OPTIMISATION OF REINFORCEMENT ELEMENTS IN CERAMIC SLABS

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ABSTRACT

The low thickness and large format of ceramic slabs compromises their mechanical performance in usage scenarios where mechanical strength is vital.

An exemplary case is flooring, mainly for pedestrian traffic with light to medium loads, therefore involving private dwellings or public retail and services premises.

To improve the mechanical behaviour of ceramic slabs, current reinforcement makes use of composite materials consisting of glass fibre meshes stuck to the back of the slabs. However, no methodological study is available that assesses the properties that such a reinforcement system contributes to the ceramic slab, and that seeks to optimise those properties or looks for alternatives that will improve them.

This study initially calls for statistical analysis of the influence played by the various elements in the ceramic slab/reinforcement assembly in regard to questions that may compromise ceramic slab behaviour on the floor, such as impact resistance and response to concentrated loads.

That information is then used to define combinations of ceramic slab, type of fabric, fibres, and adhesive for the matrix, which are assessed in regard to performance features considered important in the intended flooring use. Those performance features are as follows:

- Behaviour under static loads that subject the system to compression.
- Resistance to hard body impact.
- Behaviour in regard to dynamic rolling loads.

A further issue to be considered is the behaviour of the reinforced slab in association with either rigid or deformable underlying layers, which condition the result of the assembly designated the ceramic system.

All of the above opens up a very interesting line of study with regard to the optimisation of reinforcement elements on ceramic slabs to ensure good performance as flooring.

1. INTRODUCTION

In this paper, ceramic slabs refer to large format ceramic tiles measuring up to 3.2 m in length and with thicknesses varying from 3 mm to 6 mm. These slabs are mainly produced using specific forming technologies.

This type of product is favoured over traditional, thicker tiles for a number of reasons. Firstly, given it is a slim tile, the consumption of raw materials and energy required to manufacture it is significantly reduced, making it, a priori, a more sustainable product, while its lighter weight affords other benefits from an architectural point of view.

However, the mechanical requirements involved in more demanding uses, for example, as paving or façade cladding, restrict extended use of such slabs, due to misgivings about how they perform in those scenarios.

Therefore, when contemplating ceramic slabs for applications involving high mechanical requirements, it is essential to ensure appropriate performance that minimises the risk of malfunctions and pathologies. Some ceramic slab manufacturers currently use reinforcement systems on their slabs to improve slab mechanical performance.

Such reinforcement elements are composite materials made up of two or more components, so that the properties of the whole are superior to those of the individual components. The most commonly used composites, owing to their light weight and excellent mechanical properties, are polymer matrix composites with reinforcements in the form of a fibre fabric.

Today's ceramic sector has adopted the technique used in the manufacture of natural stone in which a glass fibre reinforcement mesh is fitted to the slab in an attempt to improve its performance. This has been implemented without any prior in-depth research on the use of other types of mesh or materials in the matrix and in the fibres that might optimise slab performance in uses that call for high mechanical strength.

Improving the reinforcement of the slab is instrumental to minimising the chances of problems arising with the demands made by the actual application, or from defects in the design or manufacturing process of the underlying layers or in the ceramic slab installation itself. Reinforcement is intended to improve impact and loading behaviour and stability. Therefore, optimising ceramic slab reinforcement is essential to enhancing the deployment of this type of tile in uses with more demanding mechanical requirements.

As a result, this study, applied to the reality of ceramic slabs (extra-large formats with very low thicknesses), seeks to identify the best combinations of the types of mesh to use, of the fibres that make up the mesh, and of the products for the matrix that bonds both the reinforcement itself and the reinforcement to the slab. Consideration will also be given to the use of natural materials that require little processing and to recycled and economically viable materials.

2. DESIGN OF EXPERIMENTS AND PRELIMINARY STUDY OF REINFORCEMENT SYSTEM VARIABLES

As a starting point, it is necessary to determine the influence played by the different variables that make up the ceramic slab and reinforcement system. To this end, a design of experiments was carried out.

In this preliminary study, bending strength and impact resistance were considered significant mechanical properties. Test conditions (Figure 1) were sought with a view to highlighting the effect on performance of the different variables, even though the test conditions may not be representative of actual conditions of use.

