Ballast Bonding additive

Laboratory testing protocol for characterizing adhesives used for ballast bonding.

Final report

Report Nr.	12GS-012908-L-01-PB-01
Commission Nr.	12GS-012908-L-01
Classification	Public
Date	2024-10-17
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1 Project description

1.1 Context

The Allianz Fahrweg Normalspur consortium has been using a ballast bonding technique for several years. This technique involves bonding the ballast particles together with adhesive sprayed from the track, ensuring sufficient stability for excavation work in the immediate vicinity of the rails while maintaining traffic flow.

As part of this process, the Allianz Fahrweg Normalspur aims to expand its range of adhesive suppliers by allowing different companies to offer their adhesives for this bonding.

The geomechanics laboratory of Bern University of Applied Sciences (BFH) has been commissioned to study the feasibility of conducting laboratory tests on bonded ballast and to propose a testing protocol to select different types of adhesives based on the determination of minimum requirements (compression strength, diffusion, concentration, etc.).

Contractual conditions:

- Offer 81.23.039 sent by BFH on March 27, 2023
- Order 4700024437 placed by Allianz Fahrweg Normalspur on July 14, 2023
- Offer 12.24.067 sent by BFH on July 11, 2024
- Order 4300002606 placed by Allianz Fahrweg Normalspur on July 18, 2024

1.2 Objectives

The objectives of the project are as follows:

- Determination of minimum requirements based on laboratory tests to characterize the properties of the proposed adhesives.
- Define reference values for these tests, in relation to the reference adhesive MC-Ballastbond 70 [1].
- Establishment of a binding test protocol internal to Allianz Fahrweg Normalspur. This test protocol is to be followed by manufacturers to validate the suitability of their product for ballast bonding.

1.3 Technical references

[1] Technical Datasheet MC-Ballastbond 70, MC-Bauchemie, 11.10.2023
[2] SN EN 196-1 Methods of testing cement – Part 1: Determination of strength
[3] SN EN 206 -A2: Concrete – Specification, performance, production and conformity
[4] Forschungsbericht SBB-Schotterverklebung, Nachweiskonzept für die Schotterschulter während dem Unterhalt, BFH Oktober 2019
[5] Boler and al., Influence of size and shape properties of railroad ballast on aggregate packing, statistical analysis, Transportation Research Record, 2014, pp. 94–104
[6] Gerber, K "FB 400-0210 Schotterverklebung",2022
[7] Schotterqualität – Prüfprotokoll Holcim Kehrsiten Juli 2023, Auftrag 2023-820

1.4 Project organization

The work requested from BFH was a forward-looking project carried out using an agile method, in which various aspects were tested before being retained or not in the final recommendations (see paragraph 7).
The results and tests carried out were regularly discussed and modified during the project, in close collaboration with Mr Kilian Gerber from the SBB.

2 Initial procedure (Big Scale)

2.1 Description

The initial test procedure is summarized in the proposal 81.23.039 :

- WP1 : Preliminary tests by manual application of the adhesive to large ballast samples.
- WP2 : Bonding of samples by spraying with a specific pump (=discuss the changeover from field to laboratory)
- WP3 : Drafting of test protocol and additional recommendations

These objectives can be summarized as shown in the Figure 1.

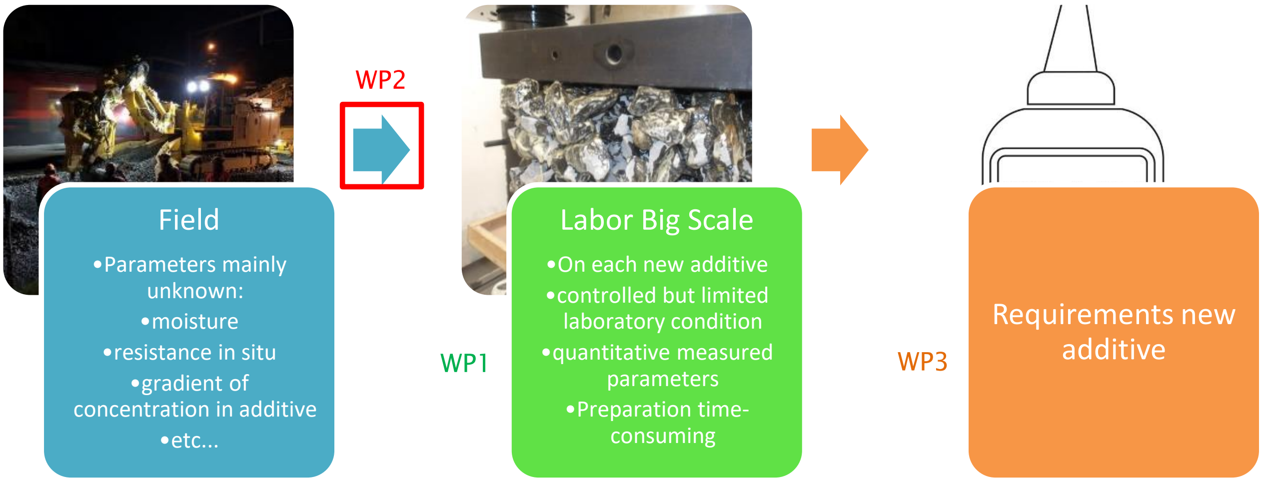


Figure 1 : Initial project procedure as listed in the proposal 81.23.039

The principle of the initial method is to represent site conditions as closely as possible using big-scale laboratory tests, and to test each potential new additive directly using these big-scale tests.
This approach assumes that compressive strength criterion can be used to validate all the properties occurring on the field at once.

2.2 Formwork

The molds used for testing the SBB ballast were specifically designed to measure compressive strengths. These molds had dimensions of 500x300x300 mm to accommodate the size of the specimens. In total, 6 molds were prepared for the tests:

- Two of the molds were made from simple plywood, with a height 30cm.
- The other two molds from plywood with a height 30 cm but featuring a mesh at the bottom. This mesh was included to facilitate the drainage of any excess additive.
- Two molds with a height of 50 cm and a mesh on the bottom, to observe the effect of a longer glue flow path.
- The samples coming from the molds with the height of 50cm and 30cm are tested only in compression (see Table 1).

Remark: Formwork with rigid bottom was initially planned but never used, because it was found to be important to measure the actual applicated concentration of bonding (see part 3.2.2).

Table 1 Two types of molds, with heights of 30 cm and 50 cm, are used; both have a mesh at the bottom

Fromwork type	Sample number	Dimension (LxWxH)
H = 30	1_1 - 1_7	30x50x30
H = 50	1_8 - 1_17	30x30x50

Figure 2 : Mold without (left) and with (middle) mesh on the bottom (Height 30 cm). Right : Mold 50cm high filled with ballast.

2.3 Application additive

2.3.1 Context

In laboratory settings, the application of additives often requires adaptation from field practices to accommodate controlled experimental conditions and equipment limitations. For this study, the gravitational method of applying glue was selected due to its simplicity and effectiveness in achieving homogenous distribution across the ballast samples. This method involves manually pouring the adhesive, allowing gravity to aid in its spread, ensuring even coverage and penetration within the ballast structure (see Figure 3).

The conventional on-site application method involves using a specialized pump that combines two adhesive components directly before application. This ensures fresh mixing and reactive bonding almost instantaneously as the adhesive hits the ballast. However, replicating this in a laboratory environment proved to be overly complex and resource intensive. The primary challenges included the technical difficulty of accurately simulating the dynamic mixing and application process on a smaller scale.

By deciding for the gravitational method, the study bypasses these complexities, allowing for a more focused examination of the adhesive's properties and effectiveness under controlled, reproducible conditions.

Figure 3 : Gravitational application of the ballast bonding resin (mesh path)

2.3.2 Tested technics

In this study, two distinct techniques were evaluated for the application of glue within the ballast samples: **multiple applications** and **single application.** Each method was designed to assess different aspects of glue distribution and retention in the ballast structure.

Multiple Application Technique: The objective here was to maximize glue penetration through repeated applications. The glue was allowed to flow through the ballast, collected at the bottom (thanks to a mesh grid that facilitated this passage), and then recirculated back through the top of the ballast. This process was repeated until the upper layers of the ballast were sufficiently saturated with adhesive. This technique was initially applied to samples (1_1, 1_2, 1_4, 1_5, 1_6, 1_7). It is important to note that retention amounts were measured for samples from 1_4 to 1_7, while samples 1_1 and 1_2 served as initial trials without retention measurement.

Challenges of Multiple Applications: The repeatability of the multiple application technique posed significant challenges. Specifically, it was difficult to standardize the amount of recirculation for the glue, which impacted the ability to consistently track and measure the amount of adhesive retained within each sample. This variability raised concerns about the method's reliability and reproducibility.

Transition to Single Application Technique: Due to the repeatability issues encountered with the multiple application technique, focus shifted towards exploring the single application method. In this approach, glue was applied just once over the top layer, aiming for the best possible initial distribution. The objective was to assess the penetration and retention without recirculation, simplifying the process and potentially increasing the reproducibility of results. Samples from 1_8 to 1_17 were tested using this technique.

To refine the application of adhesive in our experiments, three distinct methods were employed under the single application approach, each designed to assess different aspects of adhesive distribution across the ballast:

Single application:

1. Watering Can:
   - Description: A standard gardening watering can was used to apply the glue over the ballast. This method was intended to distribute the adhesive homogeneously over the surface of the upper layer of ballast.
   - Objective: To simulate a gentle and evenly distributed pouring, enhancing the coverage across the ballast particles

2. Beaker Method - Single Point Pouring:
   - Description: Adhesive was poured from a beaker at a single point onto the ballast.
   - Objective: This technique focused on observing the natural flow and spread of the glue from a central point, providing insights into the directional flow and depth of penetration within a localized area of the ballast.

