SAHC

ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

Luisa Natalia Peña Leal

Flexural Tests of Consolidation Effects on Stone

Czech Technical University in Prague

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DECLARATION

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Supervisor(s): Prof. Ing. DrSc. Miloš Drdácký

Year: 2016-2017

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

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Date: 6th July 2017

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ABSTRACT

The materials present their own mechanical properties and it is unusual to find two different materials with the same properties or the perfect natural material. Despite the good mechanical behavior of some materials used on buildings, the degradation and the properties loss are inevitable phenomena due to the time, the climatic cycles and the exposition to aggressive environments or even the common pollution levels.

The use of consolidants becomes a common technique in order to strengthening the stone. Because it is necessary to give the lost cementing during the time and to provide the join between the grains and to partially fill the pores which had become bigger.

This reseacrh studies the effects on the flexural behavior of the local sandstone from “Hořice” after the treatment with consolidants available in the Czech market. Bending tests were carried out to determine the effects on two different types of specimens with two types of test: uniaxial bending test and biaxial bending test. Cylinders and cubes were treated with the products in order to determine the depth penetration which the consolidants are able to reach inside the stone. After maturing, the cylinders and cubes were cut and tested after being tested with ultrasonic test to determine the difference of the wave velocity across the specimen along the depth profile of the element. The bending results of the plates extracted from the cubes and cylinders were compared with the ultrasonic test results and they are also presented in this document.

The flexural behavior is generally studied by unidirectional bending tests: three points bending test and four points bending test. Contrary, the biaxial bending test does not have the same popularity despite the facility to extract the specimen from a cylindrical core and the importance of the parameter of the biaxial strength, because this type of behavior is e.g. common in the stone plate structural elements [1]. The bidirectional bending test is done on a circular sample where the load is applied in the span middle and the bending is generated in all directions.

Concerning the flexural behavior of the sandstone after the treatment, in general they have good effects. However, it is important to evaluate other type of effects not related with the mechanical behavior, i.e. the visual consequences on the stone [2]. Further, the implementation of non destructive tests, i.e. the ultrasonic test, has generated well results to be used in the field.

Key words: Flexural strength of sandstone, three point bending test, biaxial bending test, consolidant, ultrasonic test.

ABSTRAKT

Každý materiál představuje soubor specifických mechanických vlastností a bylo by neobvyklé najít dva různé materiály se shodnými vlastnostmi nebo dokonalý přírodní materiál. Navzdory dobrým vlastnostem některých stavebních materiálů je, vzhledem k času, klimatickým cyklům, expozici agresivnímu vnějšímu prostředí a běžnému znečištění, degradace a ztráta různých vlastností nevyhnutelným jevem.

Použití konsolidačních prostředků je běžnou technikou pro zpevnění kamene. Ve většině případů je nutné nahradit v průběhu času vymytý tmel, zajistit opětovné spojení zrn a částečně zaplnit nově zvětšené póry.

Tato práce studuje vliv konsolidačních produktů dostupných na českém trhu na ohybové chování hořického pískovce. Byly provedeny dvě různé ohybové zkoušky (jednoosé a dvouosé namáhání) na dvou různých typech vzorků. Nejdříve byly válce a krychle ošetřeny za účelem zjištění hloubky penetrace, které je produkt schopen dosáhnout uvnitř kamene. Po vyzrání byl na válcích i krychlích proveden ultrazvukový test ke stanovení rozdílu rychlosti šíření vln v různé hloubce pod ošetřeným povrchem. Pak byly vzorky rozřezány a jednotlivé plátky otestovány v ohybu. Srovnání výsledků těchto zkoušek je v práci uvedeno.

Chování materiálu v ohybu se zpravidla stanovuje pomocí jednoosé ohybové zkoušky: ve tříbodovém nebo čtyřbodovém uspořádání. Naopak dvouosá ohybová zkouška není často využívaná navzdory možnosti získat z válcového jádrového vývrtu snadno vzorky a určit důležitý parametr biaxiální pevnosti, tento typ chování je běžný např. v kamenných deskových konstrukčních prvcích [1]. Dvousměrný ohybový test se provádí na vzorku kruhového tvaru, kdy zatížen je střed a ohyb probíhá ve všech radiálních směrech.

Obecně mají konsolidační ošetření na ohybové chování pískovce kladný vliv, avšak je důležité zvážit i další atributy, které nesouvisí s mechanickými vlastnostmi např. vizuální hodnocení kamene [2]. Také provedení nedestruktivních zkoušek (např. ultrazvukový test) poskytlo dobré výsledky pro použití in situ.

Klíčová slova: Ohybová pevnost pískovce, tříbodová ohybová zkouška, dvouosá ohybová zkouška, konsolidace, zkoušení ultrazvukem

RESUMEN

Las propiedades mecánicas de los materiales naturales son diversas en cada material, es bien sabido que no existe el material perfecto. A pesar que algunos tienen buen comportamiento en la mayoría de los aspectos relevantes para la construcción, al pasar el tiempo y la exposición de éstos a ambientes agresivos, diferentes ciclos climáticos, o incluso a niveles normales de contaminación, la degradación es inevitable y la pérdida de propiedades al pasar los años es un problema común que actualmente debe afrontar la restauración.

El uso de consolidantes que aporten más resistencia a la piedra se ha convertido en algunos lugares del mundo una técnica común, puesto que se hace necesario el uso de productos que otorguen el cementante que se ha perdido durante el paso de los años, que generen la unión de los granos y llenen parcialmente los poros que han aumentado su tamaño y actualmente se encuentran vacios.

Este trabajo se centra en el estudio de las consecuencias sobre el comportamiento a flexión de la piedra arenisca local de “Hořice” tras el uso de tres productos consolidantes disponibles en el mercado de República Checa. Se realizaron ensayos a flexión para determinar dichos efectos bajo dos tipos de muestras y en dos tipos de ensayos: unidireccional y bidireccional. Adicional, en búsqueda de determinar la profundidad que el consolidante es capaz de alcanzar dentro de la piedra, se trataron volúmenes con dos tipos de aplicación del producto, que luego fueron cortados y ensayados a flexión. Éstos resultados comparados con ensayos de ultrasonido son también presentados en este informe.

El comportamiento mecánico a flexión de un material se analiza generalmente por medio de los ensayos unidireccionales de tres o cuatro puntos a flexión. Por el contrario, el ensayo bidireccional, que consta de una probeta circular donde la carga se aplica al medio y se genera flexión en todos los sentidos del espécimen, no posee el mismo reconocimiento que los ensayos unidireccionales a pesar de la facilidad de extraer las probetas de núcleos circulares. Además, el análisis bidireccional es importante porque los elementos estructurales planos presentan éste comportamiento [1].

Refiriéndose al comportamiento mecánico a flexión los productos estudiados sobre la arenisca local tienen en general buenos efectos, sin embargo, es importante evaluar otro tipo de situaciones no mecánicas, por ejemplo efectos visuales sobre el material tratado [2]. Por otra parte, el uso de ensayos no destructivos (i.e. el ultrasonido) ha generado buenos resultados para ser utilizado en el trabajo de campo.

Palabras clave: Resistencia a flexión de la piedra arenizca, ensayo a flexión en tres puntos, ensayo a flexión biaxial (multidireccional), ensayo de ultrasonido.

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1. INTRODUCTION

The mechanical properties normally are related with the strength properties and they are generally evaluated to qualify a material [3]; it is used to evaluate the compressive, tensile and flexural strength. However the mechanical behavior is also related with other properties which should not be negligible to evaluate a material.

The flexural strength can be determined by different methodologies and all of them are standardized and studied:

- Four point bending test
- Three point bending test

Both of them are unidirectional test and with their own testing and calculus disadvantages. The three point test is probably the most known test in the field of bending and flexural strength. Contrary the bidirectional flexural test has been used, studied and analyzed but it does not have an important prestige.

The application of the bidirectional test in the field of the conservation and analysis of the stone is important, because it represents a property of the material and it should be studied and controlled as well as the other tests and properties. The multi-axial stress state, in this case the bidirectional behavior is present in an important quantity of structural elements [2].

Further, the deterioration process of the natural materials, especially the stone, is a normal process in the nature, additionally, other external factors adversely affect and the deterioration of the material is unavoidable [3].

In order to recover the mechanical properties of the materials, some chemical treatments have been used along the time, some of them with success, others with success in others fields or even useful for other type of deterioration. This research has as main purpose to compare the influences of the use of three different consolidants on the flexural behavior of a natural stone: sandstone from “Hořice”.

Studying the consequences of the use of three available products in the market in Czech Republic, in order to determine their efficacy concerning the flexural properties and studding the penetration depth reached whit two application techniques. The results of the bending strength in the unidirectional test on rectangular plates (three points test) will be compared with those of the bidirectional test on circular plates to determine the differences between the methods and between the different treatment products. The arrangement used by Wittman and Prim [4] was implemented for the bidirectional flexural test. Finally, a finite element method model (FEM) of the bidirectional test was done to compare the results from the experimental phase with the numerical results.

The non destructive tests (NDT) have taken importance along the last decades because they provide important information about the actual state of the structure with well accuracy. It does not mean the non-destructive test will replace the use of the destructive test. In this research the ultrasonic test results are compared with results from bending strength test, in order to verify the penetration depth of the consolidant products.

The research started with the documentation process about the test and materials used, followed by planning of the samples and the tests. The respective sample preparation and treatment before carry out the bending tests and ultrasonic test. The final part is the redaction of the document and the analysis of results from the tests and from the FEM model, which is a full chapter in this document.

1.1 RESEARCH MOTIVATIONS

For an important quantity of decades the three and four point tests has been used for estimate the flexural strength, even they represent an indirect tensile strength measure. However both test have disadvantages, the first is related with the shape of the samples, they have to be rectangular but the drills extracts cylindrical cores from the original stone or from the structures. During the cutting process of the material to get a rectangular sample an important amount of material is loss and the force work necessary to this operation is important.

The second disadvantage of these tests is associated with the test, the four point test is made on rectangular plates with two loading points and it ensures the crack will start between the superior two load points but is not possible to know its precise location. This is the consequence of the constant values in the bending moment diagram between these two points. While the three points test, in a homogeneous material, the crack starts exactly below the load application point in the span middle. But the high stress concentration in the load application point is the undesirable part of this method[4].

Contrary, the bidirectional flexural test is composed on a circular specimen and the loading is made in the middle of the sample describing a bidirectional state of stresses on the body. The bending test was used by Wittman and Prim[4] to evaluate the behavior in circular samples, the shape is because they were cut from cores extracted from the stone interior where it is not altered. Glandus [5] worked with ceramic materials to describe different compositions of the biaxial flexure test and analyzed the consequences of each composition studied; as well as Shetty et al.[6]. In the concrete field Kim et al.[1] worked improving the bidirectional test to their necessities in the concrete analyzes. The present document study the use of this test on stone in order to provide a method to characterize the bidirectional flexural behavior in stone.

This research was developed to compare the results of the unidirectional (three point bending test) and bidirectional flexural test in samples extracted from the same stone and treated with the same materials in the same conditions.

Further, from the antiquity the humans have used the available materials in their zones to build. The most important amount of material existing is the natural materials as the stone. Different type of stones and qualities are accessible in the nature around the world, is known the granite could be one of the best options regarding quality and price. However other stones, like limestone or sandstone don't have the same mechanical properties.

When the available stone is a material less resistant, made from the joint of older grains, sometimes without enough cementing to assure the integrity of the stone for long time, is necessary to find solutions in order to preserve the heritage built with this material. Actually the offer of stone consolidants is well developed. Different chemical principles and products have been used and studied with the same objective: give better properties to the stone referring material losses (e.g. disaggregation, sanding, etc).

Although the good performance of a consolidant or a chemical product developed to preserve the integrity of a building material is relevant also to study the visual consequences of the use of this product on the material [2]. Not only the mechanical success has to be evaluated but the visual aspect as well has to be appraised. For that reason, during this research the maturing time was also an observation time to determine the parallel consequences of the products.

1.2 OBJETIVE AND FOCUS

The main objective of this work is to characterize the performance of three different types of consolidants (Porosyl, KSE 300 and KSE 510) concerning the flexural behavior of a sandstone using unidirectional and bidirectional bending tests.

Parallel and consecutive secondary activities are necessary to achieve the main objective. The most important phases are:

- The documentation phase, it is important because it gives the theoretical bases to understand the physical and chemical phenomena present in the research.
- The experimental work, the planning and preparation of the tests and specimens have important rolls; the samples should be prepared and treated with strict specifications to follow the procedure of the tests.
- The testing process is one of the most rigorous part and demanding; three different tests are necessary to this work: unidirectional bending test, bidirectional bending tests and ultrasonic test. After obtain the results, they should be computed and analyzed to determine the mechanical characteristics of the material studied.
- The conception of a finite element model for the bidirectional bending test, it is built to compare the experimental results with numerical results.
- Finally, the discussion of the results obtained and the redaction of the final document.

1.3 OUTLINE OF THE THESIS

This document is the result of four months of work developing the research. Which is divided in eight chapters. The Chapter 1 Introduction, contains the introduction of the document, the research motivations and the objectives. The second chapter is the literature review of the products and of the tests used during this research. The Chapter 3 Methodology explains the procedure followed developing this research, the materials used, the general characteristics of the samples and the tests carried out. The results, analysis and discussion are presented in the Chapter 4 Results and Discussion. The Chapter 5 Conclusions and Solution of the Problem resumes the solution founded, explains the conclusions based on the previous chapter and provides recommendation for future researches following the same line of study. The references are listed in the Chapter 6. References.

Finally the two last chapters resume the results from the totality of the test realized during this research, Chapter 7 Annex A - Properties of Specimens contains tables with the information of the specimens, geometrical information and results of flexural strength and Young modulus. Chapter 8 – Annex B – Graphics Strength vs Deformation of the bending tests (unidirectional and bidirectional bending tests) realized during this research.

2. LITERATURE REVIEW

2.1 CONSOLIDANTS

The general and more common pathologies observed on the stone surface are: material loss, increased roughness and the porosity change [2] [consolidants]. All of them allow the entrance of harmful agents to the core of the material, in such a way, the deterioration process of the stone is guaranteed. It does not mean the solution is to close the entrance of agents. The normal transpiration and interchange of substances between the material and the atmosphere should be never forgotten. Especially when the material handed is a natural material like the stone.

The stone consolidants in general have as premise “to join the grains and to fill the internal pores” but not all of them are useful if the pores are completely filled. The real success of a product is related to the improvement of the mechanical and physical characteristics of the material treated when necessary, but also it is required to keep the aspects which are not affected by the weathering [7].

Some investigations had been carried out to determine the effectiveness of the application methods in parallel with the use of different materials. Normally the capillary absorption is the most used but others like the use of little pockets glued to the vertical surface [8], systems to maintain a steady supply [9], a vacuum system, a low pressure application technique to maximize capillary absorption had been also tested [10]. However, the common techniques used in practice are still the spray, brush, immersion and pipette[6] [10].

Different type of materials and components are available in the market, but there is not a strict procedure or general treatment to consolidate. It is always necessary to evaluate options and to check the consequences of the treatment [2] , especially when it will be used on cultural heritage, because the reversibility in this case is not possible. Effectiveness on the mechanical performance reached after the application of the consolidant should be good but also the consequences on the monument should not be appreciable from the exterior.

The products to use should have some special requirements in order to be possible to process consolidation. First, the product has to penetrate the stone, this is possible if the viscosity and the contact angle are sufficiently low to reach the internal pores of the stone [7]. After the product is inside it is necessary it becomes fixed in order to start the glued of the particles, the use of solvents or use a low viscosity system are the bests options [9]. The problems with the solvent appear when it moves, the fact the solvent enters very deep does not mean the principal product is also entering and when the solvent starts to evaporate the active product could also move inside the pores or even gets out with the solvent.