The values to be assessed in the study are the load at which the specimen breaks in the bending test and the impact energy at which chipping (loss of material) or radial cracks of more than 10 mm in length occur.

The variables and factors taken into account are listed below:

Variable	Types			
Fibre	Glass	Carbon	Aramid	Natural
Fabric	Taffeta	Twill	Net (impact only)	
Slab thickness	3 mm	5 mm (bending only)	6 mm	
Matrix adhesive	Epoxy	Polyurethane	Industrially applied polyurethane	

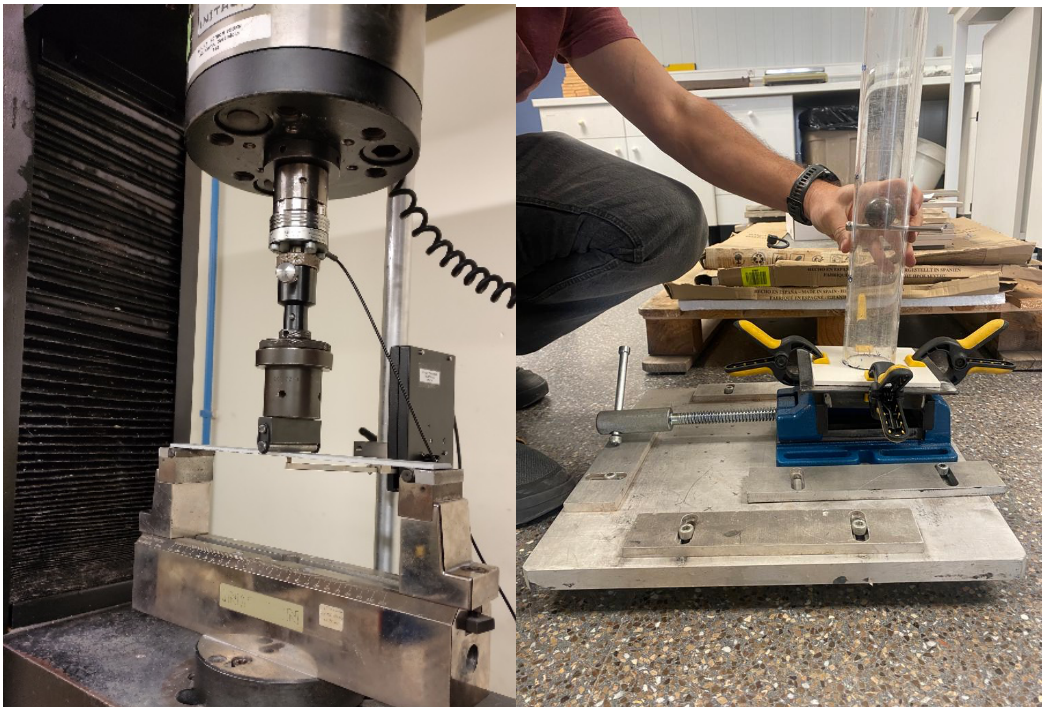
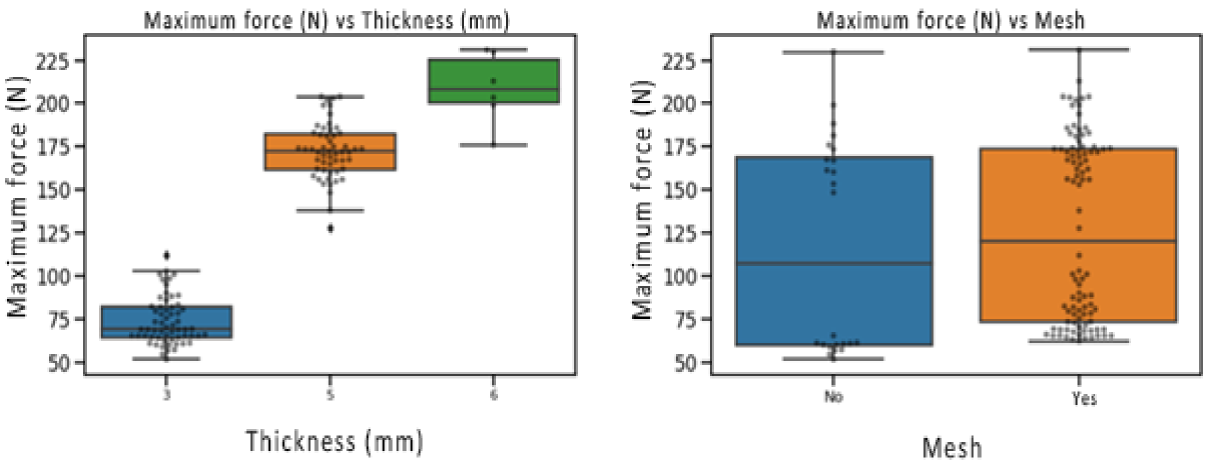