3. Plastic box with Linear Distribution:
   - Description: Plastic box was adapted to allow a linear, rather than point, distribution. This was achieved by using a square-shaped mouth beaker, enabling the glue to be applied in a line across the ballast.
   - Objective: To test the feasibility of a line application, potentially offering a more controlled and directed flow path.

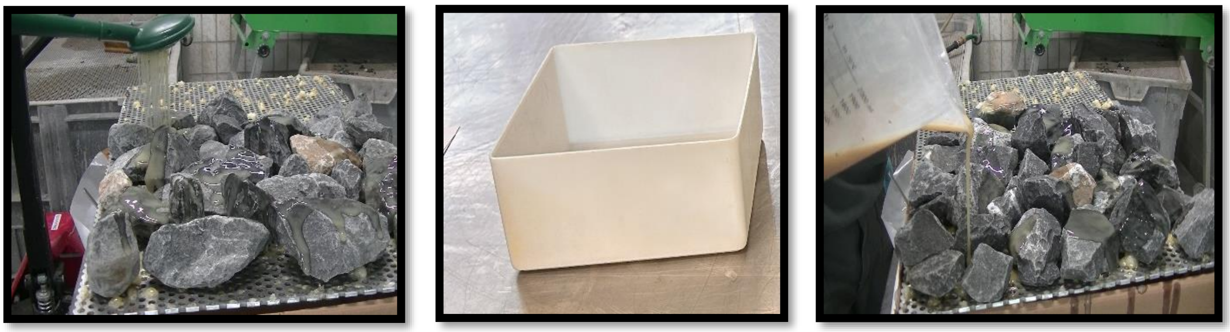


Figure 4 Watering can (Left), Plastic box (Middle), Beaker (Right)

2.3.3 Preliminary Tests

Following the application of various adhesive techniques, detailed observations have been made to assess the effectiveness and practicality of each method. Below is a summary of the findings:

1. Watering Can with Modified Nozzle (with the opening diameter of 3mm):
    - Advantages:
        - Excellent distribution: the adhesive covered all ballast stones uniformly.
    - Disadvantages:
        - Cleaning difficulty: Though they can be reused, the watering can is challenging to clean. Approximately 20 grams of adhesive remained inside after use.
2. Plastic box:
    - Performance:
        - The container did not perform well, proving difficult to control during pouring and unable to achieve a homogeneous distribution of the adhesive.
3. Beaker:
    - Advantage:
        - Easy control over the flow rate of the adhesive.
    - Disadvantage:
        - The adhesive was dispensed in a concentrated stream, making it difficult to distribute evenly across the ballast.

2.3.4 Summary

Based on these evaluations mentioned above, the **watering can with the modified nozzle** is recommended for the **single application** method and was used for representative tests 1_8 to 1_17. This tool provided the best distribution of adhesive, crucial for achieving optimal bonding in the top layer of the ballast.

2.4 Aggregates

2.4.1 Origin

To ensure consistency and reproducibility in our experiments, the ballast used was sourced exclusively from a single batch provided by Holcim Company, located in Kehrsiten. This approach was essential for maintaining uniform material characteristics across all tests. However, it is also important to note that as long as alternative suppliers can provide ballast of the same geological origin and quality, they could be considered viable options for future testing or actual application.

- **Origin**: The ballast was delivered in two large bags, each filled with 1st class
- **Grade**: The 1st class designation indicates that the ballast meets the highest industry standards for size, durability, and angularity, which are crucial for ensuring effective interlocking and load distribution in track structures.

- **Particle size Distribution**: To verify the consistency of the ballast material, a Particle Size Distribution (PSD) analysis was carried out. The PSD data presented in Figure 5 reflects the distribution of particle sizes from the ballast used in our laboratory tests. This distribution ensures that the ballast meets the standards for proper size gradation.

  Figure 5 also includes a comparison with control PSD data collected over time to monitor any variations in the ballast material's properties. The blue dashed line indicates the accepted boundaries for ballast particle size, while the yellow line (BFH) represents the current test results, and the gray line (Results SBB_2023) shows the previous testing result from [7].

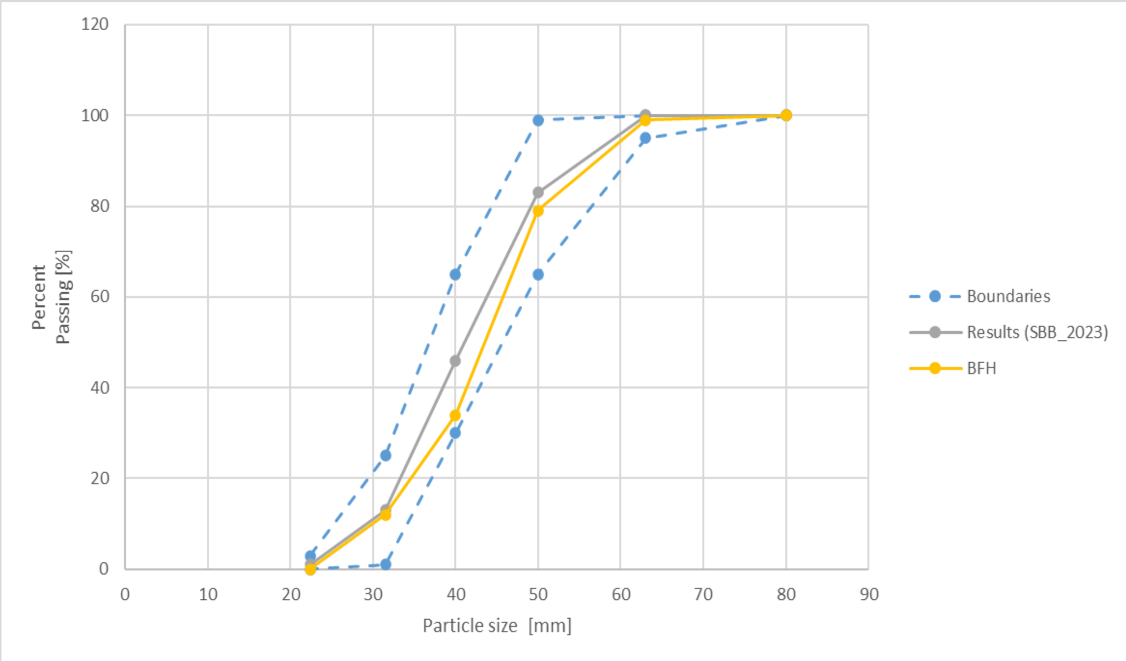


Figure 5 Particle size distribution of the used Ballast

2.4.2 Ballast Preparation
During the initial phases of testing, specific samples (1_1 and 1_2) were utilized without undergoing prior washing and were only air-dried. This approach was initially adopted to expedite the setup process; however, it introduced a variable that could potentially affect the consistency and repeatability of the test results.

Observations of Unwashed vs. Washed Ballast:

- **Unwashed Ballast**: These samples contained around 0.55% of fine particles (measure on 1 random sample of 3kg), which can significantly influence the adhesive's distribution and bonding efficiency. The presence of these fines can lead to uneven adhesive coverage and potentially weaker mechanical properties in the bonded ballast.
- **Preparation Process**: Given the variations observed in the initial tests due to the fines, a recommendation was made to implement a washing process for all subsequent ballast samples. This step was crucial to remove fine particles that could obscure the true performance characteristics of the adhesives.
- **Drying**: Post-washing, the ballast was dried in an oven to achieve a consistent moisture content, essential for maintaining the uniformity of adhesive application and curing processes.

The accompanying photo on Figure 6 illustrates the difference between the unwashed and washed ballast.

By standardizing the preparation process of the ballast, the tests aim to eliminate variables related to material cleanliness and condition, ensuring that the focus remains on evaluating the performance of the adhesives under controlled and repeatable conditions.

Figure 6 Not washed Ballast (Left) and washed ballast (Right)

2.5 Compressive test

2.5.1 Test Conditions

To evaluate the mechanical properties of the ballast samples after adhesive application, compression tests were conducted using a specialized press located at the Bern University of Applied Sciences. The specimen is tested in different directions (see Table 2)

The compression rate was set to a controlled deformation speed of **1 mm/min**, which is considered optimal for observing the mechanical behavior of the ballast under compression without introducing stress concentrations that could lead to atypical fracture patterns.

2.5.2 Methodology

- **Cross Orientation (90°):** Most of the samples were tested at a 90° angle to the direction of glue application. This orientation was chosen because it best simulates the real-life situation where the primary loading force exerted by train movements is perpendicular to the direction of glue application. Testing the samples at this angle provides valuable insights into the performance of the ballast under typical operational stresses. The test can also occur on the big face or on the small face.

- **Parallel Orientation**: Only one sample, 1_2, was tested in the same direction as the glue application. This setup was initially intended to explore the adhesive's effectiveness when the compressive force aligns with the glue layer. However, this test did not yield reliable results due to the non-flat surface at the glue application point, which could potentially introduce inconsistencies in the test outcomes.

Table 2 summarize the 4 different orientation type (I to IV) that have been tested.

Table 2 Summary table showing type of testing orientation.

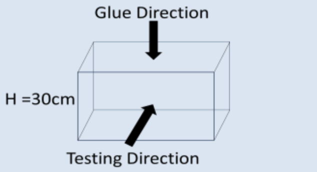
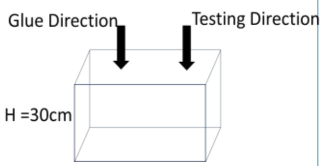
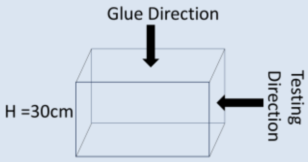
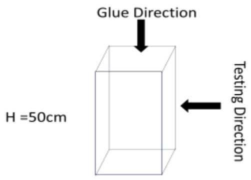
Compression test orientation type	Mold type (see 2.2 Table 1)	Glue application path	Testing direction	Angle (Glue to Testing direction)
I	H = 30	30 cm (Height)		90˚
II	H = 30	30 cm (Height)		0˚
III	H = 30	30 cm (Height)		90˚
IV (see Figure 7)	H = 50	50 cm (Height)		90˚

Figure 7: Sample of class IV being tested in compression.

