302,000 SF) was divided by the test data area (26,275 SF) to yield an area coefficient of 11.49.
2. The predicted total number of bags was obtained by multiplying the number of bags per the test area (i.e., 970 bags in Table 3.3) by the area coefficient computed in step 1 (i.e., 11.49). Thus, the predicted total number of bags was found equal to 11,144 bags.
3. Finally, the total leveling budget was obtained by multiplying the predicted total number of bags by the individual bag cost of $45/bag. Thus, the total leveling was found equal to $501,467.

Therefore, the results obtained using the developed models recommend that future projects plan for a higher percentage of leveling to be installed over the eligible floor area.

## Study Limitations

The limitations of the study can be summarized as follows.

1. The prediction models were developed using a data set collected from one project.
2. More data is also needed to validate the developed models.
3. A more rigorous statistical analysis is also needed for the development of the prediction models.
4. An effort needs to be made to develop a single prediction model rather than several ones.

# CHAPTER 5
# CONCLUSIONS

ASTM standards provide guidelines for FF and FL testing, floor leveling install, and rough correlations between FF and FL testing and straightedge tolerances. However, FF and FL testing numbers have been used for concrete. Limited research has previously addressed the use of FF and FL testing results to predict the number of self-leveling mortar bags. For this reason, flooring contractors intentionally exclude floor leveling from cost estimates even when given FF and FL testing requirements. Therefore, the burden of estimating floor leveling for a project is placed on the general contractor.

This study has shown that FF and FL testing results can be used to develop models that accurately predicts the number of bags needed for floor leveling using a data set collected from a multifamily high-rise building. The developed models were reasonably reliable in their predictions of project floor leveling costs. These prediction models could be used by general contractors after few floors' placement. Following the issuance of the FF and FL testing results, the general contractor could use the developed models to predict how many bags of self-leveling will be needed prior to the mobilization of the flooring contractor. The contractor can use this information to check the accuracy of the budget and work to mitigate risk prior to self-leveling install.

The models could be further developed to use the FF and FL testing requirements provided at the time of the estimate to predict the budget needed for floor leveling. This research would delve into how to use the current models to predict the number of bags of leveling needed according to the specified FF and FL testing numbers. Additional data from more projects would be compiled to further evaluate the accuracy of the working model. This would create a tool that the contractor could use at the time of an estimate to develop a budget for a project.

# REFERENCES

[1] Rego, A. C. A., Cardoso, F. A., Pileggi, R. G. 2,3 (2021). "Ternary system Portland cement-calcium aluminate cement-calcium sulfate applied to self-leveling mortar: a literature review", Cerâmica, Vol. 67, pp. 65-82, http://dx.doi.org/10.1590/0366-69132021673812929.

[2] ASTM C1708/C1708M (2016). "Test methods for self-leveling mortars containing hydraulic cements", ASTM International

[3] Peramin (2019). "Self-leveling screeds", https://peramin.com, ac. 18/08/2019.

[4] Kim, M.-K.; Wang, Q.; Li, H. (2019). "Non-Contact Sensing Based Geometric Quality Assessment of Buildings and Civil Structures: A Review", Automation in Construction, Vol. 100, pp. 163–179.

[5] British Standards Institution (BSI) (2009). BS 8204—Screeds, Bases and In Situ Flooring; BSI: London, UK.

[6] Henry, R.S.; Ingham, J.M. (2010). "Field Measurements of Concrete Floor Surface Regularity", Proceedings of The New Zealand Concrete Industry Conference, Wellington, New Zealand, 7–9 October 2010; p. 9.

[7] ASTM International (2020). ASTM E 1155-96-Standard Test Method for Determining FF Floor Flatness and FL Floor Levelness Numbers. Vol. 04.11, DOI: 10.1520/E1155-20.

[8] American Concrete Institute (ACI) (2015). Specification for Tolerances for Concrete Construction and Materials and Commentary; American Concrete Institute: Farmington Hills, MI, USA.

[9] Steffey, D.; Uriz, P.; Osteraas, J. (2012). "Using ASTM E1155 to Determine Finished Floor Quality: Minimum Sampling Requirements Used to Establish Compliant Floor Flatness and Levelness", Forensic Engineering, American Society of Civil Engineers: San Francisco, CA, USA, 2012; pp. 605–612.

[10] Hutchinson, T.C.; Chen, Z. Improved Image Analysis for Evaluating Concrete Damage. J. Comput. Civ. Eng. 2006, 20, 210–216. [CrossRef]

[11] Zhu, Z.; Brilakis, I. (2010). "Machine Vision-Based Concrete Surface Quality Assessment", J. Constr. Eng. Manag. Vol. 136, 210–218.

[12] Nuikka, M.; Rönnholm, P.; Kaartinen, H.; Kukko, A.; Suominen, A.; Salo, P.; Pöntinen, P.; Hyyppä, H.; Hyyppä, J.; Haggrén, H (2008). "Comparison of Three Accurate 3D Measurement Methods for Evaluating As-Built Floor Flatness", Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. B5, pp. 129–134.

[13] Tang, P.; Huber, D.; Akinci, B. Characterization of Laser Scanners and Algorithms for Detecting Flatness Defects on Concrete Surfaces. J. Comput. Civ. Eng. 2011, 25, 31–42.

[14] Bosché, F.; Guenet, E. (2014). "Automating Surface Flatness Control Using Terrestrial Laser Scanning and Building Information Models", Automation in Construction, Vol. 44, pp. 212–226.

[15] Li, D.; Liu, J.; Feng, L.; Zhou, Y.; Liu, P.; Chen, Y.F. (2020). "Terrestrial Laser Scanning Assisted Flatness Quality Assessment for Two Different Types of Concrete Surfaces. Measurement", Vol. 154, 107436.

[16] Kim, M.-K.; Thedja, J.P.P.; Wang, Q. (2020). “Automated Dimensional Quality Assessment for Formwork and Rebar of Reinforced Concrete Components Using 3D Point Cloud Data”, Automation in Construction, Vol. 112, 103077.

[17] Li, F.; Li, H.; Kim, M.-K.; Lo, K.-C. (2021). “Laser Scanning Based Surface Flatness Measurement Using Flat Mirrors for Enhancing Scan Coverage Range”, Remote Sensing, Vol. 13, 714.

[18] Zhipeng Chen, Qingquan Li, Weixin Xue, Dejin Zhang, Siting Xiong, Yu Yin, and Shiwang Lv (2022). “Rapid Inspection of Large Concrete Floor Flatness Using Wheeled Robot with Aided-INS”, Remote Sensing. Vol. 14, 1528. https://doi.org/10.3390/rs14071528

[19] Nasvik, J. (2010, December 17). ALLEN FACE - Helping us understand the realities of floor construction. Concrete Construction. Retrieved March 5, 2022, from https://www.concreteconstruction.net/business/contractors/allen-face_o

[20] Cheek, M. (2011, January). The Floor Flatness Report: What the designer needs to know. Concrete International. Retrieved February 28, 2022, from https://www.concrete.org/Portals/0/Files/PDF/WTRF6_revised.pdf

[21] ASTM International (2013). F2873-13 Standard Practice for the Installation of Self-Leveling Underlayment and the Preparation of Surface to Receive Resilient Flooring. https://doi.org/10.1520/F2873-13

[22] ASTM International (2021). F710-21 Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring. https://doi.org/10.1520/F0710-21.