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Small scale testing of shear-bond behavior in composite deck slabs with profiled steel sheeting

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ABSTRACT

This study investigates the shear-bond behavior of composite deck slabs incorporating profiled steel sheeting through a series of small-scale push-off and pull-out tests. The experimental program evaluates the influence of mechanical interlock, friction, and embossment geometry on the interface performance between concrete and steel sheeting. Specimens were prepared using galvanized steel profiles and tested under varying vertical loads to simulate realistic shear conditions. The results demonstrate that re-entrant features and embossments significantly enhance shear resistance by preventing horizontal slip and vertical separation. Frictional coefficients were quantified, and failure mechanisms were observed to resemble those in full-scale slab tests. The findings provide critical insights for developing finite element models and optimizing composite slab design, offering a cost-effective alternative to full-scale testing.

Introduction

Composite construction refers to structures made up of two different materials. In Structural Engineering, these materials can include combinations like concrete/steel, concrete/timber, timber/plastic, timber/steel, and plastic/steel, among others. The integration of these materials leverages their structural properties to create members that are stiffer, stronger, and lighter due to the effective connection between them.

Composite slabs utilize a combination of concrete and steel [1], which results in a composite material where the bending moment from a static load is primarily countered by the compressive strength of the concrete and the tensile strength of the steel [2]. The decision to use either concrete or composite construction for a specific project is influenced by numerous factors. When comparing these different types of construction methods, the predominant consideration is often the total cost, which includes material expenses, construction time, and the impact of fire resistance, which is also a significant factor.

A key requirement for the effective construction of composite profiles is a significant bond strength at the interface between its components [4,5,6,7,8,11]. The interface must withstand horizontal shear forces and prevent vertical separation. To accomplish this, the profiled steel sheeting available today typically employs a consistent arrangement of embossments (indentations) and re-entrant features [3,13]. These are pressed or rolled into the steel sheeting as required.

At present, the reliability of the composite action from steel sheeting requires physical test data [9,10]. Shear-bond resistance can be measured through full-scale tests of concrete slabs or a combination of full-scale and small-scale model tests. There have been efforts to simulate the behaviour through numerical analysis [12,14, 15,16,17]. However, this is a complex issue, particularly when modelling the individual behaviour of embossments. Recent investigations have continued to emphasize the significance of mechanical interlock and frictional resistance in enhancing the shear-bond behavior of composite slabs with profiled steel sheeting. It has been shown that the use of embossments and re-entrant features significantly improves the interface performance between steel and concrete, contributing to increased load-carrying capacity and resistance to horizontal slippage and vertical separation [18]. Experimental studies have demonstrated that variations in steel sheet thickness, deck profile geometry, and shear connector configurations directly influence the longitudinal shear strength and overall composite action, particularly under bending conditions [19]. Additionally, the role of construction techniques and environmental factors such as moisture and roughness at the interface has been identified as critical in determining the ultimate shear capacity [20]. These findings align with earlier research and support the continued refinement of composite slab systems to meet evolving structural demands.

Based on previous studies, the complexity of simulating such behaviour continues to be a challenging issue; therefore, the main purpose of this paper is to provide initial results from small scale tests, to work towards developing a numerical FEM model for determining the shear-bond capacity of composite slabs.

Research Programme and Methodology

The idea of evaluating the shear resistance between concrete and sheeting using small scale samples originated in the 1970s. In this study small samples were typically subjected to pure shear by either pulling (pull-out test) the sheeting while the samples were orientated vertically or by pushing (push off test) the concrete block with the samples set horizontally. These types of small-scale testing have been proven to be a cost-effective means of developing new sheeting profiles, as they offer significant insights into the longitudinal shear characteristics of the profiled sheeting with minimal investment.

In this paper, the pull-out and push-off tests utilized for profiled composite slabs are examined, and a version of these tests, modified by the author, is presented along with the results for various sizes and shapes of profiled steel sheeting compared. An empirical formula for shear-bond capacity has been formulated based on these tests.

The pull-out test is akin to that employed for reinforcing bars in traditional reinforced concrete, where a tensile force is exerted on one end of the reinforcing bar. The push-off test resembles those used for composite structures such as composite beams and composite slabs, where a compressive force is applied to the concrete.