2.5.3 Sample Height Selection

The 50 cm block height samples have been finally selected, as more representative of site condition, where the typical ballast layer measures approximately 30 cm, and the sleeper height adds an additional 20 cm [6]. This combined height of 50cm replicates therefore the total depth of the ballast-sleeper system, providing a more accurate assessment of the adhesive's ability to flow and bond throughout the entire depth of the ballast. The 50 cm height also allows us to evaluate whether the blocks maintain stability across the full depth, ensuring that the adhesive performs effectively over a longer flow path and supports the block's integrity under realistic conditions.

2.5.4 Determination of Adhesive Quantity

For samples with a height of 50 cm, the adhesive concentration is chosen to be between 1.5–1.7 L/m², as recommended for field applications, according to [6]. These values are typically applied to unwashed ballast in field conditions. However, for laboratory testing, different concentrations can be evaluated, potentially lower than this range, depending on the specific test objectives.

The adhesive concentrations for the samples with a height of 50 cm are tested and discussed in Chapter 3.2.2, where various concentration levels were applied to determine the optimal amount of adhesive.

The calculation for determining the required adhesive quantity follows this method:

- For a concentration of 1.7 L/m² (pro 0.1 m penetration depth) :

$$Adhesive\ Volume = 1{,}7\ x\ (0.3X0.3)x5 = 0.765\ Liter$$

  Where:
  - 0.3 x 0.3 m² is the surface area of the top of the sample.
  - 5 represents the height of the sample (50 cm) as 5 layers of 10 cm.

Meaning that the adhesive volume for a 50 cm high sample is 0.765 L, equivalent to 17 L/m³.
This method allows us to adjust and test various adhesive concentrations for samples of different heights, as seen in the results discussed in Chapter 3.2.2.

3 Results (Big Scale)

3.1 Performed Tests-Overview

The comprehensive testing regime for the big scale samples, as detailed in the project's protocol in Appendix 1, has been systematically executed with eight main sample groups from December 2023 to August 2024. These tests involved variations in the ballast preparation—either washed or unwashed, air-dried or oven-dried—to assess several critical factors such as the influence of fine particle, repeatability, slenderness ratio, and the investigative properties of longer adhesive flow paths. The adherence to specified adhesive concentrations (ranging from 11 to 20 L/m³ depending on the test setup and objectives) has been meticulously documented, ensuring each sample's preparation aligns with the project's goals of optimizing and understanding the adhesive properties under varying conditions.

Table 3 Overview of Big Scale adhesive testing: sample preparation, objectives, and conditions (December 2023 - August 2024)

Sample No.	Details	Objectives	Sample Nr.	Date	Test Orientation (See Table 2)	Adhesive Concentration	Adhesive Application technique (see 2.3)
1_1 1_2	-Ballast not washed -Air-dried	-Reference compressive strength -Feasibility -Influence of loading direction -Influence of fine particle (pollution)	2	December 2023	Type I Type II	19.7 L/m³	Multiple
1_4 1_5	-Ballast washed -Oven-dried	-Influence of pollution -Repeatability -Measure concentration	2	March 2024	Both Type III	20 L/m³	Multiple
1_6 1_7	-Ballast washed -Oven-dried	-Repeatability -Slenderness ratio -Measure concentration	2	April 2024	Both Type I	20 L/m³	Multiple
1_8 1_9	-Ballast washed -Oven dried	-Repeatability -Investigating longer adhesive flow path	2	May 2024	Both Type IV	17 L/m³	Single (watering can)
1_10 1_11	-Ballast washed -Oven dried	-Repeatability -Measure concentration -Investigating longer adhesive flow path	2	June 2024	Both Type IV	17 L/m³	Single (watering can)
1_12 1_13	-Ballast washed -Oven dried	-Repeatability -Measure concentration -Investigating longer adhesive flow path -Glue design	2	June 2024	Both Type IV	11 L/m³	Single (watering can)
1_14 1_15	-Ballast washed -Oven dried	-Repeatability -Measure concentration -Investigating longer adhesive flow path -Glue design	2	July 2024	Both Type IV	14 L/m³	Single (watering can)
1_16 1_17	-Ballast washed -Oven dried	-Repeatability -Measure concentration --Adhesive flow path	2	August 2024	Both Type IV	17 L/m³	Single (watering can)

3.2 Results for Type IV samples

3.2.1 Type IV samples

As discussed in part 2.5, Type IV samples were finally considered as they represent the specific conditions and characteristics required for evaluating adhesive effectiveness. In this chapter, we focus exclusively on the results obtained from the testing of Type IV samples, namely the samples which have the height of 50cm and a compressive testing in a direction perpendicular to the direction of adhesive application . The key findings from these tests will be presented, including the analysis of adhesive quantity, ballast detachment, and compressive strength.

3.2.2 Adhesive quantity determination

In this section, the results of the adhesive concentration tests for Type IV samples with a height of 50 cm are presented. The concentrations tested were **1.1 L/m², 1.4 L/m², and 1.7 L/m²**, calculated using the formula defined in Section 2.5.4. The adhesive quantities for each sample were determined by applying these concentration factors, with the corresponding volumes of adhesive calculated for each block.

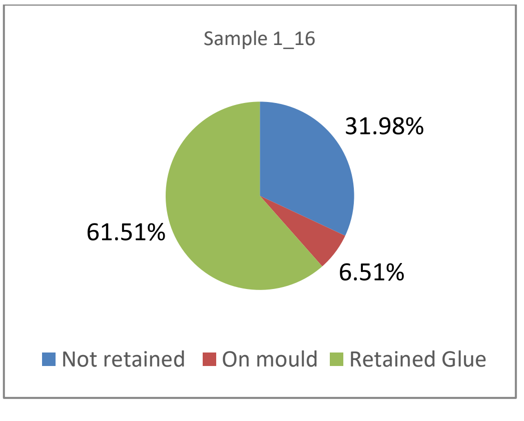
The procedure for measuring adhesive loss, namely the adhesive that was not retained in the ballast sample, is detailed in Appendix I. This appendix outlines the steps for calculating the weight of adhesive not retained in the sample and the adhesive that remained on the mold. The results from these tests are summarized in Table 4 below.

Table 4 Results of adhesive Loss for the type IV samples

Sample No	Concentration Factor (L/m²)	M_{eff}* [g]	$M_{not\ retained}$* [g]	$M_{on\ mould}$* [g]	Loss L* [%]
1_8	1.7	840	290	40	39.3
1_9	1.7	840	275	45	38.1
1_10	1.7	842	285	45	39.20
1_11	1.7	839	278	40	37.9
1_12	1.1	539	106	15	22.47
1_13	1.1	539	099	25	23.0
1_14	1.4	687	182	30	30.9
1_15	1.4	690	185	45	33.3
1_16	1.7	844	270	55	38.5
1_17	1.7	842	290	36	38.7

*The determination of these values are shown in the Appendix I/ chapter 7

To further illustrate the adhesive distribution and retention patterns in the samples, Figure 11 provides a visual breakdown of the adhesive retention for Sample 1_16 and Sample 1_17



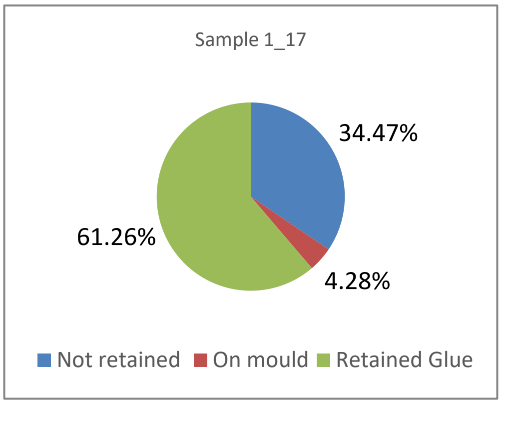


Figure 8 Illustration of the distribution of the adhesive for samples 1_16 and 1_17

3.2.3 Stability of samples

The results regarding the stability of Type IV samples after demolding are presented in the Table 5. Samples tested with an adhesive concentration of 17 L/m³ showed relatively low ballast detachment, with values ranging from 0.29 kg to 0.9 kg, and a mean detachment of 0.685 kg. In contrast, samples tested with a lower adhesive concentration of 11 L/m³ exhibited significantly higher ballast detachment, with values of 3.82 kg and 5.21 kg, resulting in a mean of 4.5 kg. Samples tested with 14 L/m³ of adhesive showed moderate ballast detachment, ranging from 1.46 kg to 1.96 kg, with a mean of 1.71 kg. These results suggest a clear relationship between adhesive concentration and the amount of detached ballast after demolding.