Figure 1: Left: Bending test on 30x300 mm samples, w/ 180 mm gap between supports. Right: Impact test, 130x130 mm samples resting on a frame with a 100x100 mm hollow centre

2.1 BENDING PERFORMANCE

First, a descriptive and graphical analysis was carried out, for which Plot-box diagrams were created to identify differences and asymmetries, outliers, and homogeneity of variance.



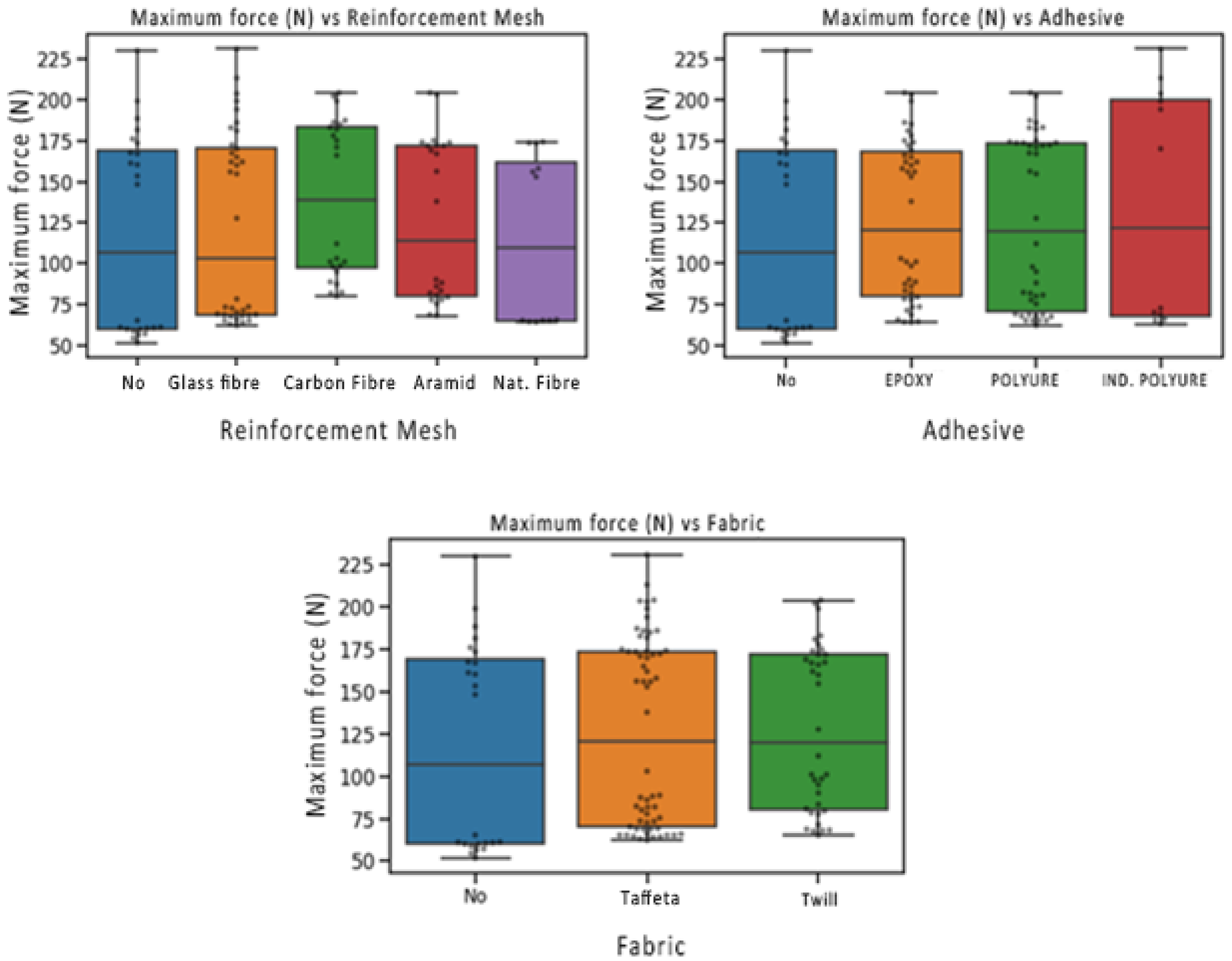


***Figure 2**: Plot-box diagrams of the series of bending tests*

Thereafter, a **full factorial experiment** was carried out for bending strength, which in statistics means an experiment whose design consists of two or more factors, each with different values or levels, whose experimental units cover all possible combinations of those levels in all factors.

Experiments of this type enable the effect of each factor on the response variable to be assessed, as well as the effect played by interactions between factors on the response variable. The tool used to analyse the characteristic factors of the ceramic slab reinforcement system is called the three-way analysis of variance (ANOVA) technique.

The results obtained from the study are summarised below:

- ✓ Slab thickness is the key variable.
- ✓ Ceramic slabs of 5 mm and 6 mm thickness do not significantly improve their bending strength when reinforcement meshes are used. However, they do have a noticeable effect on 3 mm thick slabs. In this case:
    - The most favourable reinforcement material for increasing the bending strength of the slabs is carbon fibre, followed by aramid.
    - Twill weaving seems to be the best for increasing slab bending strength.
    - The adhesives in the reinforcement matrix do not have a statistically significant impact on slab bending strength.