Different active products generate different type of consolidants, the most studied products are:

2.1.1 Inorganic consolidants

The *calcium hydroxide* inside the pores of the stone reacts with the carbon dioxide present in the atmosphere; the result is the calcium carbonate, which bonds the particles detached inside the structure of the stone [2].

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The theory affirms the chemical compatibility between the calcareous stone and the calcium carbonate is very high but the method does not work normally as well as it should [2]. According to the formula, the calcium carbonate produced by the carbonation has high compatibility with the lime stone or lime renders; however other physical effects are also related, for example the grain size and the crystal-aggregate texture, which do not allow the effectiveness of the method expected.

Another cause is related with the quantity of CO_2 presents in the inner zones. Carbon dioxide is necessary for the reaction, and when the consolidant enters inside the stone, the CO_2 is not as available as in the surface [11].

Additionally, if the material has been found in the first millimeters of depth, it means the principle of penetration is not well satisfied; however the presence of lime in the surface ensures the killing of organisms and bacteria which are the source of biological decay [9].

The *barium hydroxide* is similar to the calcium hydroxide, they react in a similar way, but the barium hydroxide is insoluble in water and the reaction is able to stabilizes sulphates and reduce the probability of salt crystallization, which is an important advantage. Nevertheless, it tries to create a crust in the surface of the stone, which results in danger to the material [10].

2.1.2 Acrylic polymers

The idea of the method is, after the evaporation of the solvent (organic solvent or water), the acrylic particles are able to create long chins filling the pores of the stone in order to create a continuing material [2] [10]. The acrylic resins need an organic solvent (e.g. acetone) and the emulsions are solved in water.

It has been used from the 1960s decade and in general the results are good. Due to the joint of small molecules the polymer can be formed inside the material, afterwards the use of an organic solvent is necessary to ensure the penetration of the molecules. A volatile solvent (as the acetone) generates a good penetration but also, a rapid evaporation assuring the location of the molecules near to the surface, which is not desirable. Contrariwise, a less volatile organic solvent ensures the penetration and the staying of the polymers inside the stone [10].

However, the polymers resins tend to be hydrophobic, and are recommended to inner treatments because the presence of water and moisture do not have a good consequence on the product. Conversely, the polymers emulsions work well in ambient moisture and exterior zones [10].

2.1.3 Silane- based materials

It is a famous technique that has given good results along the last decades. The product is solved in an alcohol to reach the desirable workability, and after being absorbed by the stone inside the pores and unfilled spaces, the process of polymerization starts with the hydrolysis and condensation reactions [7]. The result is the formation and deposition of the amorphous and hydrous silicon dioxide (silica gel).

After the consolidation process the pores are not completely filled because when the solvent product enters the spaces it gets a part of the space, but disappears during the evaporation process [10]. Even if the spaces finally are not completely filled the method provides good consolidation to the particles [2]. The product normally works in materials with a medium level of degradation. It means, it is not useful when the idea is to join lost elements or big gaps [10].

However, some disadvantages have to be considered in the decision to use it. It is not possible to break-down the chains formed after the treatment with any type of solvents, and then it is not reversible. Additionally, concerning the formulations with water used on stones with high contents of clay or presence of salts, it is important to control strictly the situation because the water could hydrate and get problems of swelling [10].

2.2 THE BENDING TEST AS MECHANICAL CHARACTERISTIC OF THE STONE

The stone is a natural material present around the world. It is the reason why people always have taken the stone to build, because it is available in big quantities. Additionally it looks enough strong to be the material to protect the mankind against the external attacks (natural or anthropogenic).

The characteristics more used to describe the quality of a stone are normally classified in physical, chemical and mechanical properties, which represent an important quantity of characteristics values. The mechanical properties are specifically related to the response of the material in the face of external forces that affect directly the material [3]. For example, the compressive, tensile and flexural strengths are related with an external load affecting the material; even the hardness and abrasion resistance describe the external attacks response.

This study is oriented to the way of the flexural capacity and the consequences of it after the use of a consolidant material available in the market. The bending strength describes the behavior of the material under a moment load located at a strategic point, in order to generate in a cross-section one compressive zone and other zone in tension. This is the reason why the bending is also related with an indirect tension measure.

Two types of test are normally applied for the evaluation of the bending strength: i.e. unidirectional and bidirectional bending tests.

2.2.1 Unidirectional bending test

Unidirectional tests are represented by three point bending (one point for load and two points as supports) and four point bending test (two points for load and two points as supports). The main purpose of both tests is to apply the bending load on a rectangular specimen in the middle span by a transversal plate, while the specimen is supported on two transversal lines near to the edges (two points as support). The flexural strength of the sample is the highest stress registered on the outer surface of the specimen at the failure moment and is calculated as [12]:

$$\sigma = \frac{3\,P\,l}{2b\,(h^2)}$$

Where σ denotes bending strength; P ultimate load; l span length; b specimen width and h specimen height.

The principal difference between the 3 point and 4 point bending tests is the location where the tensile crack appears. In a four-point bending test the moment is applied by a device composed by two loaded contact points and the crack is expected anywhere between the two points of load application because the two points generate a constant zone in the moment diagram between them. On the other side, thinking of a homogeneous material, during the three point bending test the crack will appear at the mid-span because it is the most loaded point; additionally, due to the stress concentration the zone around the load application point will show localized deterioration [13]

Further, the Young module, is one of the most important parameters to describe the elastic behavior of the material and for the unidirectional bending test is calculated as [14]:

$$E = \frac{\Delta F\, l^3}{48\, I_y\, \Delta u}$$

Where ΔF is the value of the force; l is the span; I_y the inertial modulus in y and Δu the total displacement (deflection) at the span middle in the last point of elastic behavior.

2.2.2 Bidirectional bending test

The bidirectional test is performed on a circular sample applying the bending force in the center of the circle described by the specimen face, which should rest on a continuous support (ring) or punctual supports (balls) located near to the external limit of the sample. The load is applied on the upper face in an area (piston), a line (ring) or a point (ball). In this case of study a ring is used as support and a ring to apply the load, it creates a system conformed by a continuous support and a continuous loading line on the upper part of the sample.

Different configurations were studied by Glandus (1986) [5] He discovered that the configuration ring - ring gives better results than an important number of balls as support. He also affirms to get a good accuracy between the theoretical and the testing values the thickness of the sample should be near to

3.5mm [5]. The use of balls was also studied by Kim et al. (2013) [1] showing the case of three balls as support described in ASTM F394, with the particularity that the cracks of the failure shape always follow the position of the support balls due to the non uniform stress caused by the balls [1].

The maximum flexural strength in the bidirectional bending test is calculated as [4]:

$$\sigma = \frac{3\,F}{4\pi\,(h^2)} * \left\{2 * (1+\nu) * ln\left(\frac{a}{b}\right) + \frac{(1-\nu) * (a^2 - b^2)}{a^2} * \frac{a^2}{R^2}\right\}$$

Where F is the maximum force reached during the test; h is the thickness of the plate; ν is the material Poisson modulus; b is the ring load application radius; a is the support ring radius and R is the sample radius.

The Young modulus is calculated as [4]:

$$E = 1{,}5\,\frac{F}{f_0}\frac{1}{h^3} * (1-\nu^2) * \left\{b^2 * ln\left(\frac{b}{a}\right) + \frac{(a^2 - b^2)(3+\nu)}{2 * (1+\nu)}\right\}$$

Where F is the value of the force; f_0 is the total displacement at the span middle in the last point of elastic behavior; ν is the material Poisson modulus; h is the thickness of the plate; b is the ring load application radius and a is the support ring radius.

2.3 THE ULTRASONIC TEST

The object of the ultrasonic test is to determine the velocity of the wave emitted and make relations of this velocity with the porosity, the level of damage of the material, location of cracks or empty spaces inside the material that are not accessible to an auscultation process [3].

The test is composed by an emitter of a P (compression) or a S (transversal) wave, a receptor of the respective wave and the idea is to measure the time taken by the wave to arrive at the receptor and the respective length travel by the wave. The velocity is easy calculated as space over time.

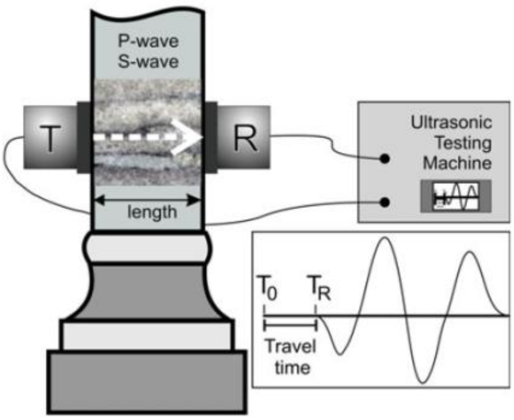


Figure 1 Ultrasonic test principle[3]

The general method used in the laboratory is known as pulse transmission, the functioning is to send an electrical pulse generating a deformation, which travels around the sample. And at the other side, a receiving transducer converts the mechanical signal into an electrical signal[3].

3. METHODOLOGY

3.1 RESEARCH STEPS

All phases of this research were developed in the laboratories of The Institute of Theoretical an Applied Mechanics in Prague with the support of the people mentioned. In order to reach the main propos of this research, different activities were necessary to carry out:

1. Documentation about the tests, consolidant products and stone treated.
2. Sample extraction from the natural stone.

   The extraction was made in two different directions in order to take into account in this study the geological layering. Cylindrical and prismatic shapes were extracted to fabricate circular plates, rectangular plates, cylinder and cubes.
3. Treatment of the different type of samples with the products.

   All the samples were treated with three different consolidant products. The circular and rectangular plates were impregnated by soaking; the cubes and cylinders were treated with two techniques: soaking and brushing. Finally, a wall made on the same stone and lime mortar was also treated with the same products by brushing.
4. Testing.
   a. Measurement of the samples.
   b. Flexural test (unidirectional and bidirectional test) on circular and rectangular plates.
   c. Determine the depth of penetration of the consolidant.
   d. Ultrasonic test on the cubes and cylinders treated.
   e. Flexural test on plates extracted from the cubes and cylinders treated.
   f. Ultrasonic test on the wall treated with different products.
   g. Process of the data obtained during the testing phase.
5. Construction of a finite elements model simulating the bidirectional test.
6. Analysis, discussion and redaction of the report.

3.2 DESCRIPTION OF MATERIALS

3.2.1 Stone

The material tested in this research was the “Hořice” sandstone. Previous studies have evaluated the basic mechanical properties of the material described in Table 1.

	Hořice sandstone	
Flexural strength	3,06	MPa
Compressive strength	23,59	MPa
Peeling test	6,22	x 1000 gr

Table 1 Hořice sandstone properties [14]

3.2.2 Consolidants

In order to define and compare the effect of different consolidants, three different substances available in the commercial field were tested:

Product A: Porosil Z – AQUA Bárta:

Consolidant designed to increase the strength of the porous materials; according with the producer, the active principle is to transform the liquid in a silica gel which will join the particles inside the pores of the stone. The composition is based in two parts: part A (active product) and part B (solvent), which should be mixed with the same proportion (1:1) [15].

Product B: Ethylsilicate based Steinfestiger KSE 300 – Remmers (Wacker)

Stone strengthener without solvent. It is recommended to use in medium pored materials like sandstone. According with its technical sheet KSE 300 reacts with the water which is inside the pores, and an amorphous and hydrous silicon dioxide (silica gel) is deposited inside the cavities and this is the binder expected [16].

Product C: Ethylsilicate based Steinfestiger KSE 510 – Remmers (Wacker)

Consolidant which generate a binder as silica gel due to the deposition of a material made from the water present inside the pores and the product quantity absorbed [17]. The difference with the KSE 300 is the quantity of gel deposited (Table 2).

Table 2 provides general information of the products described:

	POROZIL Z	KSE 300	KSE 510	
Density at 20°C[16] [17] [15]	0,87	1	1,02	gr/cm^3
Color[17] [16] [15]	clear	clear	clear	
Amount of SiO_2 gel [18]	290	271	442	gr/lt

Table 2 Properties of consolidants

3.3 DESCRIPTION OF SAMPLES

The experiments aim at testing of differences in results of biaxial bending tests on thin discs (circular plates) and unidirectional bending tests on thin rectangular plates. In addition, the testing was used to study effects of different consolidation agents and different application modes on change of mechanical characteristics of one type of sandstone ("Hořice" sandstone). The agents were applied on laboratory specimens and a section of a real ashlars' masonry wall.

From a block of sandstone cylindrical cores of diameter of 55 mm and length approximately 40 mm and cubes of dimensions 50x50x50 mm^3 were extracted. Then thin circular discs of thickness of 4 mm and rectangular plates 20x50x4 mm^3 were cut. The cores and prisms were cut in two directions perpendicular each other in order to have specimens with different spatial arrangement of geological (bedding) layers – direction 1 across the layers and direction 2 along the layering (Figure 2).

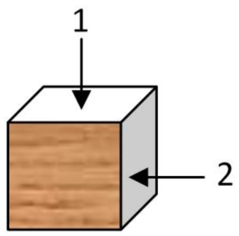


Figure 2 Extraction direction of the samples

Each type of sample has its own purpose: the circular plates were used in flexural testing in two directions; the rectangular plates were used in flexural testing in one direction; the cubes and cylinders were treated with the three different consolidants and two different techniques (capillary absorption and brushing), with the aim to evaluate the depth of impregnation in each case by flexural testing and ultrasonic test; finally, the wall was impregnated by brushing with the three products and was submitted to ultrasonic tests. The samples were distributed as showed in Table 3.

Type of sample	Extraction Dir.	Quantity	Propose
Rectangular plates	1	6	Flexural testing
	1	18	Impregnation, flexural testing
	2	6	Flexural testing
	2	18	Impregnation, flexural testing
Circular plates	1	6	Flexural testing
	1	18	Impregnation, flexural testing
	2	6	Flexural testing
	2	18	Impregnation, flexural testing
Cubes	1	4	Impregnation, ultrasonic test, flexural testing
	2	4	Impregnation, ultrasonic test, flexural testing
Cylinders	1	4	Impregnation, ultrasonic test, flexural testing
	2	6	Impregnation, ultrasonic test, flexural testing

Table 3 Testing samples

3.3.1 Untreated specimens:

6 discs direction 1 and 6 discs direction 2 – (12 discs totally cut under water cooling), then dried naturally in a box with controlled relative humidity (RH) 55% before testing.

3.3.2 Treated specimens:

I Mode of application – capillary rise

6 discs direction 1 and 6 discs direction 2 for each consolidants – (36 discs totally cut under water cooling), dried naturally in a box with controlled relative humidity (RH) 55% and treated up to saturation by capillary rise.

6 cubes naturally dried in a box with controlled relative humidity (RH) 55% were treated up to saturation by capillary rise. After maturing the depth of penetration was measured using ultrasonic measurement with a step of 5 mm along the depth from the surface. Then the cubes were cut into plates of 4 mm thickness after maturing. Some 7 plates from each cube were expected.

6 cylindrical cores naturally dried in a box with controlled relative humidity (RH) 55% were treated up to saturation by capillary rise. After maturing the depth of penetration was measured using ultrasonic measurement with a step of 5 mm along the depth from the surface. Then the cylinders were cut into discs of 4 mm thickness after maturing. Some 6 discs from each cylinder were expected.

II Mode of application - brushing

2 cubes naturally dried in a box with controlled relative humidity (RH) 55% were treated up to saturation by brushing. After maturing the depth of penetration was measured using ultrasonic

measurement with a step of 5 mm along the depth from the surface. Then the cubes were cut into plates of 4 mm thickness after maturing. Some 7 plates from each cube were expected.