Table 5 Detached Ballast from the sample after demolding

Sample No	Weight of detached Ballast W_L [kg]	Mean Weight [kg]	Adhesive Concentration [L/m3]
1_8	0.7	0.69	17 L/m3
1_9	0.8		
1_10	0.29		
1_11	0.63		
1_16	0.9		
1_17	0.79		
1_12	3.82	4.5	11 L/m3
1_13	5.21		
1_14	1.46	1.71	14 L/m3
1_15	1.96		

3.2.4 Compressive Strength

The graph in Figure 9 presents the Load (kN) versus Displacement (mm) response from compression tests conducted on six type IV samples (1_8 to 1_17) treated with an adhesive concentration of 17 L/m³, under the Type IV testing orientation (See 2.5 for testing orientation). It demonstrates a consistent trend across all samples in terms of deformation behavior under compression, despite slight variations in peak Load values. Notably, the graph underscores the similarity in mechanical response, with a mean peak stress of **77 kN** and a standard deviation of **12 kN.**

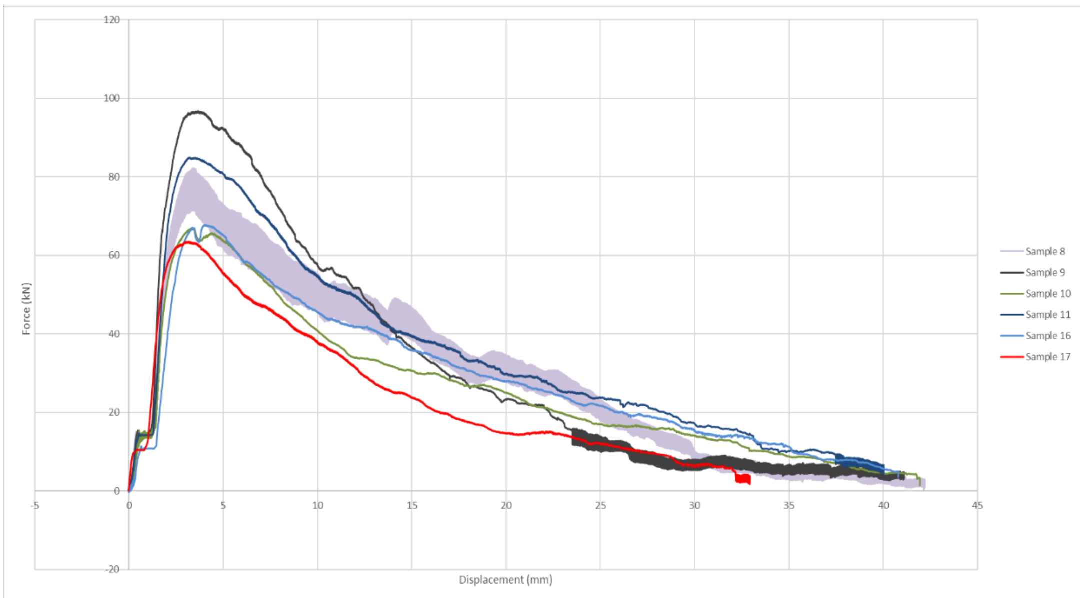


Figure 9 Load-Displacement diagram of 6 Samples with testing orientation Type IV

3.2.5 Adhesive concentration gradient

The application of adhesive from top to bottom in the samples leads to a pronounced gradient in adhesive concentration, with a higher accumulation at the top and significantly less towards the bottom. This pattern can be attributed to several factors like the viscosity of the adhesive vs. the force of gravity as well as the working time before hardening, causing more adhesive to settle before it can reach the lower regions of the sample. This uneven distribution is evident in the photos provided on Figure 10: the left photo shows uneven compression of the plate during testing, and the middle photo highlights the bottom side of the sample at a height of 26 cm from the reference point, while the top side measures 29 cm.

Figure 10 Sample 1_8 during and after compression testing: Left - Uneven compression observed; Middle - Bottom side at 26 cm post-test; Right - Top side at 29 cm post-test, illustrating the gradient in adhesive distribution and its impact on sample integrity

The uneven elevation of the plate during testing serves as one indicator of the gradient in adhesive concentration across the sample. Another critical indicator of this gradient is the type of failure observed in the sample; specifically, the separation of the ballast from the bottom side of the sample, despite the plate remaining even during testing. This phenomenon is clearly depicted in the accompanying photo in Figure 11can , providing visual confirmation of how the uneven distribution of adhesive affects the structural integrity of the sample.

Figure 11 Sample 1_10: Even compression plate with visible ballast separation at the bottom, indicating adhesive concentration gradient

This phenomenon of a concentration gradient varying with height in the sample is summarized in the Figure 12:

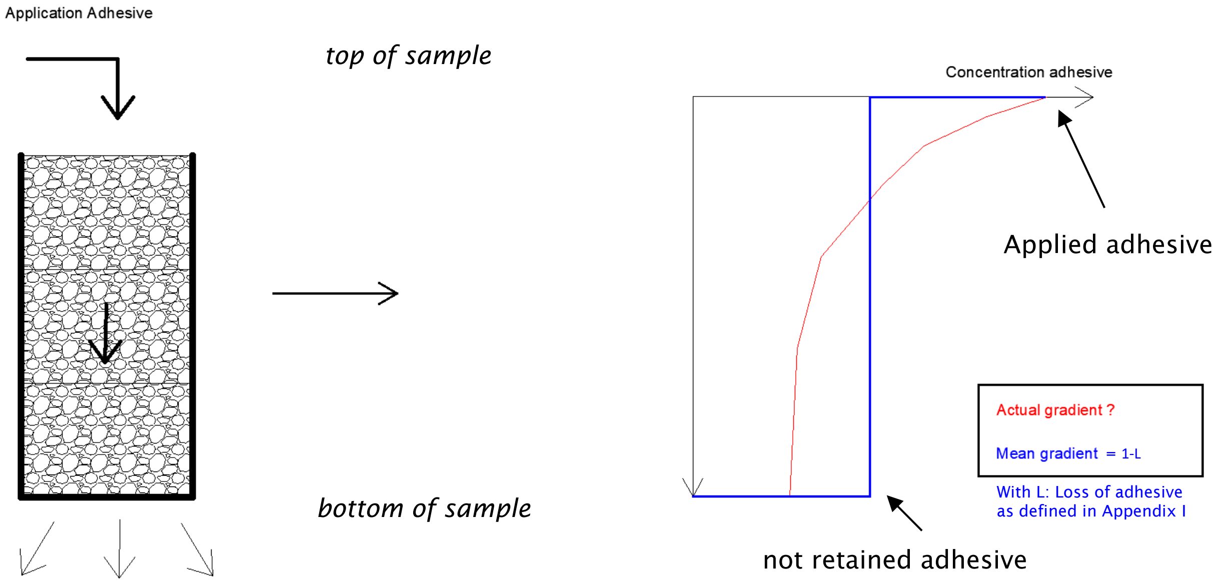


Figure 12 : Diffusion of the adhesive within the depth

In order to ensure consistency and structural integrity during these tests, specific requirements have been established regarding the homogeneity of the sample:

- **Post-Peak Behavior**: The sample must maintain structural integrity up to 70% of the maximum load (Fmax), with weight loss $WL(0.7Fmax)_{post\_peak}$ limited to less than 0.5% of the sample's total weight.
- **Differential Settlement**: The differential settlement of the loading plate must remain below 0.5 mm until reaching 0.7Fmax to ensure even load distribution and minimize deformation discrepancies.

4 Complementary Method (Small Scale)

4.1 Challenges

The method initially proposed in part 2 has some limitations:

- The actual on-site mechanical properties of bonded ballast are unknown and cannot be directly measured. Consequently, the transition from field to big scale labor compressive tests is made at the cost of strong assumptions about:
    - the actual diffusion of the adhesive in the ballast layer
    - the actual ballast compaction
    - the actual influence of ballast surface context (moisture, dust…)
- Parametric tests on the influence of each of these factors cannot easily be undertaken due to the significant effort required to prepare big-scale samples.

4.2 Complementary method

To address the problems listed above, a complementary method to that initially proposed was investigated during the project.
This complementary method is summarized in Figure 13 and consists of the following complementary steps:

- separate study of the properties listed in Table 1
- study of these properties on small samples, with prior knowledge of the relationship between small and large samples. The use of smaller sample sizes requires the use of aggregates with smaller grain sizes, so that the maximum grain size is 5 times smaller than the smallest sample size.
- comparison of these properties with reference values for the reference adhesive

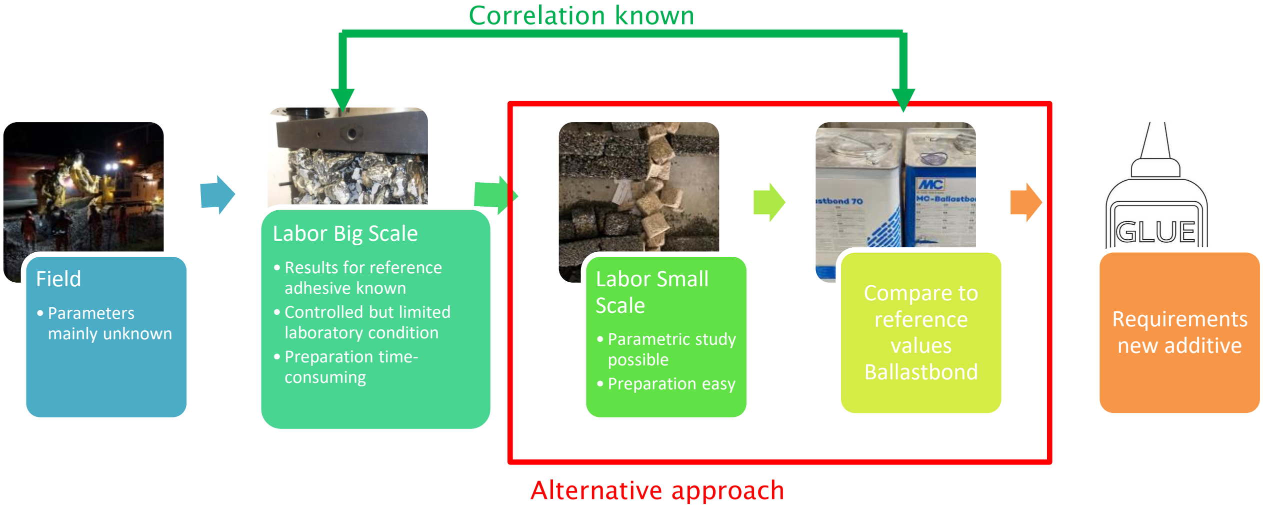


Figure 13 : Alternative method

4.3 Aggregates

For screening purposes several types of sand and aggregates were used:

- Sand round 0-2 mm EN 196-1 (Normensand GmbH)
- Crushed aggregates 1-3 mm (Hornbach),
- Crushed aggregates 2-5 (Hornbach)

The sand was used in its dry state – purchased packed.
The small aggregates, specifically those sized 1-3 and 2-5, were dried in an oven overnight.