The aim of the tests conducted in this research is to provide insights into the mechanical interlocking mechanism and the behaviour of composite slabs, as well as to utilize the findings for finite element modelling of the full-scale slab performance.

A total of ten small specimen tests, including push-off and pull-out tests, were performed to assess the impact of the re-entrant portions in profiled steel sheeting, using a simple test rig designed for this purpose. This testing also evaluated the effects of embossments and the friction coefficient. A concrete block was cast with a width corresponding to one or two rib widths of the profiled steel sheeting, measuring 300 mm in length for the single rib and 600 mm in length for the double rib, as illustrated in Figures 1-4.

Preparation of Specimens

The specimens for the Push-off and Pull-out tests were prepared through a carefully sequenced process. Initially, the steel sheeting was sliced lengthwise into segments, each incorporating either one or two ribs of the profile. These segments were then cut across their full thickness to a typical length of 300 mm, as illustrated in Figures 1–8. Once shaped, the steel sheeting was welded securely to heavy-duty I-beams on both sides and at the rear to ensure stability during testing. Formwork was then arranged to achieve a total concrete thickness of 165 mm. A plastic tube, measuring 27.2 mm in depth, was placed in the central trough to facilitate the test setup. Concrete with a nominal characteristic strength of 25 N/mm² at 28 days was prepared for casting. Just before pouring, the surface of the steel deck was thoroughly cleaned to ensure proper bonding. Finally, the specimens were manually compacted, covered, and left in the formwork to cure, completing the preparation phase.

Test set-up

The test configuration is shown in Figures 1-8 for both the Push-off and Pull-out tests. In the Pull-out test (Figures 3, 4, 7 & 8), a steel bar is dragged through the fixed horizontal tube located in the concrete block. One side of the steel bar is connected to a nut that is welded to a steel bar, while the other side is attached to a nut with a steel plate functioning as a washer at the back end of the concrete block. To prevent vertical uplift, the concrete block is secured using a roller support linked to a load cell, which is mounted on a sturdy steel frame that contains a hydraulic jack. The purpose of the load cell is to measure the initial vertical force (5 kN, 10 kN, or 20 kN) that is applied to the specimen. This is accomplished by affixing the jack and load cell to a steel frame. The load cell's output reading is then utilized to regulate the vertical load's value. Vertical loads of 5, 10, or 20 kN were employed depending on the specific test being conducted.

For the Push-off tests, the configuration remains the same, but the horizontal load is applied as indicated in Figures 1, 2, 5 & 6. A hydraulic jack was employed to uniformly push the specimen. The horizontal displacement at the back end, situated just above the applied load point, was recorded at each load increment using dial gauges. The horizontal force is exerted by a hydraulic jack on one end of the steel bars. This force is transmitted to the far end of the concrete block via the embedded tube. The horizontal load is applied in consistent increments until failure is observed. The horizontal displacement at the back end, positioned just above the load application point, was measured at each load increment using dial gauges.

Frictional coefficient

The results from the Push-off and Pull-out tests were used to evaluate the frictional coefficient between the concrete and the steel sheeting, specifically using 0.99 mm galvanized steel ComFlor CF70. The procedure began with the use of a hydraulic jack to either push or pull the concrete block away from the steel sheeting, thereby breaking the chemical bond at the interface. Once separated, the concrete block was returned to its original position. A vertical load was then applied and maintained on the upper surface of the concrete block. Following this, a static load was gradually introduced at the tip of the steel bar using the hydraulic jack. This load was increased until movement of the concrete block was observed. After recording the movement, both the horizontal and vertical loads were removed, and the block was repositioned. The vertical load was then increased incrementally, and the corresponding horizontal load required to initiate movement was recorded. This cycle of repositioning, increasing vertical load, and measuring the horizontal force was repeated several times to obtain a reliable assessment of the frictional coefficient.