4 cylindrical cores naturally dried in a box with controlled relative humidity (RH) 55% were treated by brushing. After maturing the depth of penetration was measured using US measurement with a step of 5 mm along the depth from the surface. Then the cylinders were cut into discs of 4 mm thickness after maturing. Some 6 discs from each cylinder were expected.

3.3.3 Codification of samples

The codification used for the samples has the information necessary to recognize the samples: type of product, method of application, original core's extraction direction, type of sample and consecutive number. Table 4 explains an example.

PRODUCT	CONSOLIDANT	POROSIL Z	A	C
		KSE 300	B	
		KSE 500	C	
	UNTRATED SPECIMEN		U	
APPLICATION METHOD		Capillary rise	I	I
		Brushing	II	
DIRECTION OF EXTRACTION		Across	1	2
		Along	2	
TYPE OF SPECIMEN		Rectangular plates	RP	CP
		Circular plates	CP	
		Cubes	CUB	
		Cylinders	CYL	
CONSECUTIVE NUMBER			1…6	4
				CI2CP4

Table 4 Codification mode of samples

All the dimensions were measured in order to characterize geometrically the samples, the length and width of the rectangular plates were measured in two points and the thickness in four points, the central width and thickness was measured separately 3 times for the calculus of the bending strength. Each face of the cubes was measured four times; even those with some irregularities and the irregularities were taken into account for the volume calculus. In circular plates the height and diameter were measured 3 times and cylinders 3 diameters in each side (top and bottom). The plates extracted from the cubes and cylinders were measured after the cutting for the calculus of the strength.

Figure 3 Types of samples: circular and rectangular plates, cubes cylinders and ashlars wall

3.4 TREATMENT OF SAMPLES

For the process of application of the products two techniques were used: capillary absorption (method I) and brushing (method II). In order to compare the effectiveness of the techniques they were used on the same type of samples, applied at the same time and in the same conditions.

3.4.1 Capillary absorption (Method I)

Six circular plates, six rectangular plates, one cube and one cylinder of each direction of extraction of samples (1 and 2) were submerged in the solution of each consolidant. The depth of submersion of the plates (both types) was between 1 and 2 mm, it means they were not completely submerged in the solution; at least half of the thickness of the plate was not in contact with the product and the time of contact with the liquid was enough to fill completely the pores of the sample. The Figure 4 shows the process of impregnation of the plates seeing from the contrary face of contact.

Figure 4 Capillary absorption in rectangular plates

Due to the important height of the cubes and cylinders the depth of submersion was approximately 8mm and the time of submersion was variable for each sample; the time necessary to reach 15 and 20 mm of impregnation inside the sample and the change in the weight were measured in order to calculate the quantity of product absorbed in the area in contact. The contact with the product was stopped when any level of the rising inside the sample reached the 20mm. Figure 5 shows the impregnation process by capillary rise in one cube and one cylinder.

Figure 5 Cubes and cylinders in process of treatment with capillary rise

3.4.2 Brushing (Method II)

This technique was used in one cube and four cylinders using the same amount of consolidant absorbed during the process of capillary rise. The surface treated during the application and curing process was in vertical position, in order to simulate the situation of a wall. Also the wall of testing was impregnated with this technique keeping the amount of consolidant per mm^2 used in the capillary process. The Figure 6 shows one of the samples treated with this technique

Figure 6 Cylinder in process of treatment with brushing

The wall built with the same type of stone and lime mortar was treated with this method with similar amount of product per mm^2. The Table 5 shows the amounts of material used and the surfaces treated with the three different products.

Sample	Superficial Area	Weight of product used	Efficiency
	[mm2]	[gr]	[gr/mm2]
AI1CUB1	2475,049	4,06	0,00164
AI1CYL4	2275,119	5,49	0,00241
AI2CUB3	2520,464	6,44	0,00255
AI2CYL1	2307,359	4,31	0,00187
		average	**0,00212**
BI1CUB3	2468,824	7,65	0,00310
BI2CUB1	2678,314	7,37	0,00275
BI1CYL1	2283,017	6,72	0,00294
BI2CYL4	2233,323	6,85	0,00307
		average	**0,00297**
CI1CYL3	2283,440	6,81	0,00298
CI1CUB4	2483,262	7,44	0,00299
CI2CUB2	2525,619	7,50	0,00297
CI2CYL5	2269,487	6,58	0,00290
		average	**0,00296**

Table 5 Weight of product absorbed by the samples

With the efficiency resulted in Table 5 was calculated the quantity of product necessary to cover the areas by brushing and capillary absorption showed in Figure 7.

Figure 7 Wall treated with products A, B and C

3.5 DESCRIPTION OF TESTS

3.5.1 Unidirectional bending test – three points test

The three points bending test is composed of one line of load and two support lines (Figure 10). In this case, the span between the supports is 40mm and the load is applied at the middle of the span with a loading speed of 0,15mm/min. The loading device used was a WOLPERT load frame (Figure 8), a load cell LUKAS 100N (Figure 9) with a deformation sensor HMB LVDT 1µm located at the middle of the span.

Figure 8 load frame used

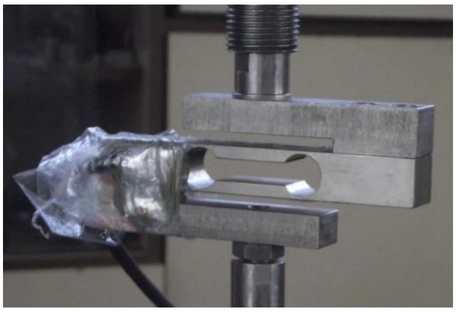
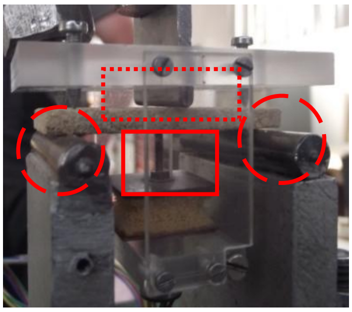


Figure 9 Load cell LUKAS 100N



LVDT

Load plate - load point

Support points – two supports

Figure 10 Three points bending test

Figure 11 General configuration three points bending test

3.5.2 Bidirectional bending test

The bidirectional flexural tests were applied to the circular plates. They were made using a configuration test with a ring support with diameter of 42,5mm and a line charged by a ring with diameter of 15m. The loading device used was a WOLPERT load frame (Figure 8), a load cell LUKAS 500N (Figure 12) with a deformation sensor SM3 SOLATRON LVDT 1µm located at the middle of the plates.

Figure 12 Load cell LUKAS 500N

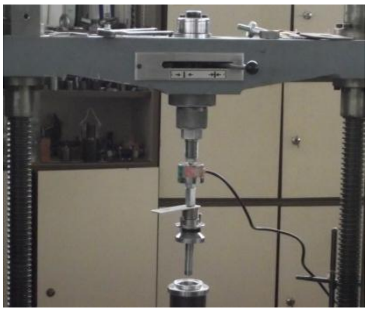
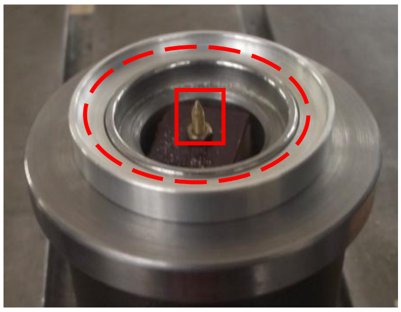
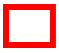


Figure 13 General configuration bidirectional bending test

Figure 14 Ring that applies the load




LVDT


Ring support

Figure 15 Support of bidirectional test

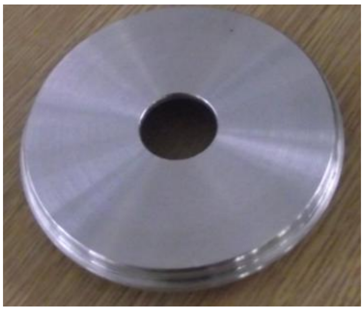


Figure 16 cover for the circular samples

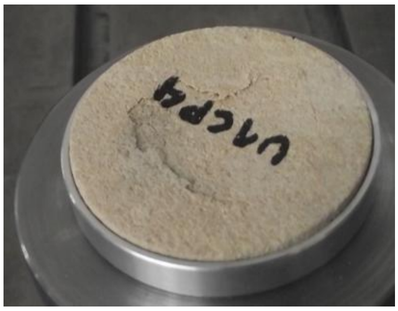


Figure 17 Circular plate in the support device

Figure 16 describes the loading device built to ensure the location of the ring load in the center of the specimen; it works like a cover which lets apply the load in the specific zone described by the hole. The bottom of the loading device is described in Figure 15. The general arrangement of the test is showed in Figure 18 a). The device located with the propos of do not let the movement of the sample and ensure the centering of the load is showed in Figure 18 b) (red line).

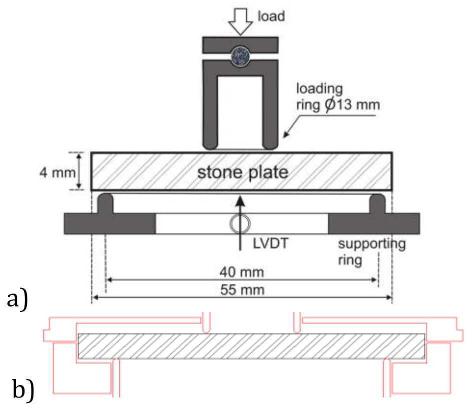


Figure 18 Bidirectional bending test arrangement

3.5.3 ULTRASONIC TEST ON CUBES, CYLINDERS AND WALL

The main purpose of the cubes and cylinders is to determine the depth penetration of the consolidants agents applied with two different techniques, following this, the ultrasonic test was carried out in order to make relations between the flexural test and the ultrasonic test.

In order to determine the variance inside a same sample, which could be related to a variance in the flexural strength in the same sample. Before starting the bending test stage of the cubes and cylinders, they were tested in different depths by ultrasonic test. The cubes were measured in 8 points, and the cylinders in 6 points, all of them distributed along the height of the element trying to do the measurements in the central points of the future plates cut from these specimens.

The ultrasonic device used is a UKS 12 produced by Geotron Elektronik. It is composed by a generator of electric signals (Figure 19), a couple of emitter and receptor (Figure 20) of the signal and a microsecond timer where is possible to see the reception of the emission and the starting point of reception.

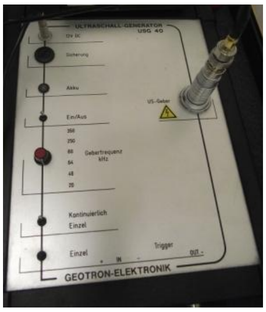


Figure 19 Signal generator

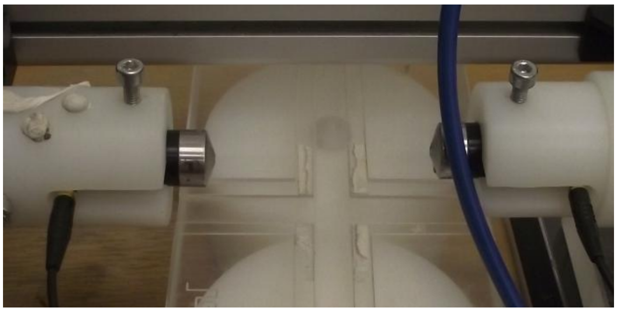


Figure 20 Couple of emitter and receptor

Figure 21 Microsecond timer

Figure 22 Screen of the microsecond timer

An extra device is used in the Laboratory to ensure the well contact between the surface analyzed and the emitter and receptor; it is a system of air pump which compresses one of the faces of the specimen to the receptor making sure the contact necessary to capture the signal.

Figure 23 Air pump in the ultrasonic test

Finally, the masonry wall done with the same stone and lime mortar was also tested in the zones where the products A, B and C were applied and also in an untreated zone to get a reference to compare the results. The main idea of this test was to determine the depth of penetration of the consolidants applied on the wall by brushing.

Figure 24 Disposition of the points to ultrasonic test

The device used for the ultrasonic test was the same, except the couple points of the emitter and receptor. Which is a device conformed by two cylinders movable in two directions. It allows changing the distance between the emitter and receptor and also is possible to be longer the couple and measure in different depths of the wall. To reach more depth points inside the wall was necessary to do holes on the wall to enable the test along the first 5cm inside the wall.

Figure 25 Ultrasonic test on the wall

Figure 26 Points of the device to reach different depths

4. RESULTS AND DISCUSSION

This chapter presents the data, results and graphics obtained during the testing process. All the graphics showed were made from the data extracted from the tests realized in The Institute of Theoretical an Applied Mechanics in Prague.

4.1 FLEXURAL TESTING

4.1.1 Rectangular plates

The flexural test for the rectangular plates was conformed as three point bending test based on the outline described in the chapter 3 Methodology.

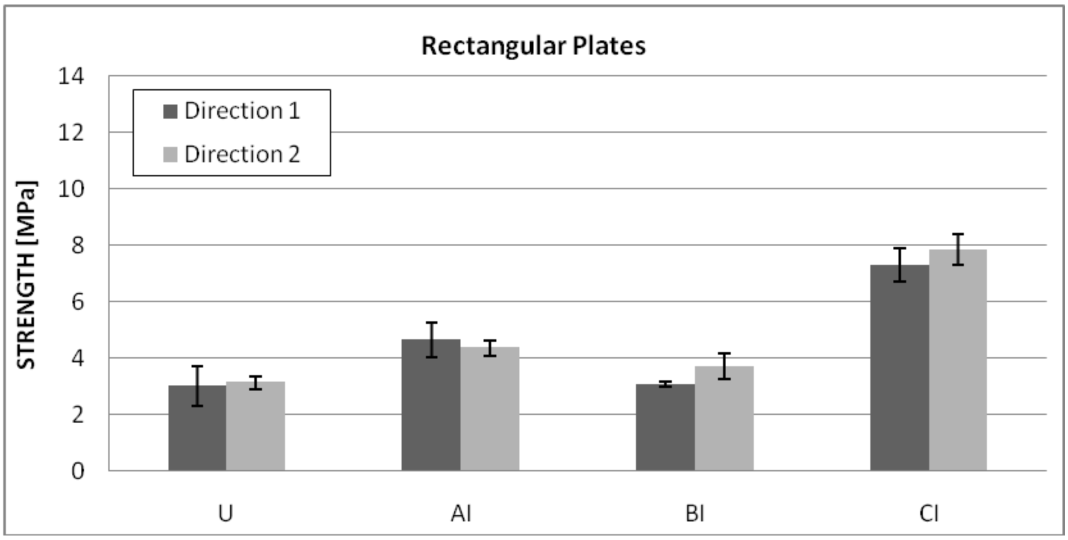


Figure 27 Flexural strength of the treated rectangular plates

The first type of sample tested was the rectangular plates untreated (U) and then the treated samples with the three different consolidants (AI, BI and CI). According to the Figure 27 the average of the flexural strength in the samples (untreated and treated) in direction of extraction 1 and 2 do not present important differences. Which means that the geological layering does not have important effects on the bending behavior of the stone.

As it was expected, the treatment with the consolidants generates an improvement of the mechanical properties of the stone. Figure 27 shows the significant improvement of the flexural strength using the Product C, the bending behavior increased 144% in direction of extraction 1 and 151% in direction of extraction 2. The case with the product A is not as advantageous as with Product C but it presents also a good behavior; the bending strength increased 55% in direction of extraction 1 and 39% in direction of extraction 2. The minimum improvement of the bending behavior with the use of the product B is because of the less precipitation of silica gel deposited in the pores, Table 2 in chapter 3

Methodology shows the less amount of silica gel for the product B. Which in direction of extraction 1 the flexural strength increased 2% and 18% in direction of extraction 2.