2.2 IMPACT RESISTANCE

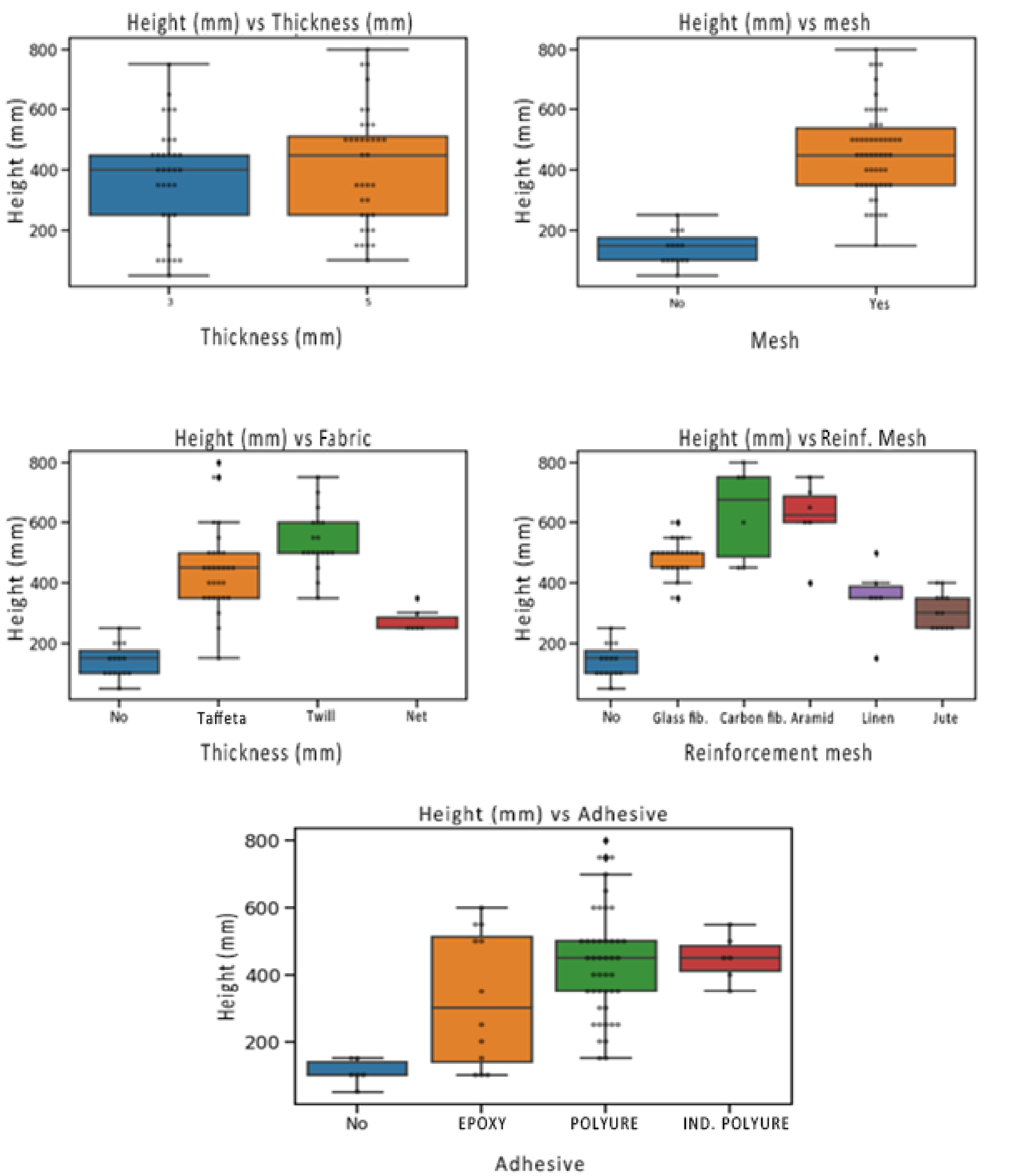


Figure 3: *Plot-box diagrams of impact resistance tests*

A statistical analysis of the results of the impact tests enabled us to design the experimental analysis.

The conclusions drawn from the study of the results in regard to impact resistance are as follows:

- ✓ The presence of reinforcement significantly increases impact resistance.
- ✓ Thickness (3-5 mm): In reinforced slabs, no significant differences attributable to thickness were observed.
- ✓ Fabric: Twill-woven fabric seems to be the best fabric option for reinforced slabs.
- ✓ Reinforcement mesh: The best reinforcement meshes are carbon fibre, aramid, and then glass fibre, in that order.
- ✓ Adhesive: No significant differences occur as a result of the adhesive.
- ✓ Slabs with no reinforcement: In this case, thickness does have a significant influence.

On the basis of these results, this study classifies reinforcement meshes as being of **high performance** (carbon fibre and aramid), **standard** (glass fibre), and **natural materials**.

3. VALIDATION OF PROPOSALS FOR REINFORCEMENT SYSTEMS

A study of the state of the art revealed that current reinforced ceramic systems are mostly made up of ceramic slabs reinforced with taffeta-woven glass fibre mesh of about 200g/m^2 and polyurethane resin as the matrix, so that was the type of system taken as the reference against which to measure performance.

As pointed out above, to study the influence on mechanical performance of a slab with reinforcement used for flooring subject to pedestrian traffic, its response to progressive point loads, hard body impacts and dynamic rolling loads was assessed.

Furthermore, slab behaviour was also studied on both a rigid base (4 cm thick concrete slab) and on a deformable base (XPS Styrofoam board covered on both sides with a reinforcement material and a geotextile top layer with a total thickness of 19 mm).

3.1 STUDY OF REINFORCEMENT SYSTEMS VERSUS PROGRESSIVE POINT LOADS

The test consisted of exerting a normal progressive compressive force on the upper face of the samples over a central area of 625 mm^2. A hardened steel cylindrical load locator punch, 28.21 mm in diameter (=625 mm^2 area), was used to exert the pressure. The resistance and deformation to point loading of different models with a square area of 300 mm x 300 mm were measured.

To identify the force and deformation at which the first crack or defect occurs in the samples, progressive force is exerted in intervals, stopping and unloading every so often to observe the surface. The intervals applied were 2, 4, 8, 16, 20 and 25 MPa.