Figure 14 : Crushed aggregates 1-3 and 2-5 mm (left) – Normensand (right)

4.4 Formwork preparation

We utilized standardized PE (plastic) molds measuring 160x40x40 mm for small aggregates and sand. These molds are commonly used in assessing the mechanical properties of cementitious materials. The size and shape of specimens was chosen to facilitate testing of both flexural and compressive strengths, particularly in specimens bonded with additives. (below an example of a mould with aggregates (1 3 mm and 2-5 mm) bonded with MC Ballastbond 70.

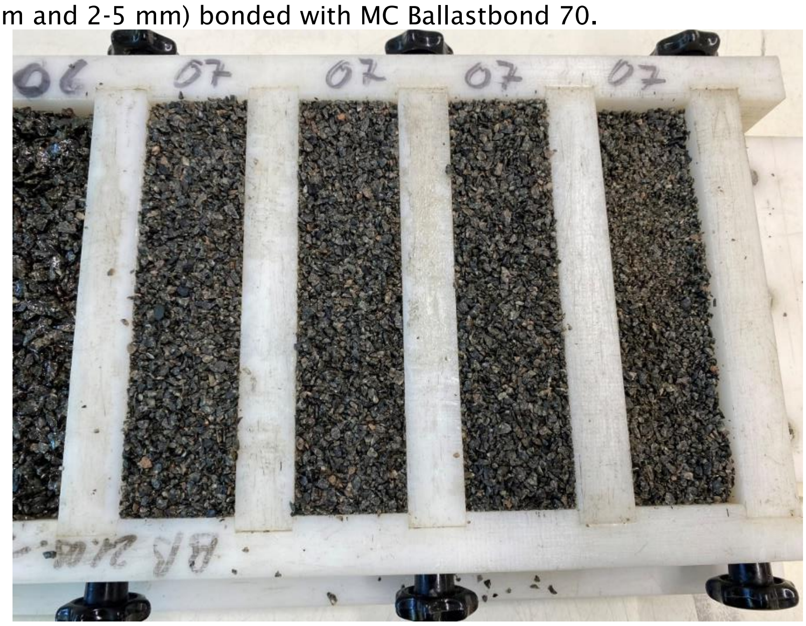


Figure 15 : Mold prisms

4.5 Application of the additive

For the small-sized aggregates and sand, we employed only a **direct mixing method**. We first prepared the required amount of ballast bonding additive in a separate small container. This additive was then added to the container with sand/aggregates. To ensure complete utilization of the additive, particularly given its small quantity, we adopted a thorough mixing approach. This involved transferring some of the aggregates into the container holding the additive. This step helped in complete incorporation of all the additive into the mix.

For the mixing process, we used two methods:

- manual mixing (with a silicon spatula – mix until all aggregates were covered – obtain a shiny-glossy effect – take up to 5 minutes- function of the dosage)

- mechanical mixing – for some specimens, we utilized a kitchen mixer (Landi Primavista model), to ensure a homogeneous mixture.

This approach ensured that the additive was completely added and evenly distributed throughout the aggregate mixture, crucial for the repeatability and effectiveness of the bonding process.

4.6 Compressive Strength

The small samples were broken in 3-point bending and then in compression, in accordance with SN EN 196-1 [2].

Figure 16 : 3-points bending test on small samples

5 Results (Small Scale)

5.1 Performed tests

The performed tests on small scale samples are summarized in Table 6.

Table 6 : Summary of small samples tests

Type	Details	Objectives	Number Samples	Date
Small scale	Compressive strength on Prisms 40*40*160 mm Sand Aggregates 1-3 mm Aggregates 2-5 mm Several concentrations	Influence of adhesive concentration on strength Feasibility of using different materials Variation in compactness Curing time	22 Prisms	Septembrer 2023
Granulometry	Granulometry + Specific weight	Inputs to measure porosity	2	September 2023
Small scale	Compressive strengths on prisms 40*40*160 mm Aggregates 1-3 mm Aggregates 2-5 mm	Measure additive concentration Reference compression value for low concentrations	9 Prisms	April 2024

5.2 Raw results

Prism test results show an increase in strength with increasing adhesive concentration (Figure 17), and a high degree of variability in results.

This variability can be explained by the great variability in material density, which can be quantified by calculating the porosity of each sample, as shown in Figure 18.

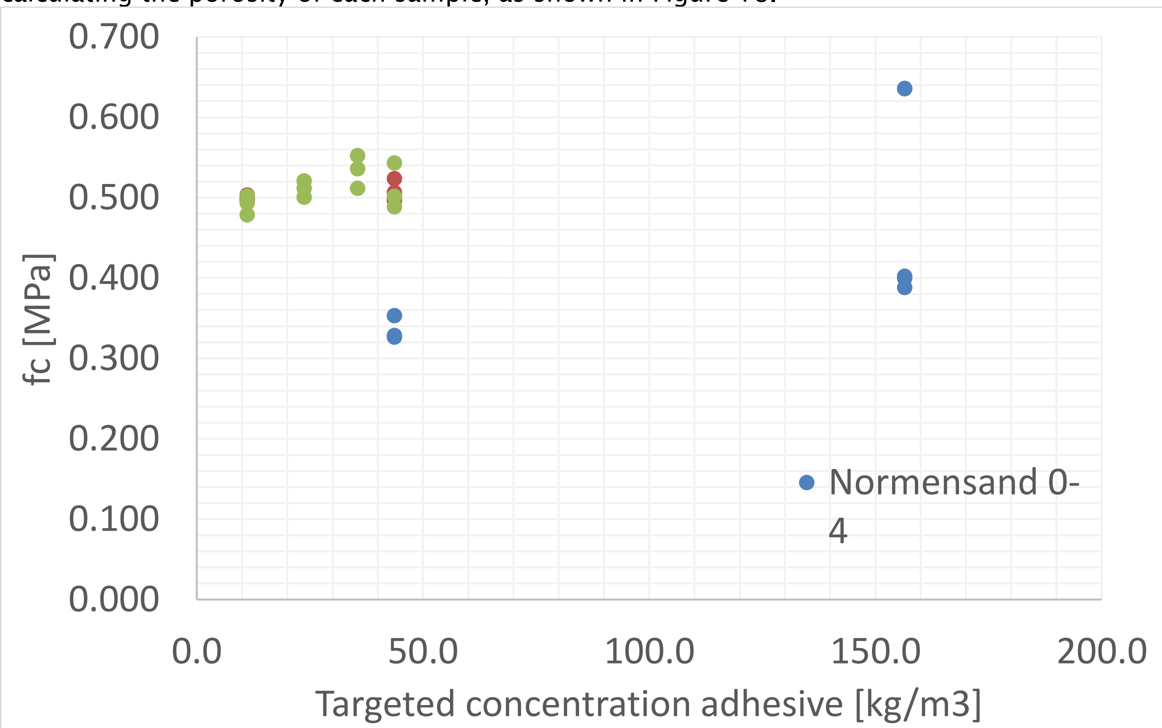


Figure 17 : Compressive strenght of prisms

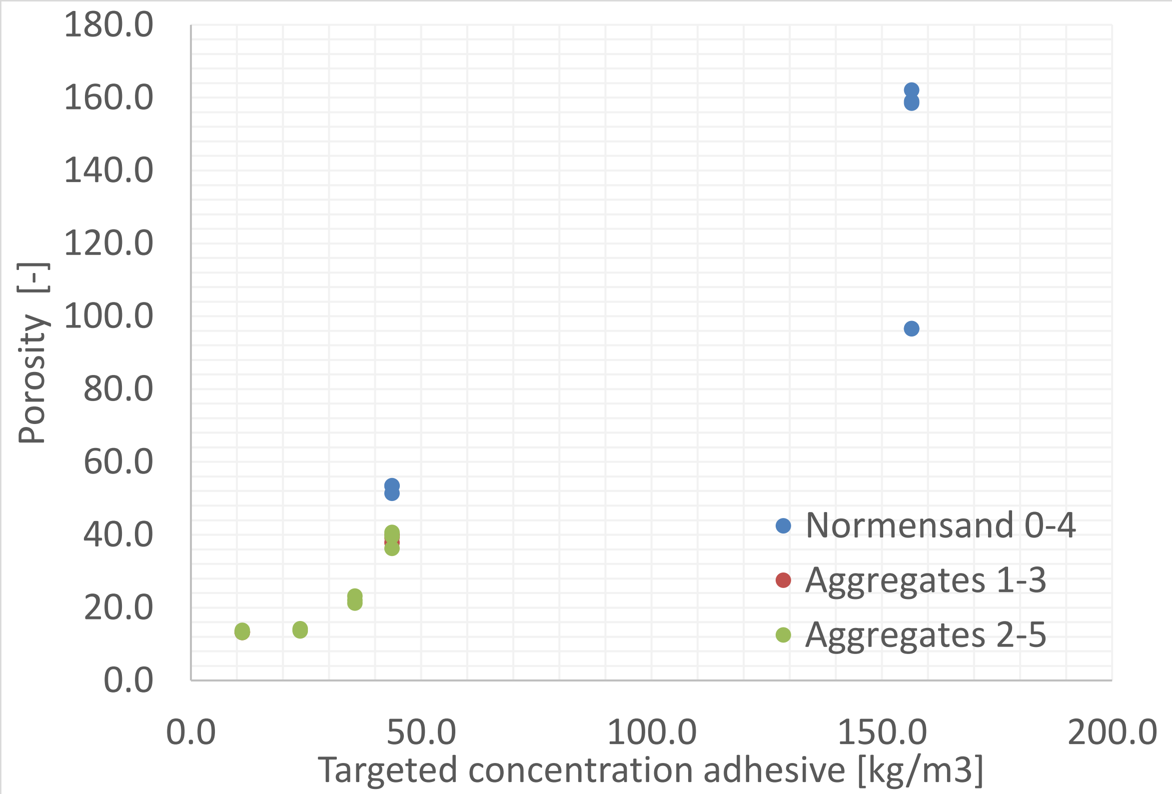


Figure 18 : Variation of porosity for the prisms

5.3 Multivariate correlation

A statistical analysis of the parameters "*porosity*" and "*effective adhesive concentration*" shows that these two parameters could contribute to explain the measured resistance, according to the following regression:

$$f_c = -2.01 + 0.25 * c_{eff} + 0.11 * \eta$$

with

f_c: Uniaxial compressive strength of prism halves [MPa], according to norm SN EN 196-1 [2]

c_{eff}: effective adhesive concentration [kg/m3]

$$c_{eff} = \frac{Mass\ adhesive\ in\ aggregates}{Volume\ sample}$$

η: Porosity [-]

$$\eta = 1 - \frac{mass\ aggregates}{2.65 \left[\frac{kg}{m3}\right] * Volume\ sample}$$

The statistical correlation table is given in Table 7 and the correlation line is shown in Figure 19.

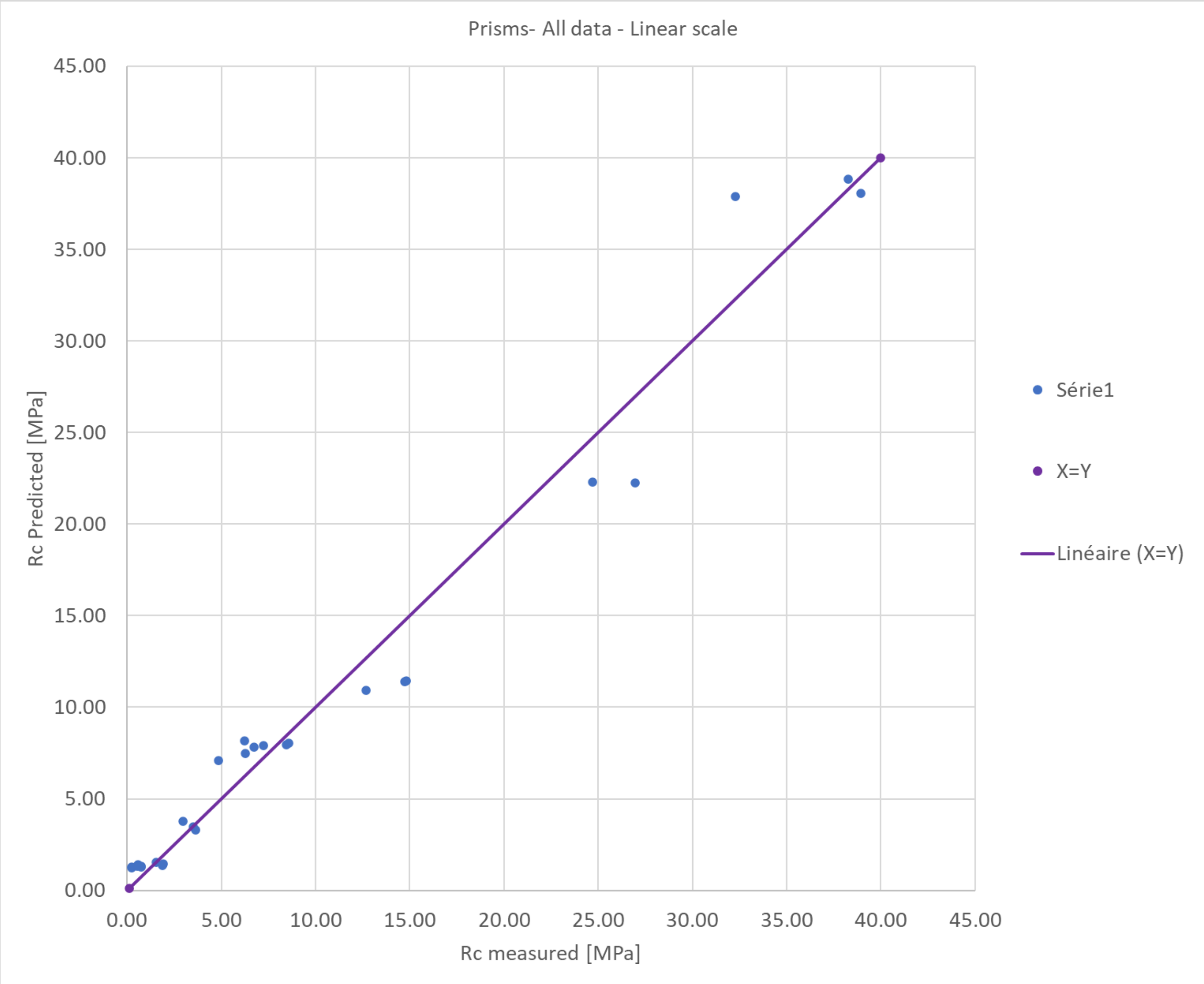


Figure 19 : Estimation of the compressive strength of prism as a function of the porosity and adhesive concentration

Statistics of the regression				
Coefficient of determination R^2				0.97
Standard deviation				2.07
Number of observations				27
	Coefficients	***Error***	***Statistic t***	***Probability***
Constant	- 2.008278767	2.898492157	-0.692870175	0.4950417
Variable X1 – effective adhesive concentration [kg/m3]	0.252062425	0.009228892	27.31231615	1.3758E-19
Variable X2 – Porosity [-]	- 0.112577439	5.569042645	-0.020214864	0.9840391

Table 7 : Statistics of the regression

6 Discussion

6.1 Stability of the Ballast Samples

The stability of the ballast samples was evaluated by correlating the adhesive concentration used during the tests with the amount of detached ballast after demolding, as presented in Chapter 3.2.2. Specifically, three different adhesive concentrations—**17 L/m³, 14 L/m³, and 11 L/m³**—were tested, and the results are summarized in Table 5.

Among the three concentrations, the samples prepared with **17 L/m³** of adhesive exhibited the most stable behavior, with an average of 0.69 kg of detached ballast after demolding. This relatively low detachment indicates that the adhesive provided sufficient bonding strength to maintain the integrity of the block, allowing it to proceed to further testing, including the compression tests.

In contrast, samples prepared with **11 L/m³ and 14 L/m³** of adhesive experienced significant deformation after demolding. These blocks showed substantial ballast detachment, and the deformation was severe enough to prevent them from undergoing further testing, including compression tests. This observation suggests that lower adhesive concentrations are inadequate for ensuring the structural stability of the big ballast samples, particularly for samples with a height of 50 cm.

Thus, the results demonstrate that **17 L/m³** is the optimal adhesive concentration for maintaining stability and minimizing ballast detachment of the sample, while concentrations lower than this lead to structural weaknesses that affect the performance of the samples.

6.2 Adhesive Loss and penetration issues

An important issue that arises from the adhesive concentration tests is the significant adhesive loss, particularly at higher concentrations. For the **17 L/m³** concentration, while it provided the most stable sample with 0.69 kg of detached ballast (as discussed in the previous section), Table 5 shows that 38% of the adhesive was lost during the application. This raises concerns about the adhesive leaking out or not sufficiently penetrating the ballast bed.

By comparison, lower adhesive concentrations—**14 L/m³ and 11 L/m³**—had lower adhesive loss percentages, with 32% and 23% lost, respectively. However, despite the reduced loss, these concentrations were not sufficient to ensure the stability of the samples. As discussed in 6.1, the deformation of these blocks after demolding made it impossible to proceed with compression testing.

In real-world applications, it is expected that the adhesive loss would be reduced compared to laboratory conditions, potentially due to fine particles that would increase adhesive retention.

6.3 Compression Strength

The compressive strength of the six samples was evaluated, and the results are presented in 3.2.4. The graphs for all samples follow a similar trend, demonstrating repeatability and consistency in the results, as shown in Figure 9. Each graph exhibits a typical elastic deformation phase up to the peak load, where the displacement reached approximately 4 mm.

It was also observed that all the samples maintained structural integrity even after reaching the peak load. This consistency indicates that the adhesive bonding was effective enough to prevent significant damage or detachment of ballast particles during the testing process. Due to this, it can be expected that up to **0.7Fmax after the peak**, no significant ballast detachment or falling occurred during the compression test, reinforcing the adhesive's capacity to maintain stability under load.

6.4 Adhesive diffusion within the depth

The tests carried out revealed three important trends for single-pass applications of the reference adhesive:

1. a significant quantity of adhesive is lost, passing through the sample without actually sticking to the grains. The average retention ratio over the 50 cm is around 65% for a concentration of 17 L/m³.
2. for the retained adhesive, a significant concentration gradient has been highlighted, with little adhesive at the bottom compared to the top. The measurements carried out did not enable us to quantify this gradient and especially the adhesive bounded in the bottom of the sample, although this bottom remained consistent during demolding.
3. No pore clogging is observed visually.