Results and Discussion

All specimens underwent testing at 10 days. The shear stress was determined by dividing the horizontal load by the area in contact between the sheeting and concrete. The concrete is secured by the re-entrant section of the sheeting, which helps resist vertical separation. The mechanical interlocking forces, which arise from the presence of indentations, depend on the web stiffness as well as any frictional locking created by the shape of the re-entrant section that secures the concrete. The highest recorded loads are presented in Table 1. The overriding of concrete at the embossment locations during the tests (Figure 9) is comparable to what was observed in full-scale composite slab tests. The relationships between load horizontal slip for the tested profiled steel sheeting, along with the shear stress and horizontal slip, are illustrated in Figures 10 to 19. Figures 20 to 23 demonstrate the increase in maximum load and shear strength resulting from the full interaction of the re-entrant portion of the profile in tests 1, 3, and 9, in contrast to the limited contribution of the "dovetail" shape observed in tests 8, 6, and 10. Figures 24 to 27 illustrate that an increase in vertical load enhances friction and maximizes shear stress.

The general findings were:

• At lower loads, the slip was minimal (chemical bond was effective). This is similar to what has been observed by previous work. [21].

• As slip initiated, the concrete block began to override the embossments at the front of the specimen, as depicted in Figure 9.

• After failure, the concrete block was lifted from the sheeting at the free end, revealing that the concrete was held against vertical uplift due to its contact with the undersides of the embossments and at the re-entrant sections.

• The concrete remained intact except at the sides of the embossments and the re-entrant portions.

• A horizontal line was imprinted on the concrete block at the sides of the embossments due to bearing and friction.

• No changes were noted in the load cell readings (the vertical load) until the concrete block was nearly off the roller support.

• No plastic deformation could be detected in the profiled steel sheeting.

The correlation between the static load (horizontal force, H) that caused the movement of the concrete block and the static vertical load on the surface of the concrete block (vertical load, V) is illustrated in Figure 28 for the Push-off test and Figure 29 for the Pull-out test. The slope of the regression line from the results indicates a coefficient of friction of 0.412 and 0.388, respectively.

During the tests, the failure was caused by the concrete overriding the embossments. Damage to the steel and minor crushing of the concrete was noted at the base of the embossments, which resembled the damage seen in the full-scale slab tests. The re-entrant portions showed minimal damage in the test, while in all other tests, the re-entrant nib of concrete was found to be broken after the failure. The load recorded in the cell remained unchanged until the final phases of the test, when the block had lifted and shifted several millimetres. These tests highlight the significance of simple friction. The results presented in Figures 10 to 13 also indicate that the re-entrant portion has a considerable impact. It can be inferred from the damage observed in the concrete and embossment steel that the majority of shear resistance seems to originate at the base of the embossment. Furthermore, since the normal load remained steady until the very late stages of each test, it may also be concluded that the concrete's overriding occurred due to the local deformation of the web plate.

CONCLUSION

This study has demonstrated that small-scale push-off and pull-out tests are effective in evaluating the shear-bond behavior of composite deck slabs with profiled steel sheeting. The results confirm that shear resistance is governed by a combination of adhesion, mechanical interlock, and friction, with the re-entrant features and embossments playing a critical role in resisting horizontal shear and vertical separation. The observed failure mechanisms, including concrete overriding and localized deformation at the embossment base, closely resemble those seen in full-scale slab tests, validating the relevance of the small-scale approach. The influence of vertical load on enhancing frictional resistance was clearly established, with friction coefficients determined to be 0.412 and 0.388 for push-off and pull-out configurations, respectively. These findings provide valuable parameters for numerical modelling and support the development of reliable finite element models for predicting composite slab performance. The methodology and results presented here offer a cost-effective and practical framework for advancing the design and analysis of composite floor systems. The parametric values derived from the tests can be directly applied in a physical model based on partial shear connection theory, which provides accurate predictions of slab strengths. Consequently, these tests can enhance a testing program that includes full-scale slab testing. The numerical findings from these tests will be utilized in the analysis and modelling of composite slabs.