The reference value for compressive strength is 4 N/mm^2 (**4 MPa**), which corresponds to a concentrated load of 255 kg for light loads, and of 8 N/mm^2 **(8 MPa)**, which corresponds to a concentrated load of 510 kg, for medium loads.

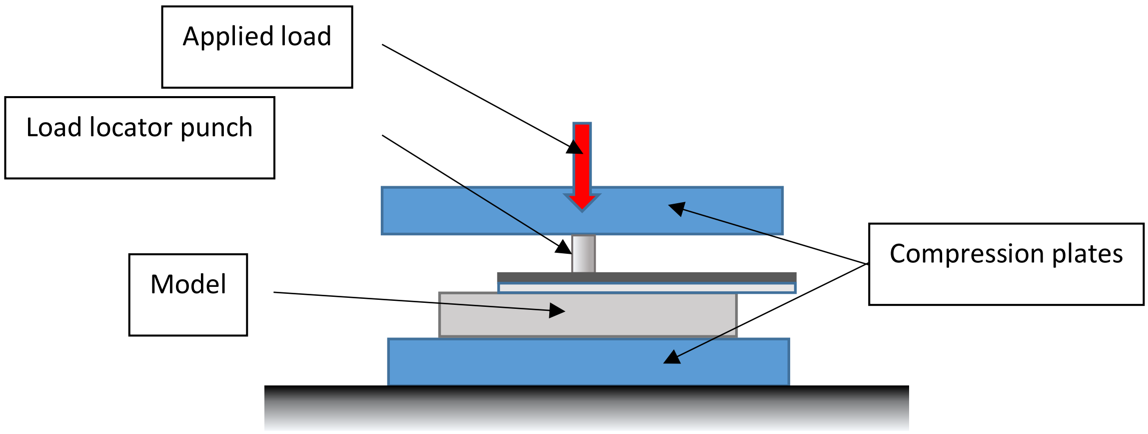


Figure 4: *Diagram of test*

The results obtained for the systems evaluated are given below.

Rigid base

System	Result
6 mm thick slab with twill-woven carbon fibre reinforcement	Withstands loads of 25 MPa with no defects appearing
6 mm thick slab with no reinforcement	Withstands loads of 20 MPa with no defects appearing
3 mm thick slab with twill-woven carbon fibre reinforcement	Withstands loads of 4 MPa with no defects appearing

Deformable base

System	Result
6 mm thick slab with twill-woven carbon fibre reinforcement	Withstands loads of 4 MPa with no defects appearing
6 mm thick slab with taffeta-woven glass fibre reinforcement (industry standard reinforcement)	Withstands loads of 2.1 MPa with no defects appearing

Interpretation of results

In general, the base or background on which the reinforced or non-reinforced ceramic slab is laid conditions its behaviour. Ceramic slab on a deformable base displays worse results under progressive loading than on a rigid base.

The 6 mm thick ceramic slab on a rigid base far exceeds pre-set specifications, even without reinforcement. On a deformable base, however, it only surpasses that mark reliably under light loads if reinforced with high-performance meshes.

The 3 mm thick ceramic slab needs high-performance mesh reinforcement to ensure adequate performance at least under light loads and on a rigid base. On a deformable base, it cannot offer good performance in any case.

3.2 STUDY OF REINFORCEMENT SYSTEMS VERSUS IMPACT

To perform the test, the apparatus was set up as shown below.