Systematic measurement of the average retention ratio (*mean gradient*, see Figure 12) respectively of *loss ratio* as a function of the quantity poured is, however, an important advance on the initial information available at the start of the project.

In our opinion, this measurement makes it possible:
- to eliminates the need to discuss the representativeness of the laboratory application method compared with the on-site application, since it is sufficient to target only the quantity of adhesive that is required in the sample, and to correlate this quantity with the compressive strength.
- to consider indirectly testing the effect of the gradient by carrying out tests on homogeneous samples (see proposed additional test on Figure 24).

6.5 Curing

The working time mentioned on the technical sheet is **10 min**.

The results do not show any significant difference in the strength of small specimens depending on whether the tests were carried out at 5 or 12 days (see graph below).

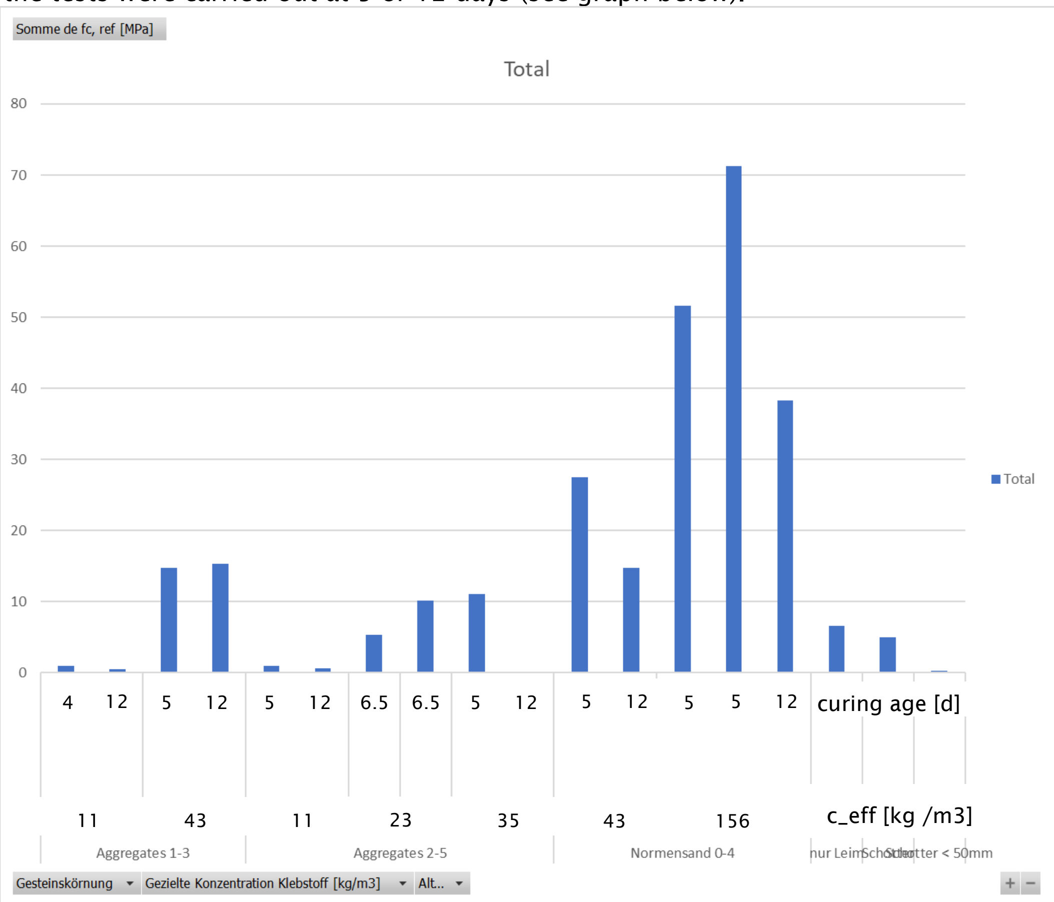


Figure 20 : Resistance pro small sample category and pro concentration

Tests on large specimens were carried out for a curing period of between 5 and 8 days, and the results do not reveal any significant differences in this respect.

We therefore consider that demolding and compression tests can be carried out from 5 days after the application of the additive.

6.6 Reproducibility

The big scale and small-scale tests, for identical parameters, show very good repeatability (see Figure 21 for big scale tests and Figure 19 for small samples).

This reproducibility highlights the fact that sample sizes (both big and small scale) are appropriate for the measurements that have been performed.

A comparison with the results from the big triaxial tests from [4] has been performed. This highlights a very good accordance with the results from big sample tests (see Figure 21).

The equivalent uniaxial compressive strength f_c has been derived from the big triaxial test using the following relationship:

$$f_c = \frac{2\,c\,cos\varphi}{1 - sin\varphi}$$

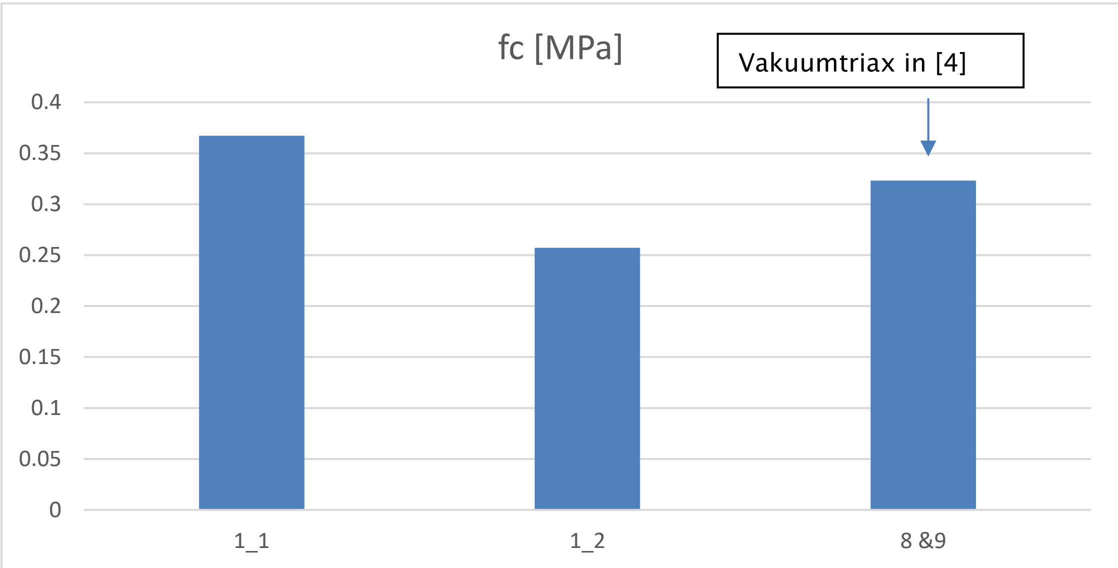


Figure 21: fc [MPa] for big samples and big triaxial, not washed

6.7 Compaction

The compaction of the ballast may be assessed by measuring the porosity of the samples before adhesive application.
For the big scale samples, the compaction has been performed with a vibrating table. It leads to a very good homogeneous distribution of the porosity (Figure 22), around **44%** that is in the range of porosities found in the litterature [5] for fresh, new compacted ballast.

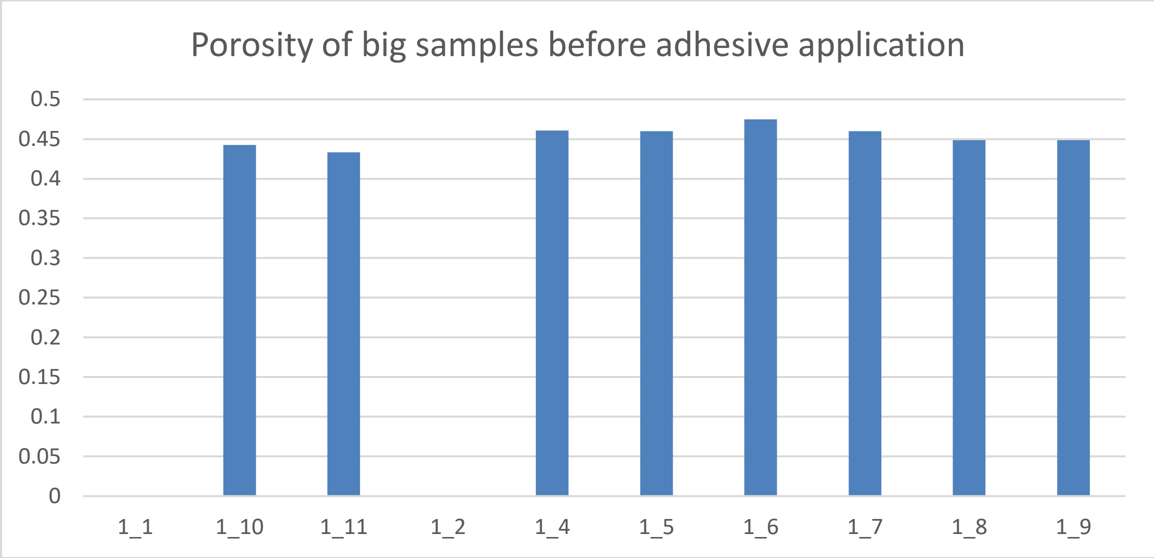


Figure 22 : Variation of the measured porosity of big scale samples

For the small-scale tests, the variation in porosity was modeled using materials with different particle size fractions (Figure 18).

It has been shown in the chapter 5 that compressive strength for small samples, for a given concentration, is directly proportional to porosity and therefore to material compactness.

For the measurement protocol, we therefore recommend setting a criterion for sample porosity before adhesive application, to ensure consistency by compression results.