Table 1 Maximum applied load of Push-off, and Pull-out test

Specimen No.	Maximum applied load kN
1	23.15
2	25.52
3	22.87
4	24.91
5	11.6
6	10.1
7	14.76
8	13.45
9	88.95
10	59.8

Table 2 Profile Steel Details

Specimen No.	Thickness t (mm)	Depth h (mm)	Width b (mm)	Young's Modulus	Area of Steel A_p (mm^2/m)	Neutral Axis e_p (mm)
1-10	0.9	70	300	202777	1166	30.34

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Table 3 Specimen Details

Test No.	Length (mm)	Width (mm)	Depth (mm)	Density of Concrete KN/m^3	Concrete strength at failure N/mm^2	Maximum applied horizontal load kN	Vertical applied load kN
1	300	300	165	23.79	44	23.15	5
2	300	300	165	23.79	44	25.25	10
3	300	300	165	23.79	44	22.87	5
4	300	300	165	23.79	44	24.91	10
5	300	300	165	23.79	44	11.6	10
6	300	300	165	23.79	44	10.1	5
7	300	300	165	23.79	44	14.76	10
8	300	300	165	23.79	44	13.45	5
9	600	600	165	23.23	34	88.95	20
10	600	600	165	23.23	34	59.8	20

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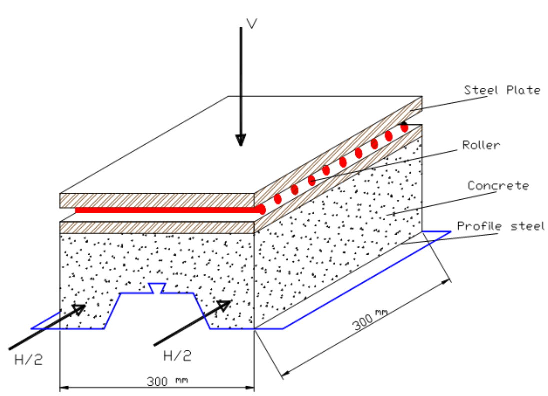
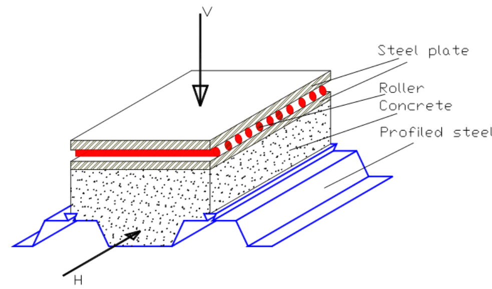


Figure 1 Typical Push-off test – Full Interaction



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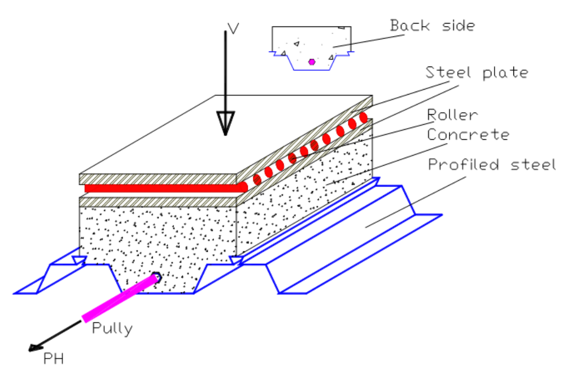