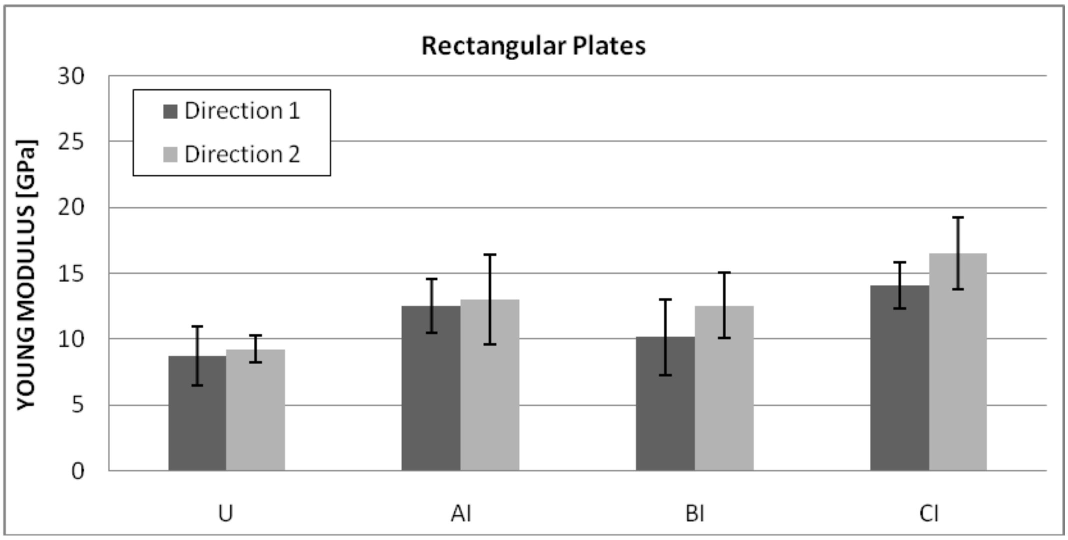


Figure 28 Young modulus of the treated rectangular plates

Concerning the Young modulus calculated from the bending test on the rectangular plates, the Figure 28 shows an increment between the untreated (U) samples with values around 8GPa to 15GPa in the product A. Additionally, the difference in the results between the samples extracted in direction 1 and direction 2 become important in products B and C. The average value for the direction of extraction 1 of the product B is near to the elasticity modulus of the maximum untreated sample. However, in all events the Young modulus shows an augmentation with the use of the consolidants.

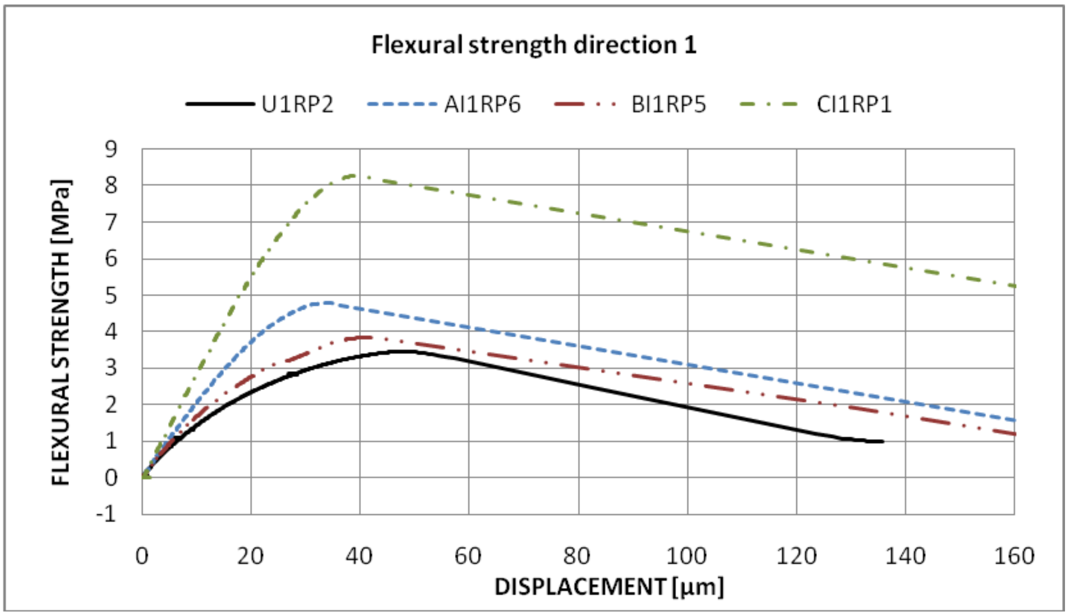


Figure 29 Example flexural strength in direction of extraction 1 in treated rectangular plates

The Figure 29 shows the curve strength vs displacement of four specific specimens tested (one sample for each type of product used). The purpose of this graph is to show the elastic behavior of the samples and compare the different products. It confirms the observation done in the last paragraph related with the similitude of the Young modulus between the untreated sample and the product B sample.

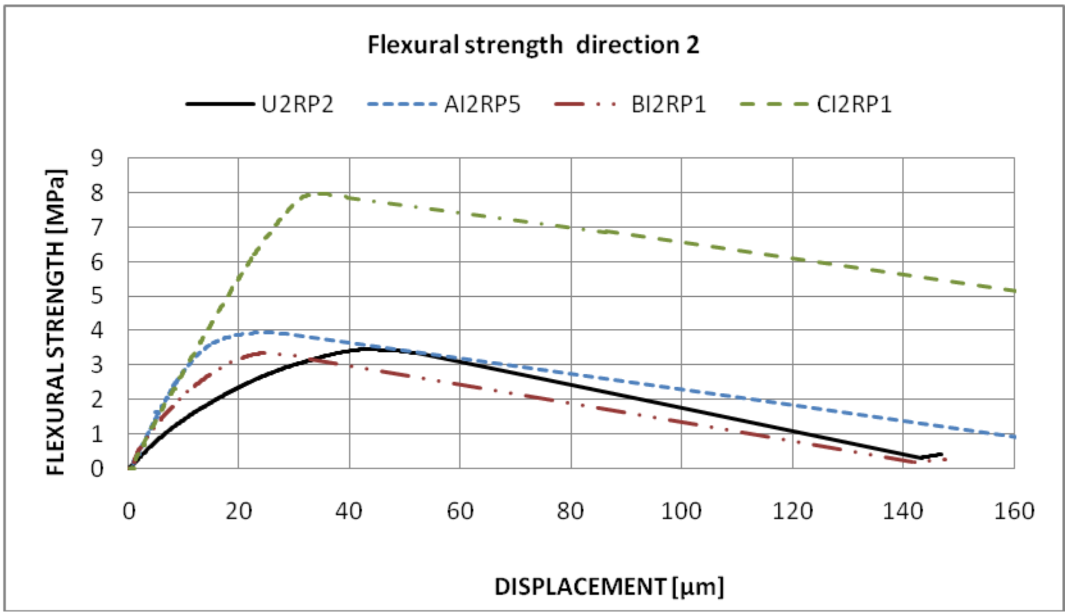


Figure 30 Example flexural strength direction of extraction 2 in treated rectangular plates

In the case of the direction of extraction 2 (Figure 30), the elastic behavior of the product B is more similar to the other consolidants, which in direction 2 present an elastic modulus near to the double of the untreated case. It is possible to observe in the last two graphs the expected behavior, when the strength is improved the fragility increase and the deformation at the failure decreases.

4.1.2 Circular plates

The flexural test for the circular plates was conformed as bidirectional bending test based on the outline described in the chapter 3 Methodology. The test was realized on the specimens 4 weeks after the impregnation of the consolidants.

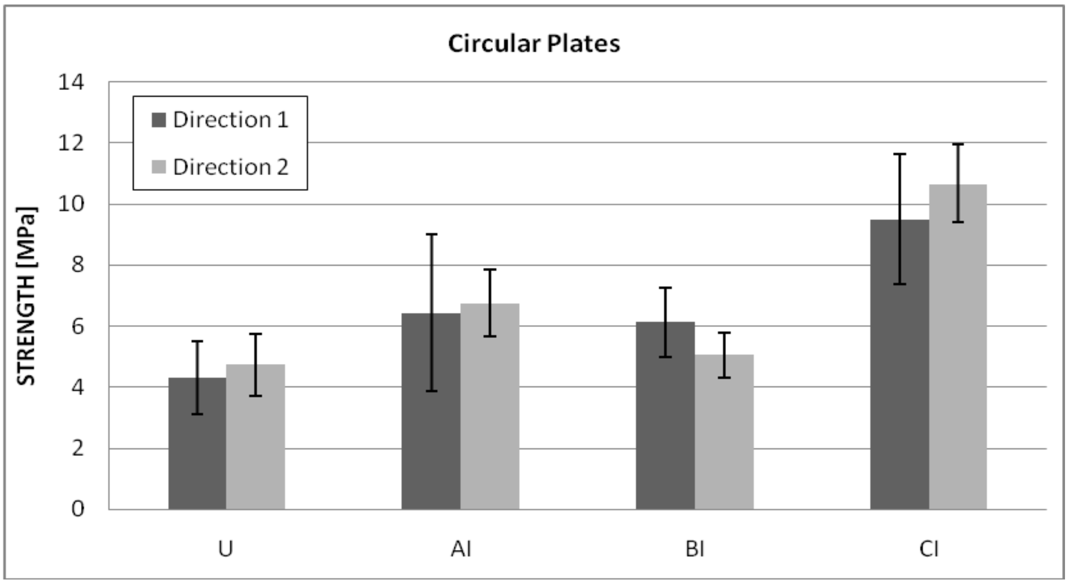


Figure 31 Flexural strength of the treated circular plates

Referring the bidirectional bending behavior of the products used (Figure 31), it is visible the improvement in the flexural strength, especially regarding the product C which shows an improvement of 120% in direction of extraction 1 and 159% in direction of extraction 2. The situation with the product A is not as well as with the product C, but is still good with an improvement of 49% in direction of extraction 1 and 64% in direction of extraction 2. The situation with the product B ameliorates in the bidirectional test, in direction of extraction 1 the improvement is 42% concerning the untreated samples and in direction of extraction 2 presents an improvement of 23%.

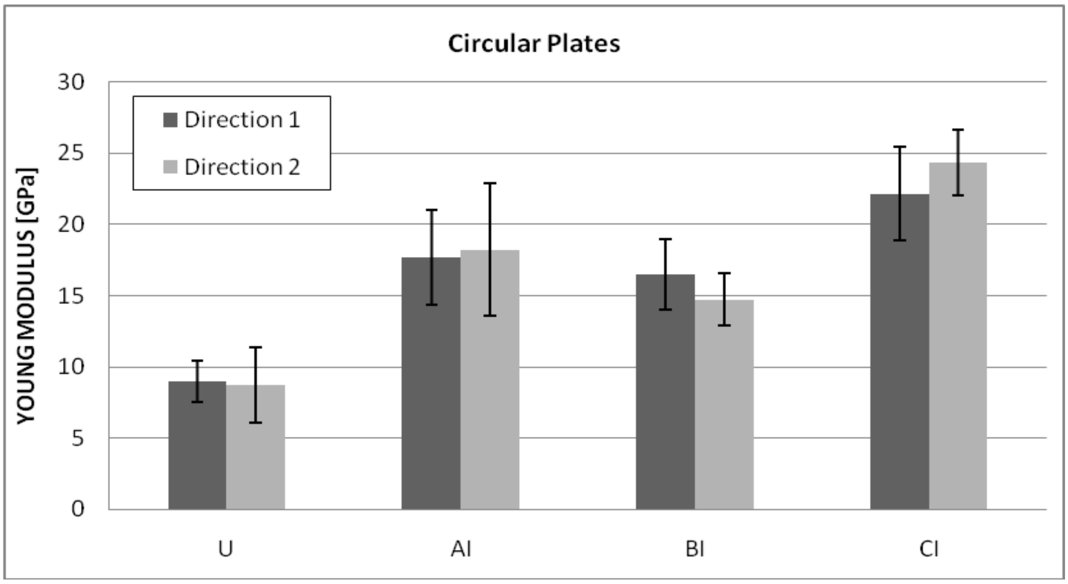


Figure 32 Young modulus of the treated circular plates

The Figure 32 shows the important increasing in the Young modulus when the consolidants are used. The product C presents a Young modulus 227% in direction of extraction 2 bigger than the untreated sample, and the case in direction 1 is similar with an augmentation of 183%. Again the less effective is the product B but is not close to the untreated case.

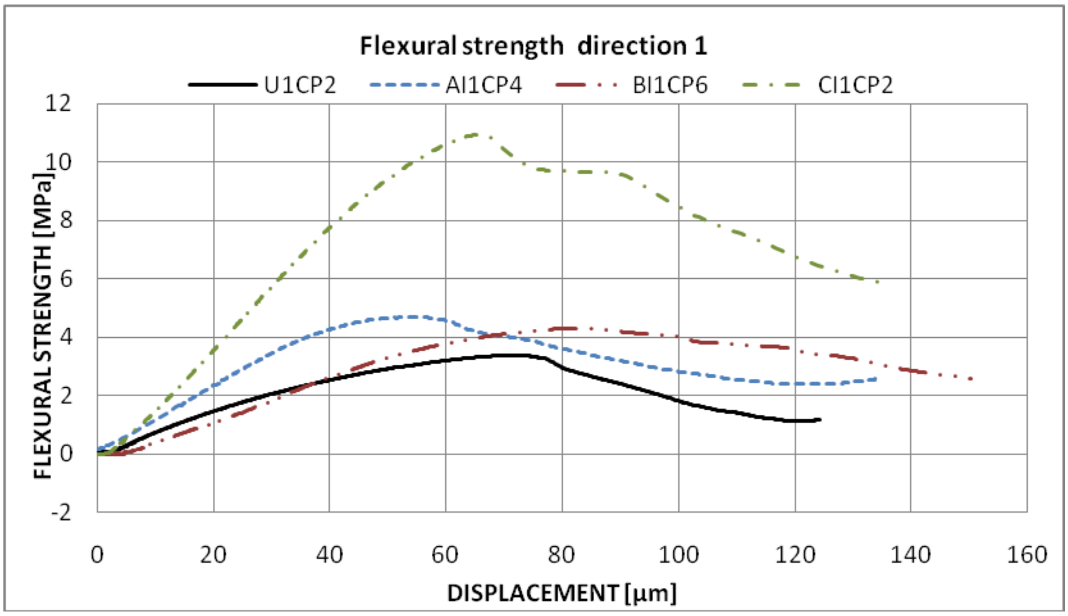


Figure 33 Example flexural strength direction of extraction 1 in treated circular plates

In Figure 33 is possible to observe the proximity of the Young modulus between the untreated sample and the Product B. Additionally, referring strength and elasticity of the specimen treated with the product C is remarkable its excellent behavior.

The performance of the curve strength vs deformation of the sample CI1CP2 with a flat zone after the maximum strength was observed in an important quantity of samples. Which could be attributed to the extra strength given by the zones that were not cracked in the maximum load point. Also it could be related with the configuration of the bidirectional test; the existence of an external centering ring (Figure 18 b)) could confine the sample after failure and could generate an extra deformation without an increase of the load.