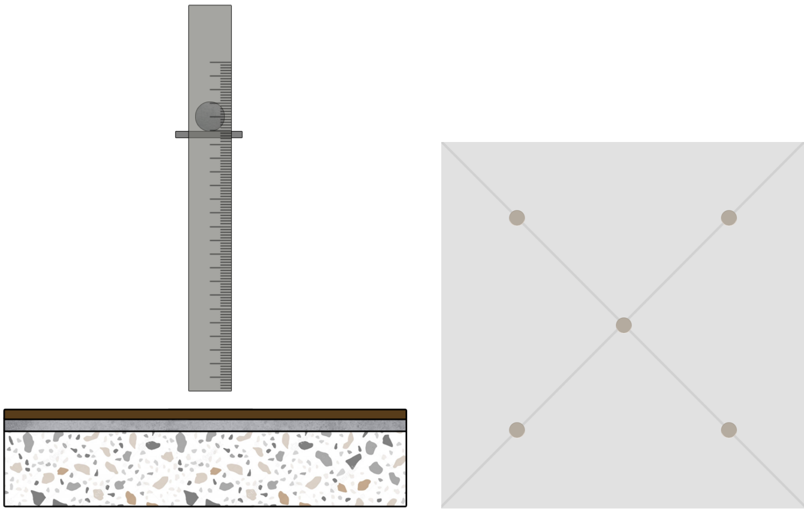


Figure 5: *Left: Diagram of the test. Right: Impact points*

A tube with height markings and holes was arranged to place the stop that holds the m=510 g steel ball at the desired height until it is allowed to fall freely onto the 300x300 mm samples of the system under test.

When the metal stop is removed, the steel ball drops so that the point of impact is located in the centre of the tube. A single impact is made and the ball is collected after its first rebound.

With an impact energy of 3J, a level of **damage equal to or less than level 3** as shown in Table 1 below is acceptable.

Level	Apparent defects
0	- No marks around the point of impact
1	- Circular cracks around the point of impact - No radial cracks or chipping
2	- Radial crack(s) of length l < 5 mm (specify number) - No chipping
3	- Radial crack(s) of length 5 mm < l < 10 mm (specify number) - No chipping
4	- Radial crack(s) of length l > 10 mm (specify number) - No chipping
5	- Chipping (loss of material)

Table 1: *Defect level classification in Annex 6 of the CSTB's Cahier 3778 v.5 bis (France).*

The results obtained are summarised below:

Rigid base

System	Impact energy producing defect level $\leq$ 3 as per Table 1
3 mm thick slab with twill-woven aramid fibre reinforcement	1 J
3 mm thick slab with taffeta-woven carbon fibre reinforcement	1.5 J
5 mm thick slab with taffeta-woven natural linen fibre reinforcement	2 J
5 mm thick slab with taffeta-woven natural jute fibre reinforcement	1 J
6 mm thick slab with twill-woven carbon fibre reinforcement	3.5 J
6 mm thick slab with taffeta-woven glass fibre reinforcement (standard industrial reinforcement)	3 J
6 mm thick slab with taffeta-woven natural linen fibre reinforcement	2 J
6 mm thick slab with no reinforcement	3 J

Deformable base

System	Impact energy producing defect level $\leq$ 3 as per Table 1
6 mm thick slab with twill-woven carbon fibre reinforcement	3 J
6 mm thick slab with taffeta-woven glass fibre reinforcement (standard industrial reinforcement)	2.5 J
6 mm thick slab with no reinforcement	0.5 J

Interpretation of results

In the case of impact performance, considering a ceramic system comprising the ceramic slab, the reinforcement, and the base or background on which it rests, all the variables are significant. Therefore, whether or not slab behaviour is adequate will depend on how the different variables are combined.

On a rigid base, the 6 mm slab with no reinforcement or with standard industrial reinforcement complies with specifications. High-performance mesh reinforcement improves slab performance, while natural mesh reinforcement compromises performance. Slab thicknesses of less than 6 mm should be assessed as a function of intended use and type of reinforcement.

On a deformable base, only ceramic slabs with high-performance mesh reinforcement are able to meet the requirements.

3.3 STUDY OF REINFORCEMENT SYSTEMS VERSUS DYNAMIC ROLLING LOADS

The test used is based on the method described in Annex 5 of Cahier 3778 v.5 bis of the Centre Scientifique et Technique du Bâtiment "*Détermination de la résistance au roulage lourd des carreaux céramiques non émaillés*", in which a series of characteristics were modified.

The test was carried out continuously, but instead of using 4 test specimens of 200x200 mm, this time 2 test specimens of 400x200 mm were used. The joint was filled with an epoxy adhesive to a width of 3 mm. The criterion for acceptance of the result was that **there should be no fissure or damage greater than 1 mm**.