Figure 3 Typical Pull-off test – Full Interaction

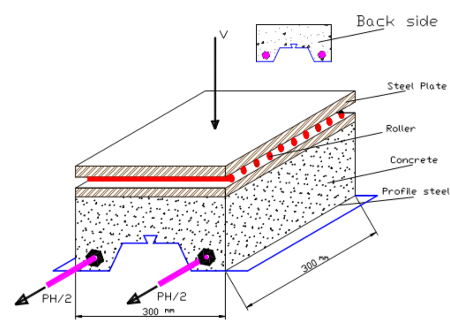

Figure 4 Typical Pull-off test – Partial Interaction

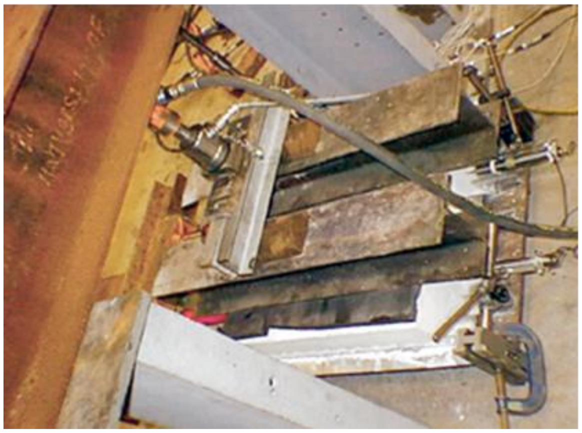

Figure 5 Push-off test view 1

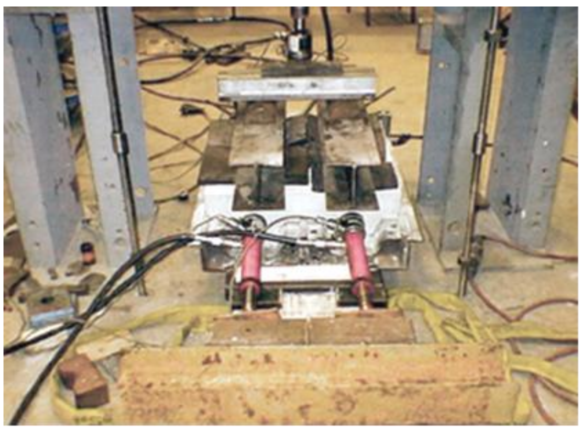

Figure 6 Push-off test view 2

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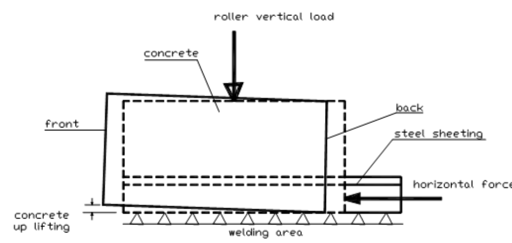

Figure 9 Failure Mechanism of tests

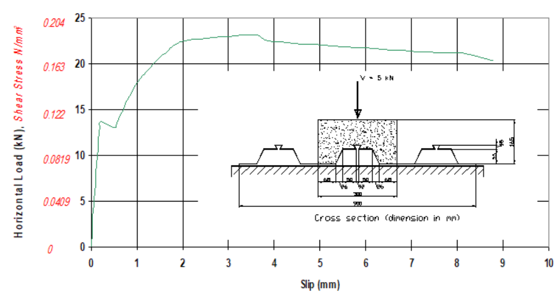

Figure 10 Load-Slip behaviour for Composite Slab (Push-off test No. 1 with vertical load 5 kN)

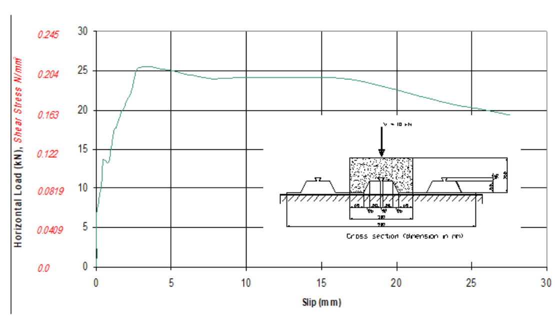

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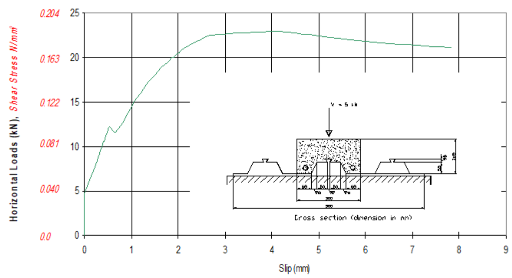
Figure 11 Load-Slip behaviour for Composite Slab (Push-off test No. 2 with vertical load 10 kN)



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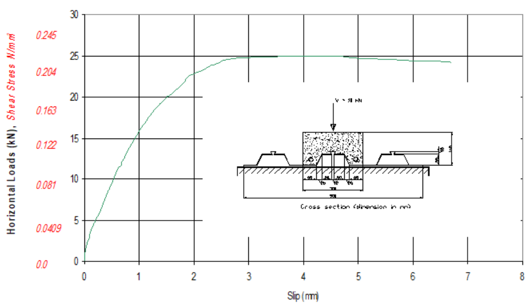