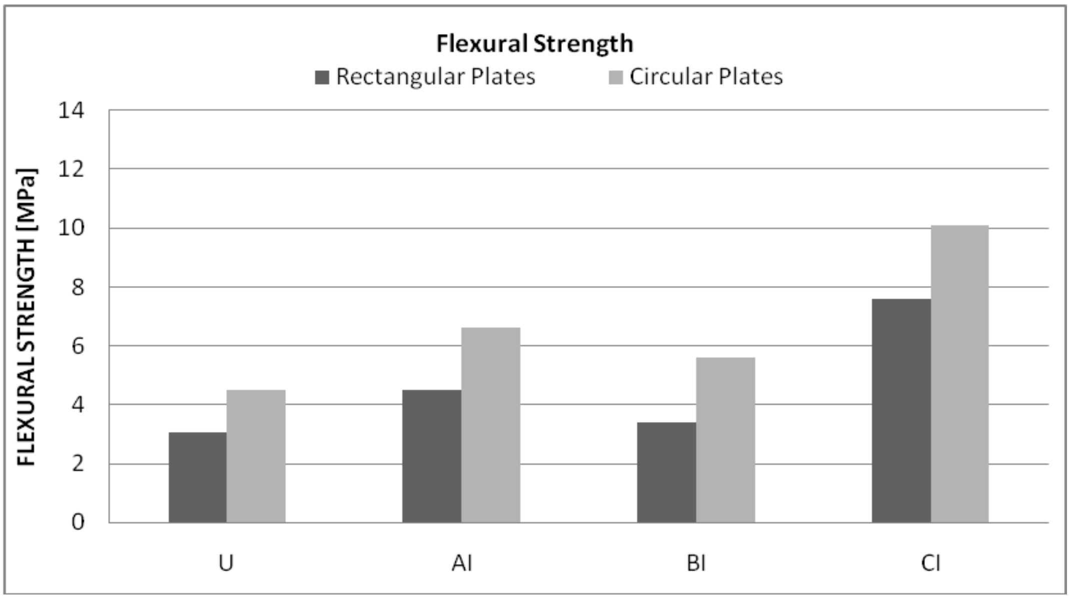


Figure 34 Unidirectional and bidirectional flexural strength results

The Figure 34 shows the difference between the two bending tests: unidirectional (rectangular plates) and bidirectional (circular plates) tests, the differences are logical because of the nature of stress state during the test. Therefore the results are different; the strengths measured in the unidirectional test (rectangular plates) are the 70% of that obtained in the bidirectional test (rectangular plates). Kim et al. [1] had described a similar situation between the unidirectional bending test and bidirectional bending test, in their research the relation was 64% between the strengths measured in four point test and bidirectional bending test. Shetty et al. [6] reported the same behavior with the unidirectional and bidirectional bending tests. However, the difference between the tests is near to 30%, therefore both tests can be used to determine the flexural strength.

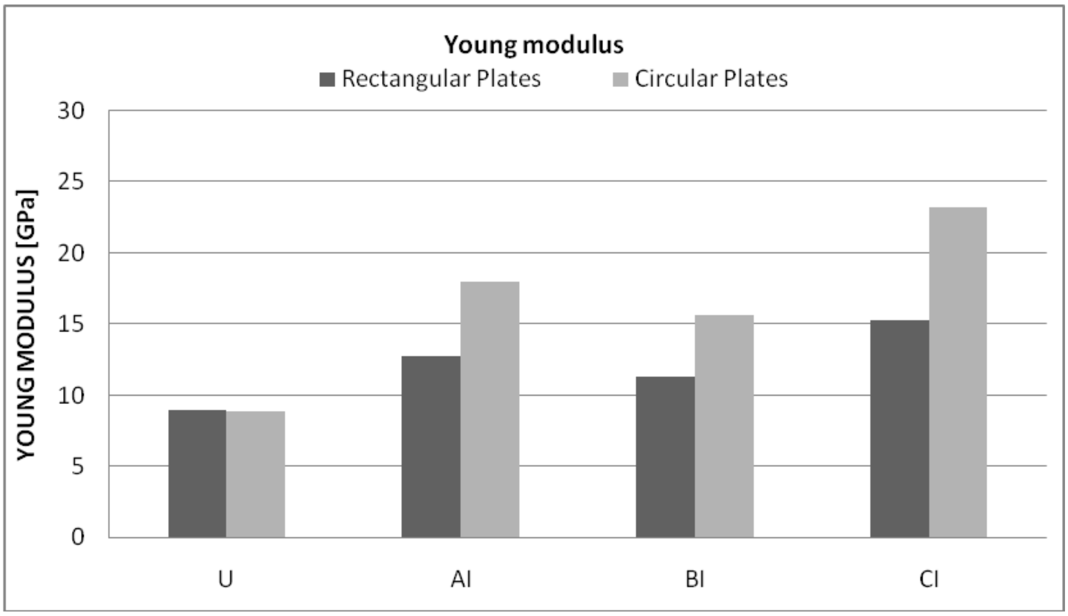


Figure 35 Unidirectional and bidirectional young modulus results

In the bidirectional bending test (circular plates) the effect of the use of consolidants on the Young modulus is more remarkable than in the unidirectional test (rectangular plates). As we can see in Figure 35, the Young modulus for the bidirectional test (circular plates), for the extreme case (Product C) in the unidirectional test the increase is 77% but the increase for the bidirectional test is 204%. In this case the differences between the results of the tests are more important, but they preserve the shape comparing with the other products.

4.2 PENETRATION DEPHT DETERMINED BY FLEXURAL TESTING

Chapter 3 Methodology describes how the cylinders and cubes after being treated with the consolidants and cured during four weeks were cut in plates to be tested. The results from these tests are presented in this section and organized like levels in the graphs in order to represent the different depths analyzed to identify the depth reached by the product. The first level presented corresponds to the face in contact with the product and the highest level is the farthest face.

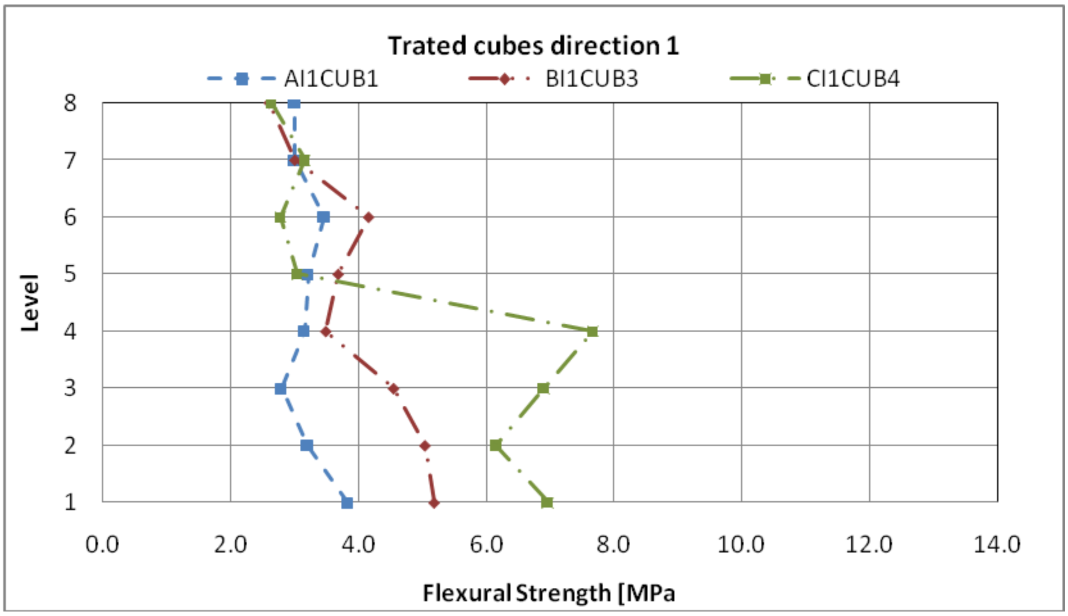


Figure 36 Penetration depth of consolidants in treated cubes direction of extraction 1

The Figure 36 represents the results for the rectangular plates tested in unidirectional bending test. The three cubes were extracted and located in the direction 1 of extraction. The excellent flexural behavior of the Product C is remarkable, and due to the high values gives in the four first levels is possible appreciate the sudden change between the level four and five, meaning the maximum depth of penetration of the product was level 4 which correspond the center of the cube is 2.5cm (25mm).

At the behavior of the cube CI1CUB4, the strongest plate does not correspond with the first level. This situation could be explained by the fact this product does not use solvents and the percentage of active product is the highest, in this way the product reaches the farthest point and starts to work exactly from there, and any transport product (as a solvent) is acting to move the active product to the surface when it is evaporating.

The depth penetration level of the product B seems to be the level 3, which corresponds to a depth of 1.9cm (19mm). Probably, the product A reached the level 6 but during the transport of the solvent in the evaporation process it transported part of the active product until the first level when it leaved the material. The most remarkable part where the product acted is the two first levels with a penetration of 1.25cm (12.5mm).

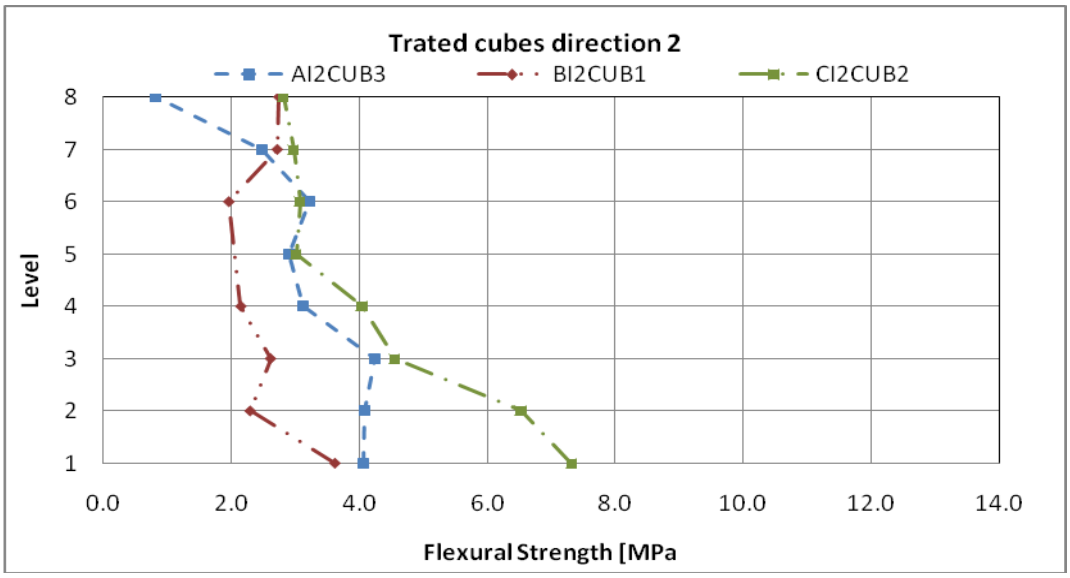


Figure 37 Penetration depth of consolidants in treated cubes direction of extraction 2

In Figure 37 the maximum depth reached was the level 6 with 3.7cm (37mm) but in the level 3 in 1.9cm (19mm) is located the best flexural behavior. The product B reached also a maximum penetration in the level 3. Conversely, for the Product C the level 3 is a transitional level because the maximum depth is 5 with 3.12cm (31.2mm).

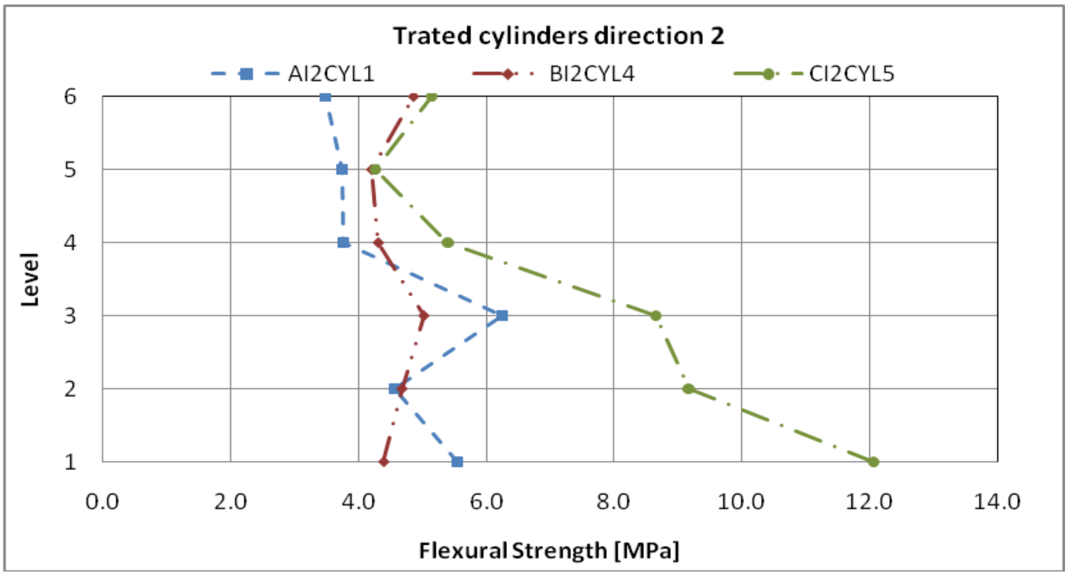


Figure 38 Penetration depth of consolidants in treated cylinders direction of extraction 2

The level 3 in the Figure 38 is the maximum reached by the products A and C. The profile described by the product B in the maximum flexural strength is 5MPa at the same maximum penetration depth of the other products in level 3 with 1.9cm (19mm).

The penetration depth of the consolidants analyzed was studied before by M. F. Drdácký and Z. Slížková (2008) [18] by unidirectional bending test. The fact that the maximum flexural strength along the profile of the cubes and cylinders is not located in the external face treated is not a surprising situation. In their research the maximum bending strength was in the maximum penetration depth which is between 2cm and 3cm (20mm and 30mm).

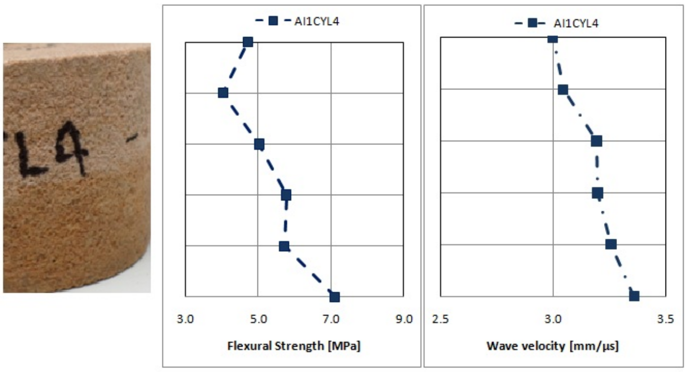
Furthermore, the maximum penetration depth is visible because the difference of the flexural strength between two consecutive levels is important and deeper this value tries to be constant. A big difference in the flexural strength in a short distance (less tan 7mm) may generate compatibility strength problems between the external treated zone and the internal zone not reached by the consolidants. Not only the strength is strongly affected, the study of the plates treated by capillary shows also important increases in the Young modulus of the material (Figure 28 and Figure 32). The use of product C generates very important differences between two successive levels; contrary is the case of product B and A, which show smoother profiles along the depth of the element.

The possible consequences of important differences in the flexural behavior between two following levels can be evaluated in further researches. In the practical field this effect should be analyzed.