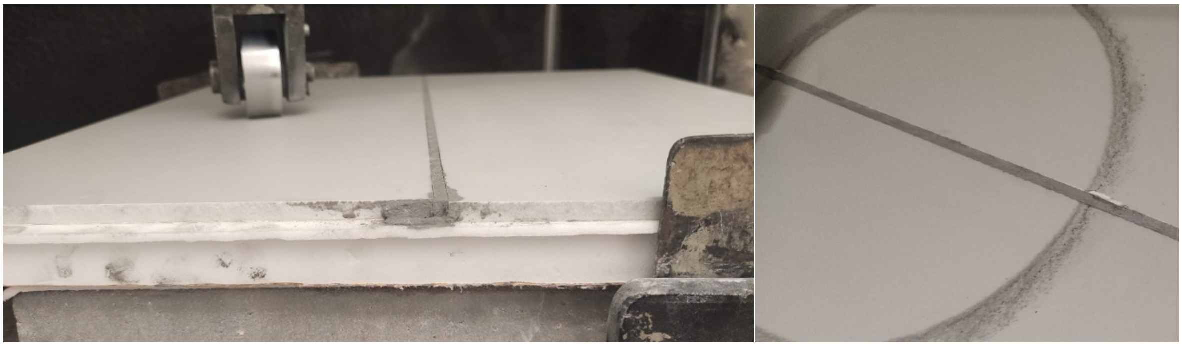


Figure 6: *Left: Detail of the test setup. Right: Example of non-compliance with acceptance criteria*

The results obtained indicate that the ceramic slab performs adequately on a rigid base, even at thicknesses of just 3 mm. On a deformable base, however, higher slab thicknesses are required to pass the test. Reinforcement systems using high-performance meshes or industrial mesh improve performance, while natural fibre mesh does not provide any improvement.

4. CONCLUSIONS

- A methodology has been defined for assessing the contribution of mesh reinforcement on ceramic slabs with regard to slab use as flooring with pedestrian traffic and in the presence of light or medium loads.
- A ceramic slab may be suitable for the use studied depending on its thickness, type of reinforcement, and the base or background on which it is adhered. Taking thicknesses of 3 mm and 6 mm as a reference, *Table 2* defines recommendations for use based on the results of this study.

Slab	Type of reinforcement	Rigid supporting base			Deformable supporting base		
		Private use	Public use, light loads	Public use, medium loads	Private use	Public use, light loads	Public use, medium loads
3 mm	No reinforcement / With any type	✗	✗	✗	✗	✗	✗
6 mm	No reinforcement	✓	✓	=	✗	✗	✗
6 mm	Natural material meshes	=	✗	✗	✗	✗	✗
6 mm	(Standard) glass fibre mesh	✓	✓	✓	✗	✗	✗
6 mm	High-performance synthetic material mesh	✓	✓	✓	✓	✓	=

Table 2: *Criteria for using ceramic slabs for flooring subject to pedestrian traffic.*

Key:

✓ Low risk of pathologies associated with the mechanical behaviour of the ceramic slab.

= Risk of pathologies associated with the mechanical behaviour of the ceramic slab.

✗ High risk of pathologies associated with the mechanical behaviour of the ceramic slab

5. ACKNOWLEDGEMENTS

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6. PREVIOUS STUDIES

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[3] *MULTI-CERAM "Aplicaciones de sistemas cerámicos multicapa en pavimentos". Starting date: 01/02/2018. Funded by the Valencian Institute for Business Competitiveness (IVACE). Co-funded by the European Regional Development Fund (ERDF).*

[4] *PAVLAM "Optimización de sistemas de pavimentación con baldosas cerámicas de espesor reducido". Starting date: 01/08/2020. Funded by the Valencian Institute for Business Competitiveness (IVACE). Co-funded by the European Regional Development Fund (ERDF).*

[5] *THINKER, "Nuevas aplicaciones con baldosas cerámicas de espesor reducido". Starting date: 01/04/2020. Funded by the Valencian Institute for Business Competitiveness (IVACE) (Autonomous Government of Valencia (GVA)) in the public call for funding for technology centres in the Valencia Region within the framework of the Nominative Line GVA 2020 programme.*