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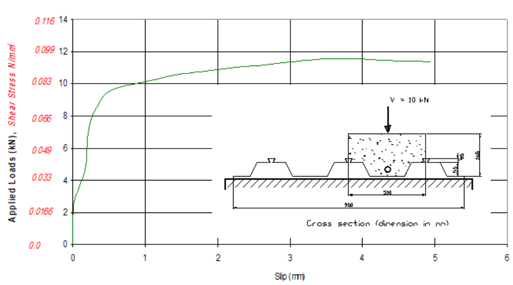

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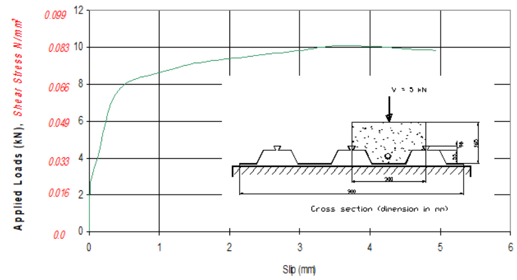

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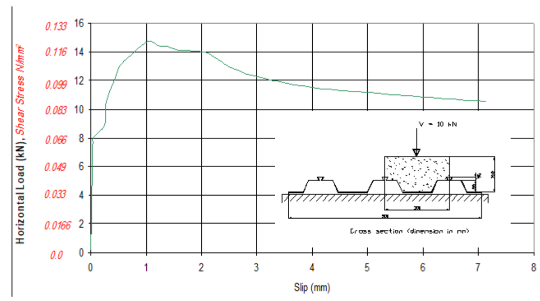

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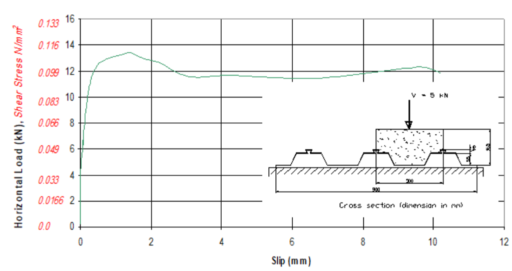
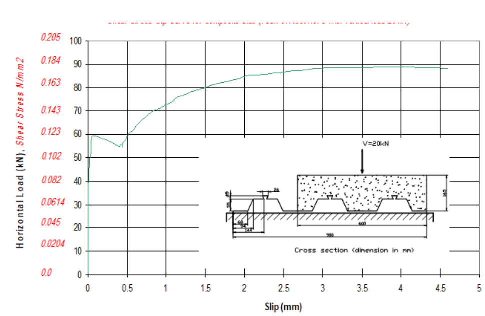


Figure 17 Load-Slip behaviour for Composite Slab (Push-off test No. 8 with vertical load 5 kN)



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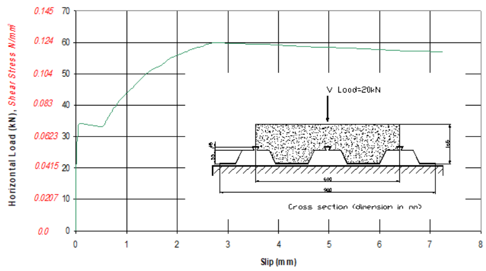

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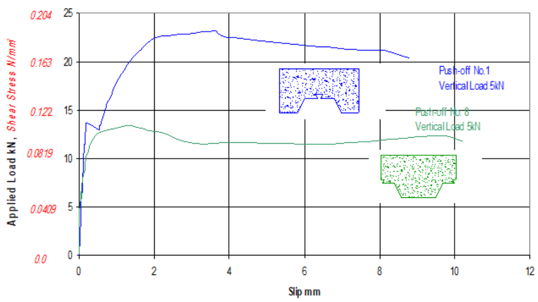

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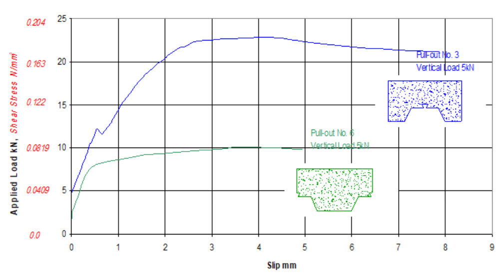