4.3 RELATION BETWEEN THE FLEXURAL TESTING AND THE ULTRASONIC TEST TO DETERMINE PENTRATION DEPTH OF THE PRODUCTS

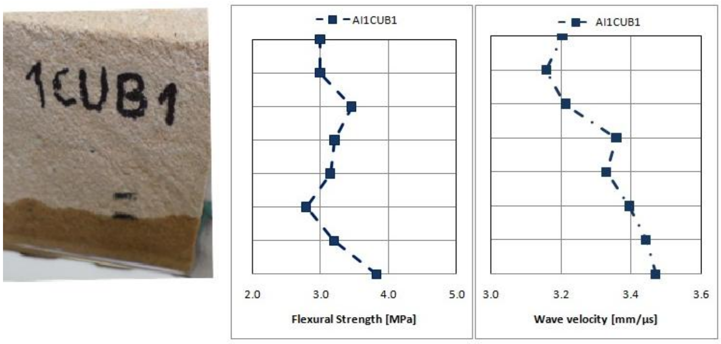
In order to determine the depth of penetration reached by the consolidants, the cubes and cylinders were tested with the ultrasonic before being cut in plates along the depth after being treated and maturing as is described in the Chapter 3 Methodology. In this section the relations founded are showed.

Figure 39 to Figure 50 present in the left side a) the image of the element during the impregnation process, in the majority it is possible to observe the maximum level reached by the product. In the middle b) is the profile of the flexural strength by bending test with three point test in cubes and bidirectional test in cylinders. Finally in the right side c) is the profile collected by ultrasonic test done along the element in similar locations of the flexural tests.



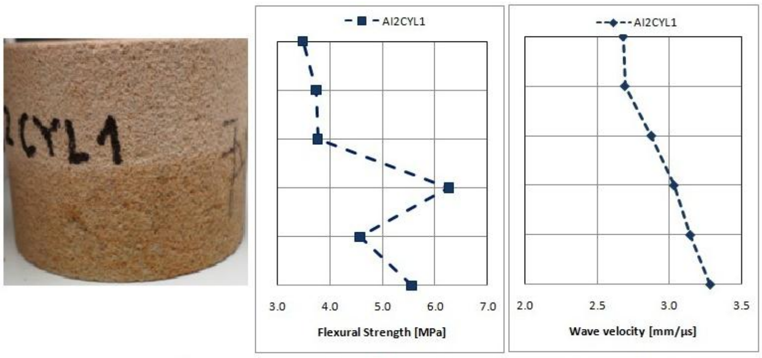
a) b) c)

Figure 39 Profile of element AI1CYL4 treated with Product A



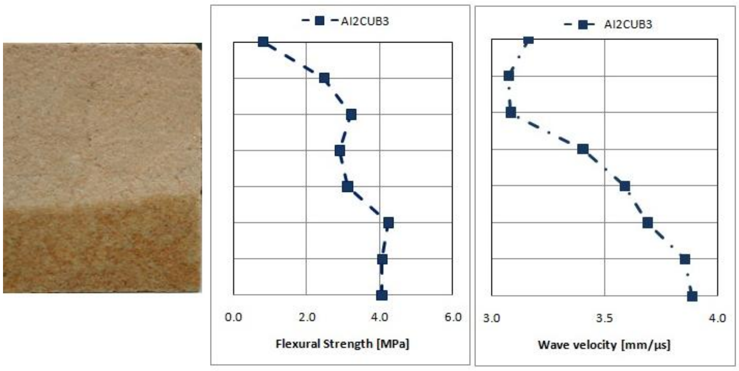
a) b) c)

Figure 40 Profile of element AI1CUB1 treated with Product A



a) b) c)

Figure 41 Profile of element AI2CYL1 treated with Product A



a) b) c)

Figure 42 Profile of element AI2CUB3 treated with Product A

Regarding Figure 39 to Figure 42 the flexural strength in average this product A with the application technique I (capillary rise) had penetrated the samples 2cm (20mm), where normally the graphics have a remarkable regression in the diagram depth vs flexural strength. In the center of the diagram of the cubes, between the levels 4 or 5 (40mm and 50mm depth) is possible to appreciate a flat zone for the value of flexural strength which represents the core of the sample not always influenced by the consolidants.

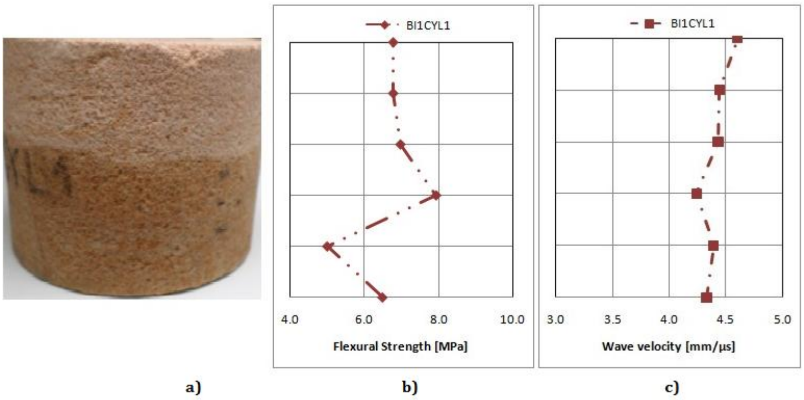


Figure 43 Profile of element BI1CYL1 treated with Product B

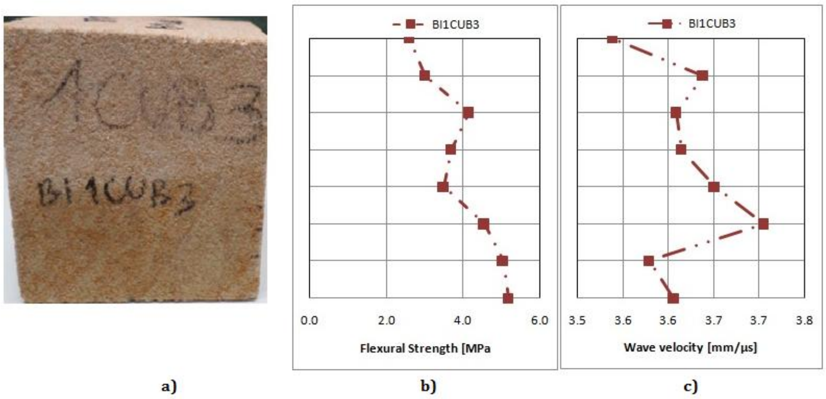


Figure 44 Profile of element BI1CUB3 treated with Product B

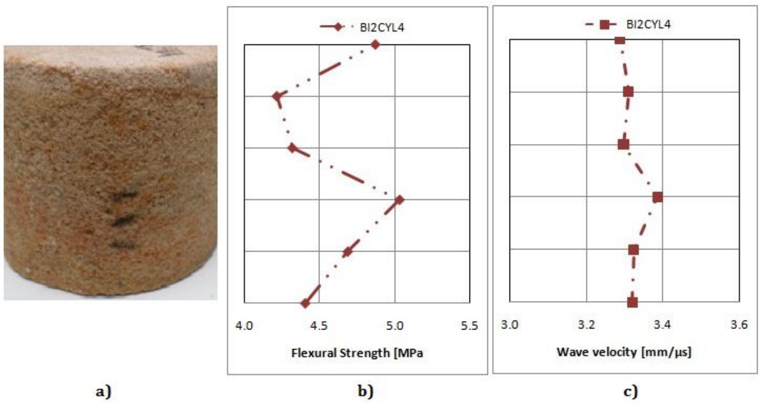
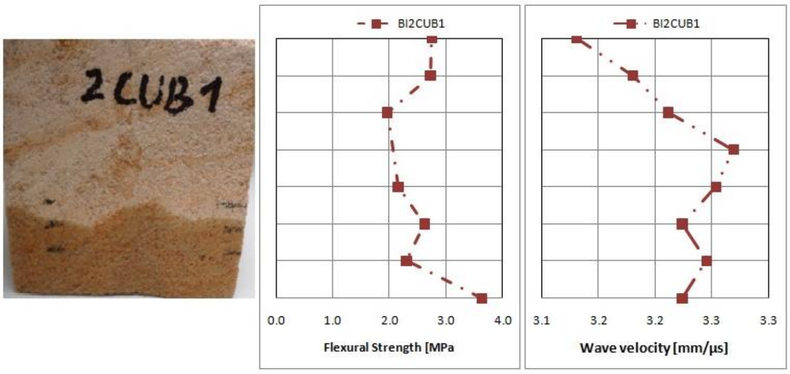


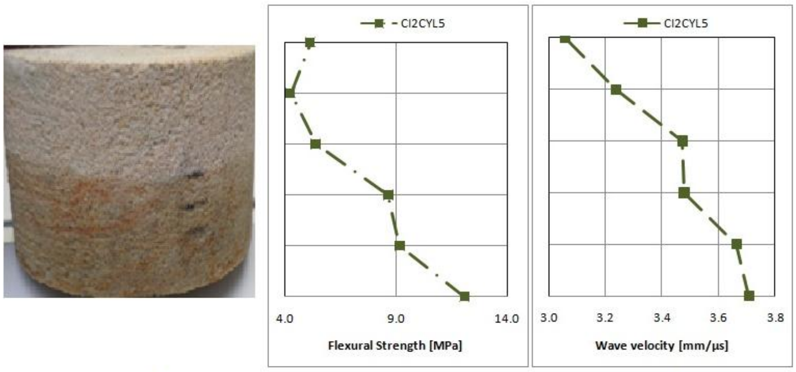
Figure 45 Profile of element BI2CYL4 treated with Product B



a) b) c)

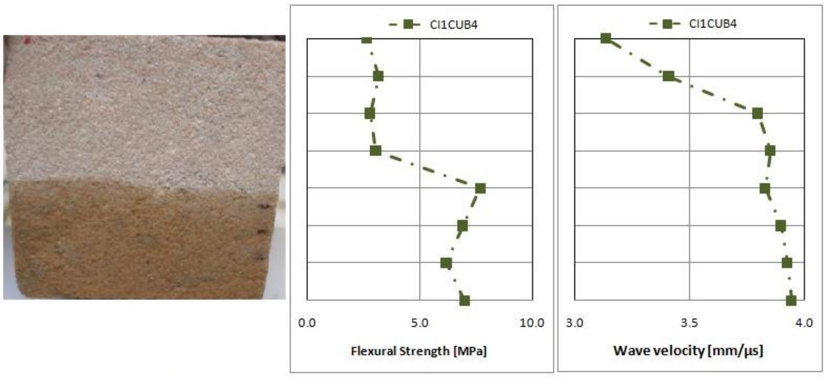
Figure 46 Profile of element BI2CYL4 treated with Product B

Particularly the samples of the product B (Figure 43 to Figure 46) have presented different behaviors. But in general the profiles in the cylinders show a peak near to 2cm (20mm) depth, where the value of the flexural strength is higher than in the surface in contact with the product (level at the bottom). The case in the cubes seems be different, a flat zone is presented after the 2cm (20mm) up 3cm (30mm) depth.



a) b) c)

Figure 47 Profile of element CI2CYL5 treated with Product C



a) b) c)

Figure 48 Profile of element CI1CUB4 treated with Product C

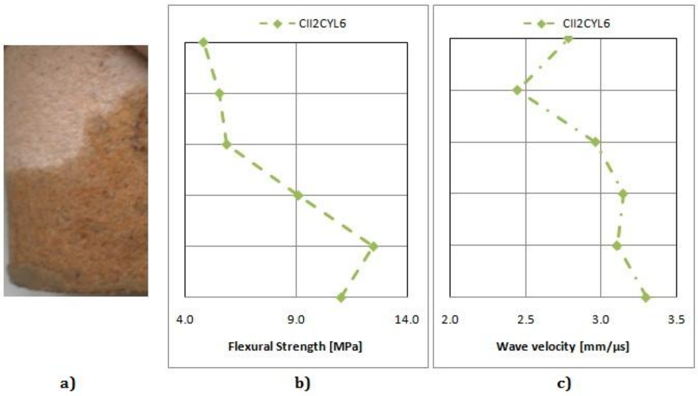


Figure 49 Profile of element CII2CYL6 treated with Product C

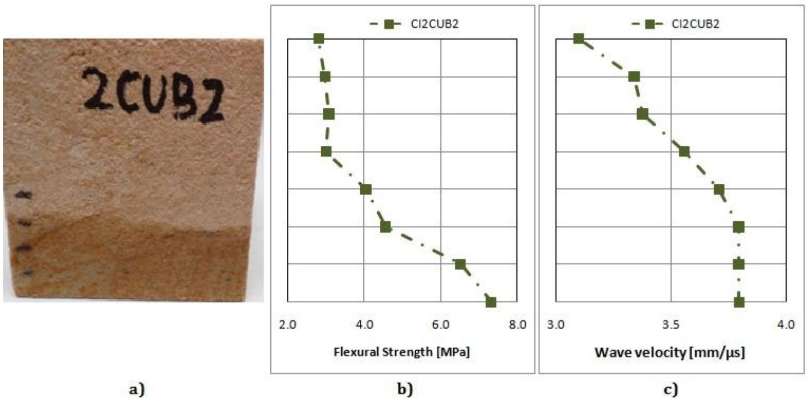


Figure 50 Profile of element CI2CUB2 treated with Product C

The profile of the treatment with the product C (Figure 47 to Figure 50) is more stable than with the others products, the Figure 50 does not illustrate regressions along the depth evaluated, and the strong change in the values of flexural strength in cubes and cylinders is near to 2cm (20mm).

In general, there is a relation between the depth observed during the treatment process and the behavior of the flexural strength in the plates extracted from the elements. The depth reached during the impregnation is closed to the depth where the consolidants used stop the absorption. In addition the relation between the results of the bending strength and the ultrasonic tests done is evident, the ultrasonic profile describes the shape of the profile flexural strength, however some interferences are presented in some points of the ultrasonic profiles, but they are not enough harmful to change the analysis which could be done only by the ultrasonic test.

4.4 APPLICATION METHODS

Two different application methods were used to treat the cylinders; the purpose is to compare the effects of the enforcement on the material. As was described in Chapter 3 Methodology, the capillary rising is codified as Method I (dark colors) and the brushing in vertical as Method II (light colors).

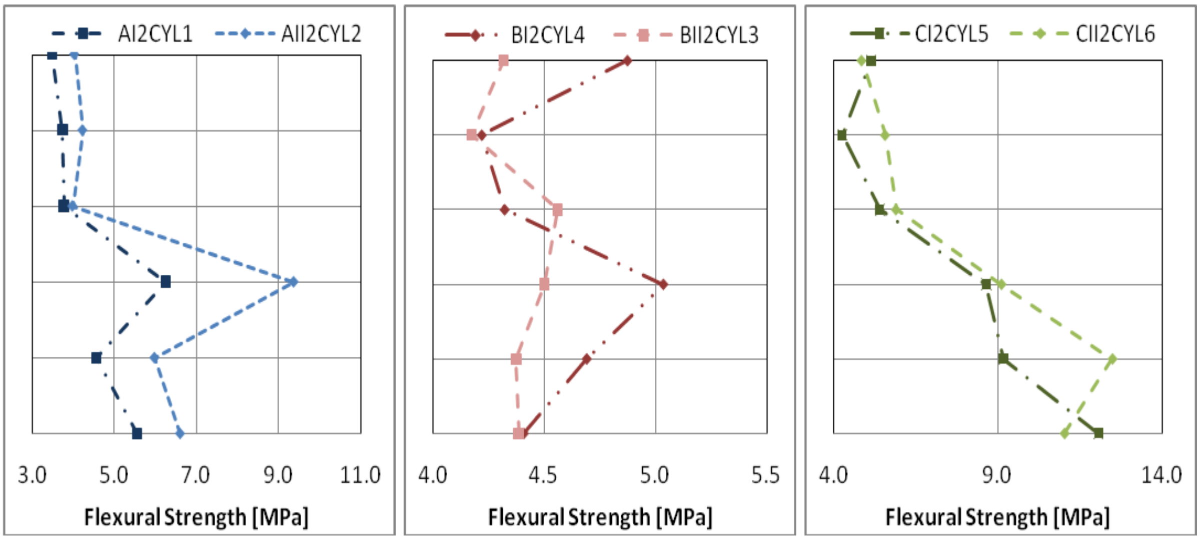


Figure 51 Application methods of the products

In Figure 51, the Product A (graphics in blue) and Product C (graphics in green) represent a pattern of shadow between the method I profile and method II profile. Both methods present the same penetration depth (in product A and product C) but the results provided by the method II on the flexural strength are bigger than those from method I (not with an important difference) specially near to the surface treated.