6.8 Physical effects

A comparison of samples from the large sample series 1_1; 1_2 (air dried, dust content 0.55%) with 1_6 and 1_7 (dried in oven, washed), see Figure 23 for identical test orientation type, reveals a significant influence of these parameters on resistance values and variability.
Further investigations, preferably on small samples, are recommended to precisely quantify this influence and set threshold values.

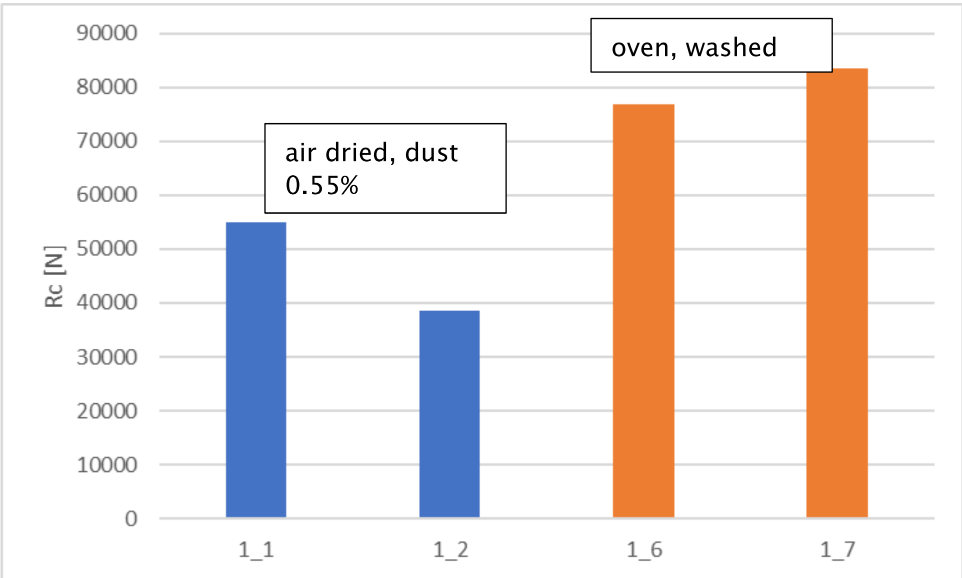


Figure 23 : Influence of moisture and dust content

6.9 Correlation Law

The correlation highlighted in the paragraph 5.3 could make it possible to predict the compressive strength of small samples from the adhesive concentration and porosity of (clean) samples.

This correlation could also be used, based on a limited number of small samples:
· to determine the minimum or optimum adhesive concentration for a given strength
· to compare other adhesives with the reference adhesive
· to study the influence of humidity or pollution on small samples
· to estimate a priori the strength of big samples and limit the need to use them (see recommended complementary method in chapter 7.2).

6.10 Drawbacks for the Big Scale tests

In conducting a series of labor tests involving filling big molds with ballast, several disadvantages have been identified. These drawbacks include the time-consuming process of washing and drying the ballast, the physical demands of handling heavy samples, and the need for specialized equipment such as a crane for transportation.

- Washing around 140 kilos of ballast is time-consuming and requires a full day to complete.
- Drying the washed ballast in an oven requires a large enough oven, the equipment needed for the job and a half day.
- Handling the samples typically requires two persons due to their weight, which can be physically demanding.
- Transportation of the samples may a crane due to their heaviness, posing a risk of back pain for workers involved
- Because of the size of the samples, tests can only be carried out on a large press.

7 Recommendations

7.1 Initial Method

7.1.1 Protocol
The protocol corresponding to the initial method (see chapter 2), is given in appendix 1.

The following parameters are measured
- The quantity of adhesive actually applied to the sample, and the quantity passing through the samples without being retained (Adhesive Loss)
- The compactness of the ballast before adhesive application
- The compressive strength of H50*30*30 samples, and the shape of the load-displacement curve
- Amount of detached particle by demolding

Compression tests for alternative adhesives to the reference can be carried out according to this protocol, which has, however, a limited range of validity, as discussed in part 4.1).

7.1.2 Minimal Requirements
The minimum criteria to be met by adhesives tested according to the protocol given in Appendix 1 are as follows:

Requirement	Reference Value
Ballast type	Class I
Adhesive application	Class IV, see appendix 1
Compression test	Class IV, see appendix 1
Adhesive Loss L [%] by Weight	L< 40%
Number test min [-]	**4**
Curing Time T [day]	T = 7
Compressive strength F_{max} [kN]	$F_{max, mean} > 75$ standard deviation $\sigma_{Fmax} < 12$
Displacement at F_{max} dL (Fmax)	$dL(F_{max}) < 4$ mm
Load-Displacement Graph	Elastic region: Curve should remain linear until F_{max}
Homogeneity of the sample: Post-Peak structural integrity until 70% of F_{max}:	Weight Loss(0.7 $F_{max, post\_peak}$) < 0.5% Sample Weight Differential settlement of loading plate < 0.5 mm until 0.7$F_{max, post_peak}$
Compactness of the ballast before adhesive application Porosity η [%]	$\eta_{mean} < 44\%$ standard deviation $\sigma_{\eta} < 0.01$
Water permeability	Visual check that pores are not clogged with adhesive.
Stability after demolding [kg]	Mass Loss $W_L < 1$ kg

7.1.3 Range of validity of the method

We would like to remind the following points:

- compression tests on the proposed big scale samples mix several physical phenomena which are not analyzed separately (compactness, adhesive diffusion gradient, effective adhesive quantity)
- they are a simplified representation of site conditions, and do not enable the following effects to be measured:
  - Influence of humidity
  - Influence of fine particles
  - Influence of temperature
- They provide only a visual estimate of
  - adhesive diffusion gradient
  - ballast pore filling
- they are tedious in terms of volume and preparation time

7.2 Complementary method

To enable each physical parameter to be studied separately, and to analyze sensitivity to variations in these parameters, we recommend that the additional tests as well as the obtention of reference values on the field listed in Table 8 be carried out.
With the exception of preliminary tests on small samples relating to variations in adhesive concentration (see chapter 4) , systematic tests were not carried out in the present campaign, and it is recommended that a specific protocol be set up and reference values obtained for the reference additive, before these tests can be imposed on other types of adhesive.

It is also emphasized to collect references values from the field to assess the range of the parametric study.

Type	To be assesed	Proposed test
References values from the field	Effective diffusion within the layer Range of humidity Range of fine particle pollution in the ballast	- Reference values ballast layers bonded on site using the on-site application method
Big scale	Diffusion into the ballast layer by application in the lab	- ensure minimal bonding in the bottom of the sample - ensure gradient correspond to what measured in the field (see Figure 24)
	Ensure adhesive does not clog pores	Permeability test trough the mold (for example before demolding for compressive test)
Small Scale on gravel 2-5 mm Series of 5 Prisms	Sensitivity to variation of bonding concentration	- Sensitivity on small scale samples
	Sensitivity to moisture	- Sensitivity on small scale samples with moisture 0% - 3% - 5%
	Sensitivity to fine particles	- Sensitivity on small scale samples with content fines particles 0% - 1% - 2%

Table 8 : Recommended complementary tests

Statistical analysis of the results of these future tests and their comparison with the reference adhesive and reference compression tests will also be essential for calibration.

A test for measuring the gradient in the sample is proposed in Figure 24:

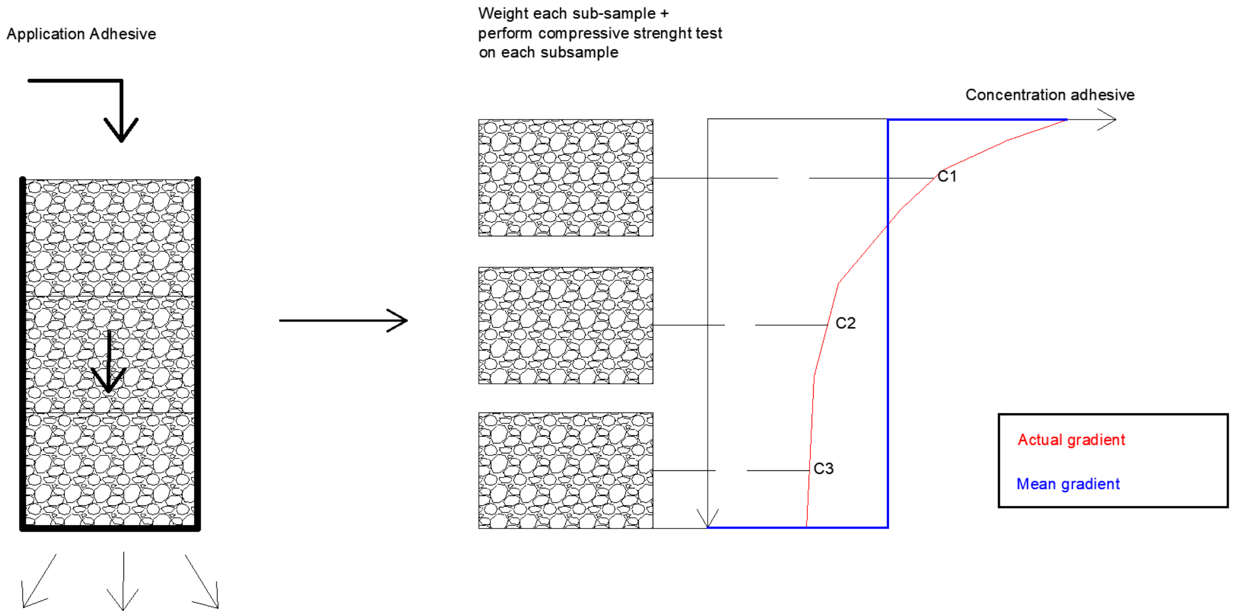


Figure 24 : Principle measure gradient of adhesive

8 General terms for this test report

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This test report includes 31 pages without appendix.