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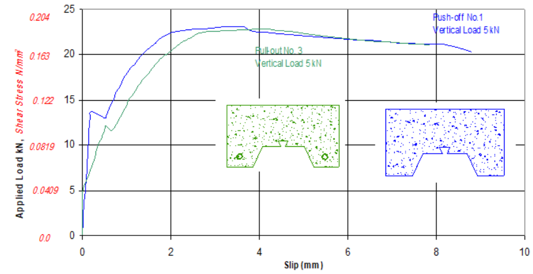

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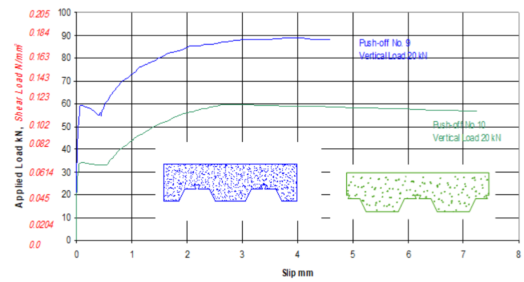

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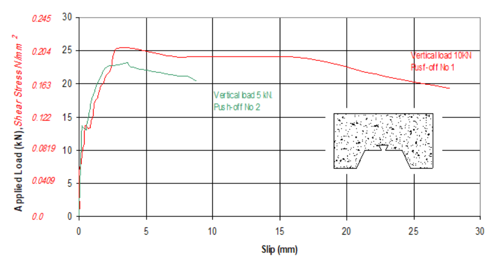

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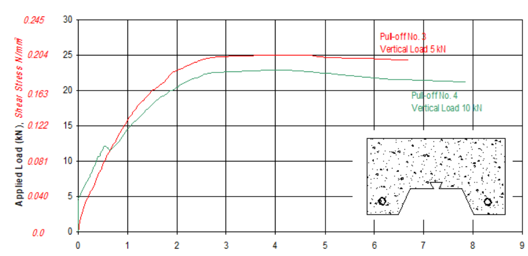

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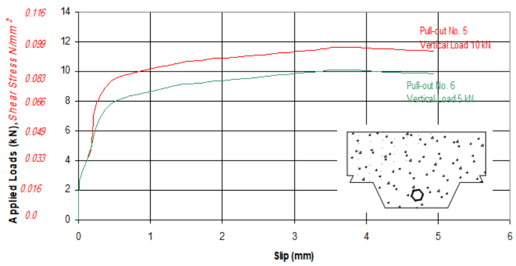

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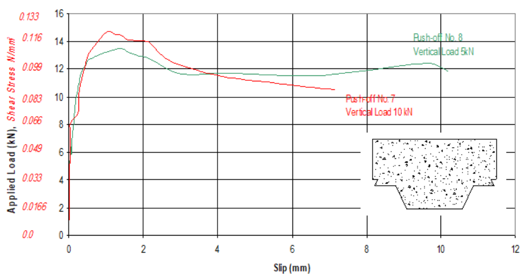

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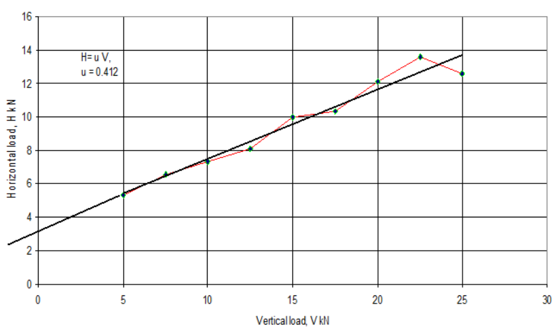

Figure 28 Determination of frictional coefficient (for the Push-off test)

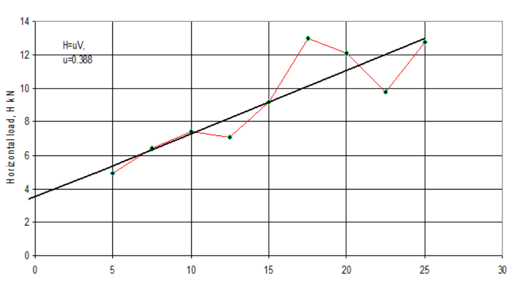

Figure 29 Determination of frictional coefficient (for the Pull-out test)

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