The product B (graphics in red), present a smoother profile for the method II (brushing) and the maximum flexural strength is less 0.5MPa than the method I. However the important points of maximum strength in both profiles are near, declaring the same point of penetration depth.

After the second day of application of the product A, white smear was detected on the walls near to the surface treated and other colored smear on the surface treated (Figure 52).

Figure 52 Smear in sample AII2CYL2

This effect are explained by the presence of excesses of product during the application, at this moment the zone near to the surface was completely saturated and it was not able to absorb more liquid treatment, the producer recommends clean the excesses of product after the application [15], the consolidant excess stayed on the surface and it worked stronger near to the surface. The two consequences of these gluts were the colorations and an extra strengthening in the zone.

The product C presents a similar situation, but the smear was not as visible as in the other case. The Figure 53 was taken three days after the application and some white dots were remarkable.

Figure 53 Smear in sample CII2CYL6

Contrary to the other products, the sample treated with the product B with method II presented important spots and discoloration on the surface treated (Figure 54) but the results of flexural strength are the same along the first three points in the profile, meaning that in spite of the consolidants excess the stone was not extra-consolidated in any zone.

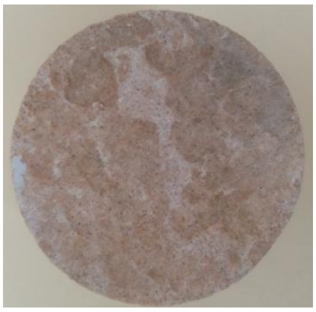


Figure 54 Smear in sample BII2CYL3

According to Dei and Salvadori [19] during their research the samples were rapidly washed in water after the application of the consolidants to remove the phase deposited and to avoid the appearance of strong white spots like results from a possible carbonation process because they worked with nanometric slaked lime.

The method II of brushing is one of the main methods used actually in the practice, after these results, it is possible to affirm the effectiveness of both methods are similar. Nevertheless it is necessary to always do some tests before decide and apply the product because, as we have seen in this research, some smear, discoloration and extra strengthening are possible.

4.5 PENETRATION DEPTH ON THE WALL TESTED BY ULTRASONIC TEST

A wall built with masonry stone of the same “Hořice” stone and lime mortar in the joints was treated with the same three products and with the two techniques analyzed. The main objective of this procedure is to determine the penetration depth of the products on a vertical plane and more realistic situation. Figure 55 presents the location where the ultrasonic test was done and the name to identify them with the results.

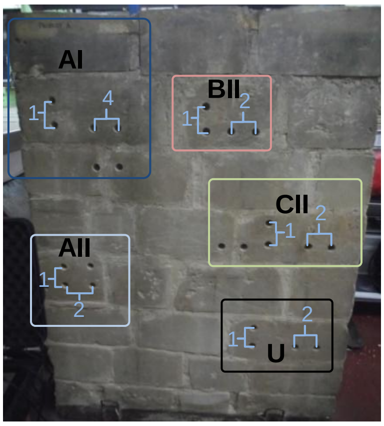


Figure 55 Location of measurements on the wall

As was described in Chapter 3 Methodology the purpose of the test is to determine the profile of depth penetration of the products. Following are the results from these tests.

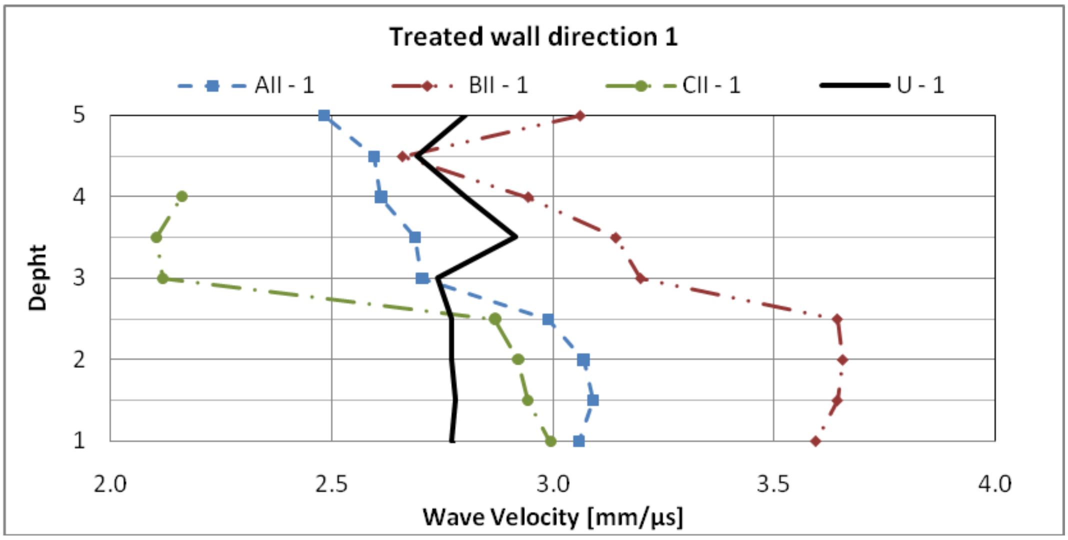


Figure 56 Profile of wave velocity on the wall treated in direction 1

According to the Figure 56 between 2.5cm and 3cm is an important change of the wave velocity. Which means the maximum penetration depth of the products applied by brushing is 3cm (30mm), in the analysis of the cubes and cylinders was 2cm (20mm). Consequently the analysis on little specimens is sufficiently accurate to relate it with the real case.

The Figure 56 shows wave velocity as result from the ultrasonic test. In spite of this is a non destructive test is possible to do some analysis regarding the wave velocities. The Product B presents the fastest wave velocity and the product C the lowest being as during the flexural testing was the contraire. Additionally, the behavior of the product C in the zone where is acting the consolidant is similar to the behavior of the product A.

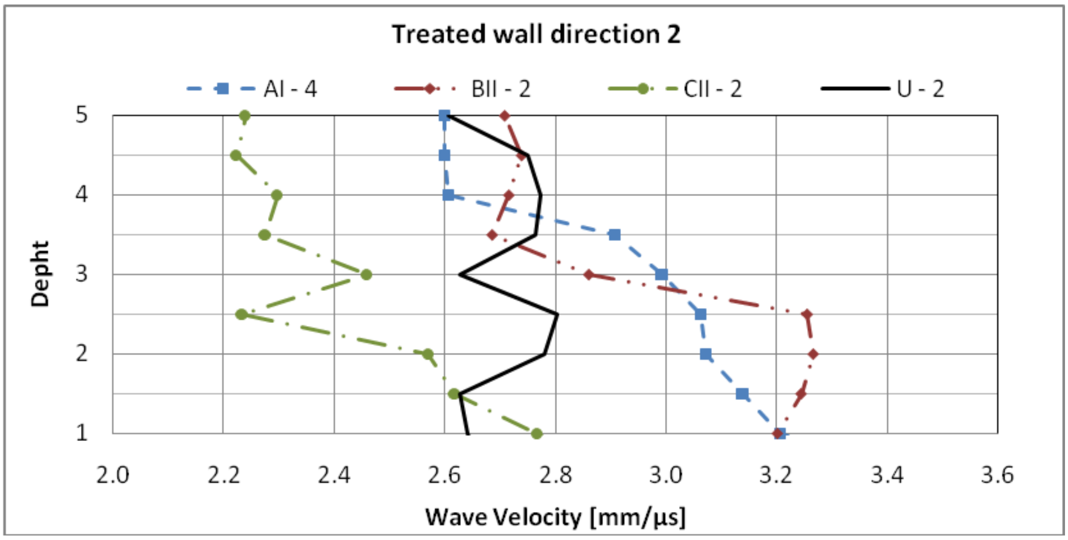


Figure 57 Profile of wave velocity on the wall treated in direction 2

In direction 2 (Figure 57) the result does not change, the maximum depth penetration of the products inside the wall was between 3cm (30mm) and 4cm (40mm). The profile of the product C is less than the profile of the untreated zone. Which is an atypical behavior; this could mean that the product C did not work on the stone. But is important always to mention this is a non destructive test and the main idea in this case is to compare the wave velocity along the profile.

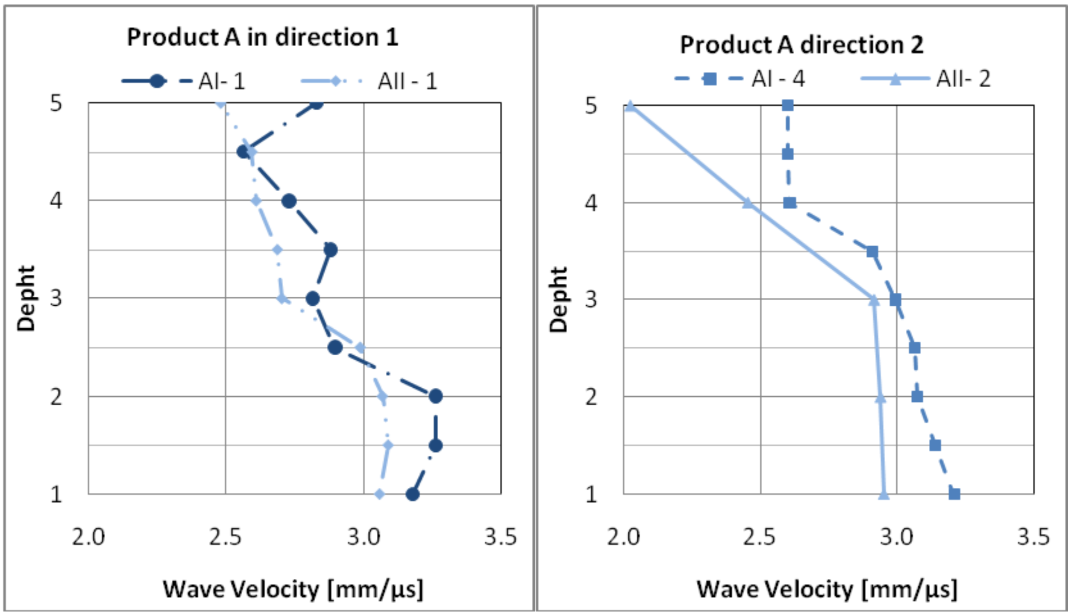
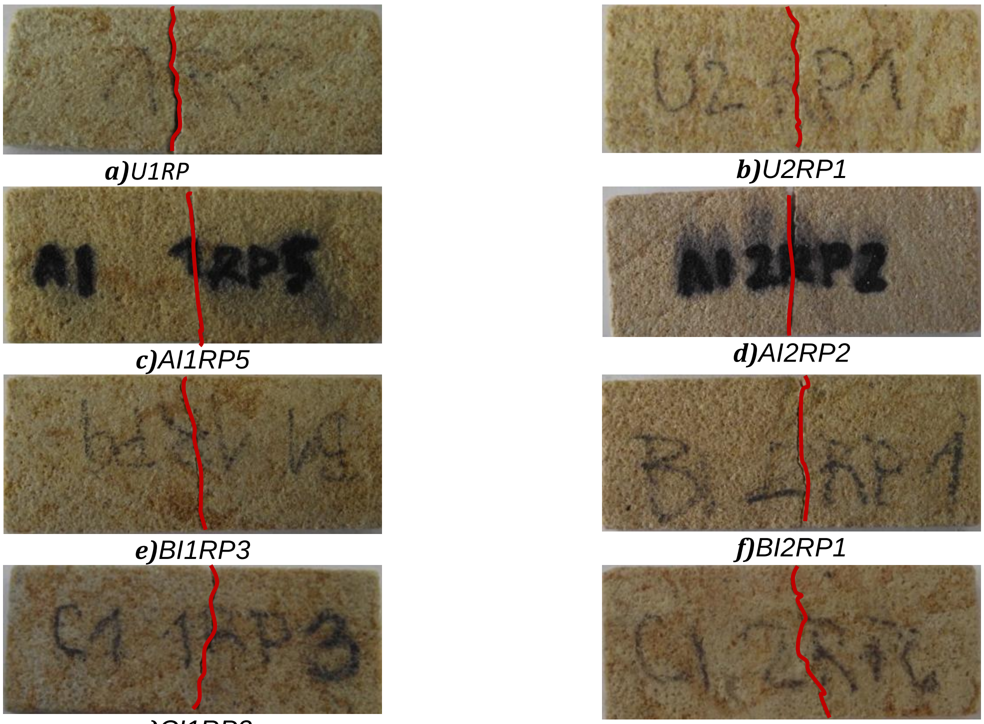


Figure 58 Comparison of the application methods on the wall with Product A

The product A was also applied on the wall by the method I (capillary absorption) in vertical position, with the same conditions that with the method II (brushing) and the same amount of material used. The Figure 58 is comparing the results of the ultrasonic tests. Where is possible appreciate the important proximity of the results from the different methods I and II. Concluding, both curves describe the same behavior, in direction 1 the maximum penetration depth is between 2.5cm and 3cm (25mm and 30mm), in direction 2 the maximum penetration depth is between 3cm and 4cm (30mm and 40mm).

4.6 FAILURE SHAPE

In this section are presented some failure shape found during this research.



a)*U1RP* ***b)****U2RP1*

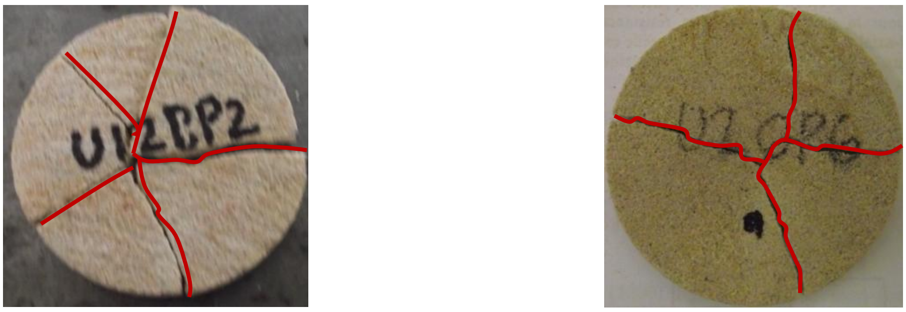
c)*AI1RP5* ***d)****AI2RP2*

e)*BI1RP3* ***f)****BI2RP1*

g)*CI1RP3* ***h)****CI2RP6*

Figure 59 Examples of failure shape in rectangular plates

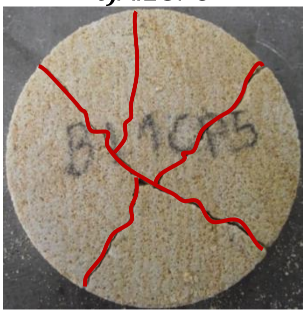
In unidirectional test and bidirectional test, the treatment with the consolidants did not change the failure shapes (Figure 59 and Figure 60), meaning the shapes are related with the configuration of the test, but not with the flexural strength of the sample or the young modulus.



a)*U1CP2* ***b)****U2CP6*

c)*AI1CP3*

d)*AI2CP1*



e)*BI1CP5*

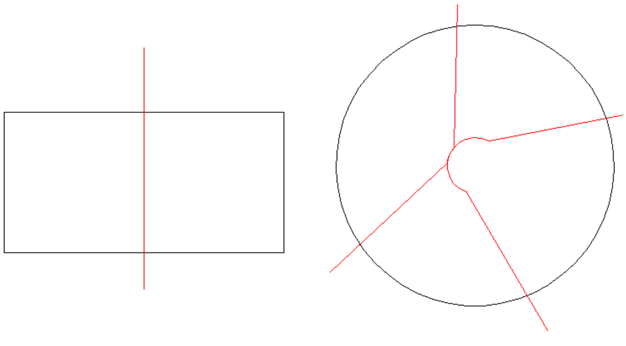
f)*BI2CP6*

g)*CI1CP3*

h)*CI2CP6*

Figure 60 examples of failure shape in circular plates

The final shape failure founded in the rectangular plates and circular plates are described in Figure 61 a) and Figure 61 b) respectively. The failure line is always affected by the heterogeneous composition of the stone but generally it describes the shape drawn.



a) **b)**

Figure 61 Final shape failures of specimens

4.7 MODEL IN FINITE ELEMENTS OF BIDIRECTIONAL TEST

The bidirectional bending test carried on the circular plates was modeled by Ing. Ph.D. Jiří Kunecký in the Software ANSYS – Mechanical APLD 15.0. The model calculate the system with non-linear solution, it is a elastic model represented by 3 cylinders: the inner loaded zone limited by the load ring, the intermediate zone limited by the support ring and the external zone beyond the support ring. The mesh used is composed by tetrahedral elements.

Figure 62 a) shows the geometry established, the mesh generated and the section of the element analyzed. In the Figure 62 b) is possible appreciate an extra ring below the specimen, which represent the ring support used during the tests. The material of this ring is defined like a metallic zone providing the correspondent support.

a) b)

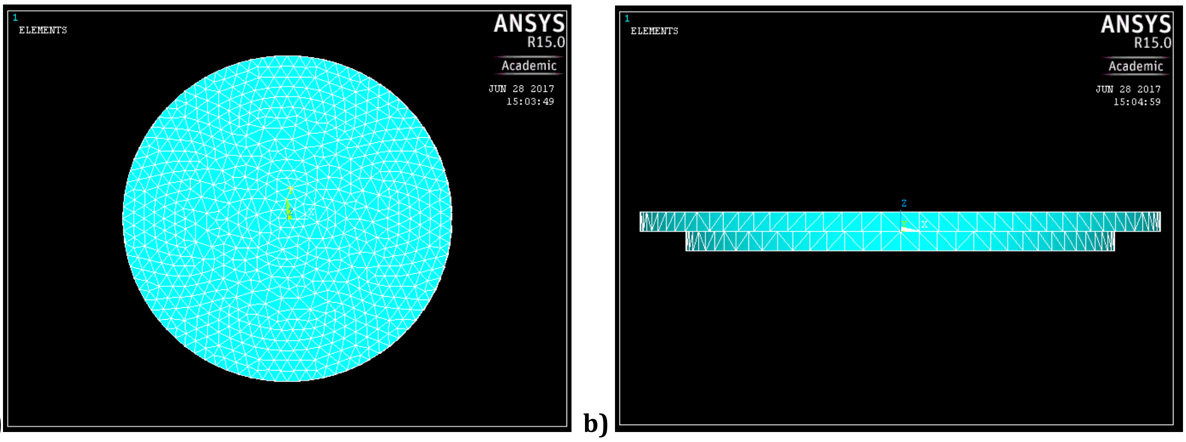


Figure 62 Model of the circular specimens

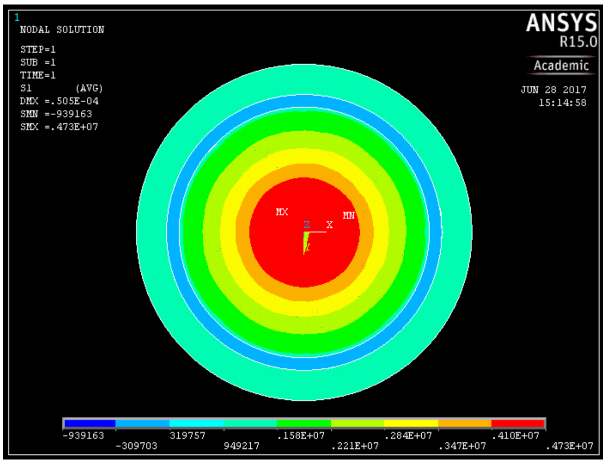


Figure 63 Flexural strength calculated by the model

The main purpose of this model is to compare the numerical analysis with the experimental results and determine their validity. Figure 64 and Figure 65 compare the results of flexural strength and Young modulus obtained from the test and form the model. The diagonal line represents the exact correlation between the results. The proximity of the majority of the points to the diagonal line evidence the proximity of the results in the analytical and practical approaches used in this research.

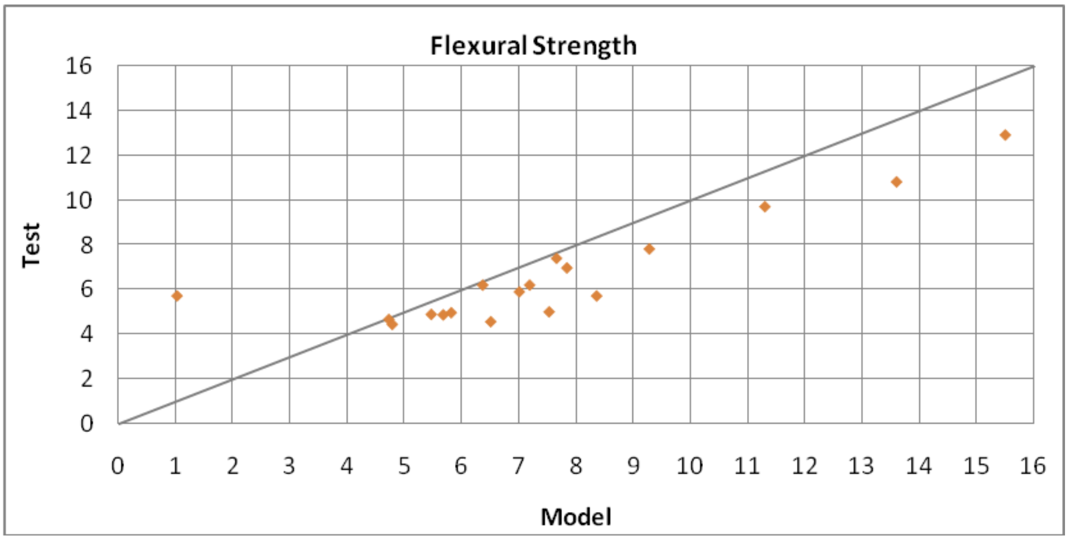


Figure 64 Comparison of results of Flexural strength

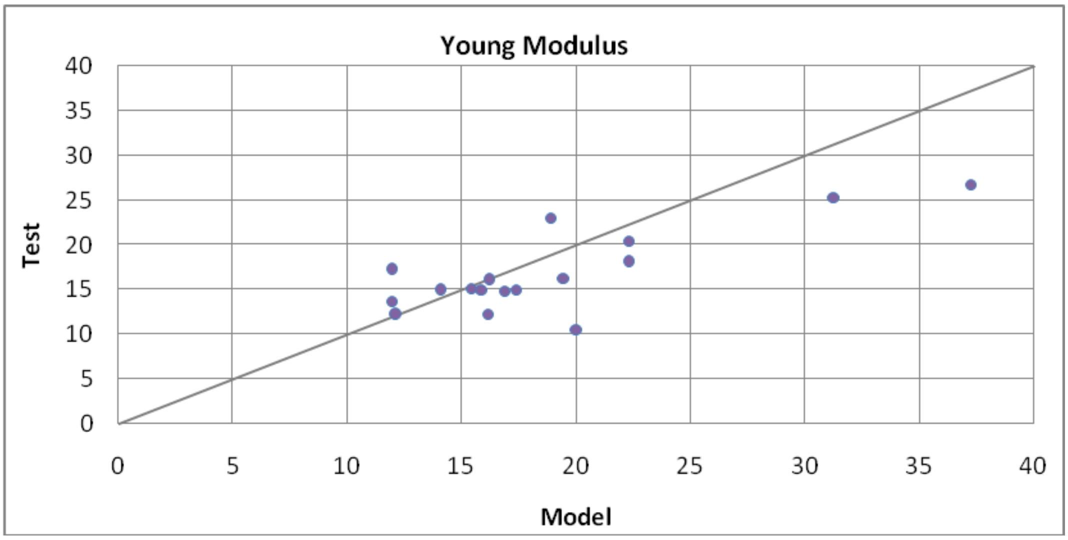


Figure 65 Comparison of results of Young Modulus

J.C. Glandus (1986) [5] did not find this relation in the system ring – ring for the bidirectional approach. The diameter of the loader rings tested were 5mm and 10mm, the dimensions could be the reason of the inconformity in the results, due to the fact that in the actual dissertation work the diameter used was 15mm.

Contrary, J. Kim et al (2013) [1] fixed the numerical and theoretical results and the consequent experimental results were well represented, the diameter used in the experimental phase was 24mm working with samples in concrete using Portland Type I. The results obtained from the actual research should not be the same of the Kim's et al. research because its goal was used an improved method in concrete, however the final shape failure are similar to theirs (Figure 61). Because, as was explained, the failure shape depends of the test configuration and not of the material tested.

5. CONCLUSIONS AND SOLUTION OF THE PROBLEM

The general deterioration of the sandstone along the time is an inevitable process. Referring the recovering of bending strengthen as mechanical property lost during the degradation process, the use of consolidants is a good strategy to strength the stone. This research had demonstrated that the flexural strength and flexural Young modulus may be recovered by a consolidant treatment.

The use of different arrangements to evaluate the mechanical behavior was the main aim of this research. For the reason of obtaining significantly different but comparative data three consolidation products of the same chemical composition but of very different amount of generated active substance were selected. The applied methods provide different results for the same property evaluated because of the nature of the stress state in each test. However the differences between the unidirectional bending test by three points and the bidirectional bending test by ring support - ring load are logical. Both of them can be used finding similar flexural strength.

The flexural strength obtained from the unidirectional bending test is the 70% of that from the bidirectional bending test. Kim et al. [1] had founded that the unidirectional bending results are the 64% of the bidirectional bending results. Shetty et al. [6] founded similar behavior comparing the unidirectional and bidirectional bending test.

Based on data analyzes on treated plates, this research confirmed that the increase in flexural strength and Young modulus is strongly related to the amount of silica gel generated inside the pores. The observed failure shapes are connected to the test arrangement used and not to the sample strength; consequently, they were not affected by the use of the consolidants. However, the circular disc failure modes were influenced by material effects.

Regarding the penetration depth of the consolidants inside the “Hořice” sandstone by the two methods used in this research (capillary rise and brushing), the penetration reached is between 2cm and 3cm (20mm and 30mm). Both methods presented similar results on the flexural bending tests; consequently they can be implemented.

The penetration depths of the products observed during the treatment process are located in similar points to the maximum value of flexural strength found along the treated elements. The results from the ultrasonic tests are strongly related with these penetration depths. The ultrasonic test approved to be an efficient and reliable non destructive test (NDT) to verify the state of the material before and after treatment.

The same efficiency was observed using Ultrasonic testing of a sandstone wall treated in the same way as the laboratory specimens. Double probe system developed by the Geotron company provides fast and reliable tool for testing penetration depth of consolidants on stone surfaces which can be temporarily damaged with small repairable holes.

The flexural strength profile along the depth of the element treated exhibit remarkable differences between consecutive levels; it depends on the efficiency of the consolidants used. The same is valid for the modulus of elasticity. Important differences of mechanical characteristics along short lengths inside the stone may generate compatibility problems between the superficial strengthened zone and the inner zone.

The excess of product on the stone surface during the application process has visual consequences announced by the producer, who recommends drying the surface and removing the agent not absorbed. Depending on the product, an extra consolidation can be observed in the surface, generating possible problems of compatibility strength not studied in this research.

5.1 RECOMMENDATIONS FOR FUTURE RESEARCHES

Future researches may study the compatibility effects between a superficial strengthened zone and a not consolidated inner zone in order to determine the consequences of the not smoother profile of mechanical characteristics.

Also, the applicability of other biaxial disc testing, namely the three ball system already used by Kim et al. [1] in specimens in concrete. However, any disc specimen is not suitable for testing other physical and mechanical characteristics because it will require a more complex measurements and loading systems.

Another interesting issue is a possibility of improvements in the double probe ultrasonic testing system less damaging the stone surfaces, e.g. drilling in the mortar joints and measurement across the ashlars corner or development of a new system with more flexible double probes.

6. REFERENCES

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7. ANNEX A – PROPERTIES OF SPECIMENS

7.1 RECTANGULAR PLATES

NAME	TYPE	WIDTH [mm]	THICKNESS [mm]	LENGTH [mm]	WEIGHT [gr]	FLEXURAL STRENGHT [MPa]	YOUNG MODULUS [MPa]
AI1RP1	Rectangular Plate	20,33	4,75	50,22	8,38	4,262	
AI1RP2	Rectangular Plate	20,07	4,83	49,94	8,83	5,792	15,889
AI1RP3	Rectangular Plate	20,36	4,79	49,90	8,32	4,257	10,957
AI1RP4	Rectangular Plate	19,12	4,68	50,30	7,88	4,212	13,230
AI1RP5	Rectangular Plate	20,23	4,84	49,68	8,37	4,584	11,150
AI1RP6	Rectangular Plate	20,45	4,78	49,88	8,45	4,774	11,505
					AVERAGE	4,647	12,546
					STANDARD DESV	0,603	2,074
BI1RP7	Rectangular Plate	19,87	4,76	50,26	8,24	2,965	
BI1RP8	Rectangular Plate	20,24	4,69	48,60	7,99	2,965	14,610
BI1RP9	Rectangular Plate	20,24	4,79	48,60	8,83	2,965	10,586
BI1RP10	Rectangular Plate	20,45	4,80	49,88	8,34	3,162	7,212
BI1RP11	Rectangular Plate	20,45	4,93	49,88	8,33	3,162	10,158
BI1RP12	Rectangular Plate	20,45	4,89	49,88	8,27	3,162	8,070
					AVERAGE	3,064	10,127
					STANDARD DESV	0,108	2,874
CI1RP1	Rectangular Plate	20,05	4,72	50,24	8,34	8,269	15,816
CI1RP2	Rectangular Plate	19,62	4,81	50,27	8,10	7,183	14,808
CI1RP3	Rectangular Plate	19,99	4,87	50,21	8,28	6,676	14,980
CI1RP4	Rectangular Plate	20,38	4,88	50,04	8,43	7,732	15,054
CI1RP5	Rectangular Plate	20,01	5,00	49,71	8,08	6,866	12,182
CI1RP6	Rectangular Plate	20,21	4,85	49,64	8,19	7,165	11,478
					AVERAGE	7,315	14,053
					STANDARD DESV	0,589	1,770
U1RP1	Rectangular Plate	19,94	4,83	49,65	8,23	3,597	10,770
U1RP2	Rectangular Plate	19,05	4,73	50,08	7,82	3,433	9,482
U1RP3	Rectangular Plate	20,18	4,74	49,84	8,39	3,249	8,629
U1RP4	Rectangular Plate	20,00	4,74	50,28	8,30	1,665	4,969
U1RP5	Rectangular Plate	20,15	4,75	49,91	8,10	3,223	9,823
U1RP6	Rectangular Plate	19,87	3,82	50,51	6,57	2,826	
					AVERAGE	2,999	8,735
					STANDARD DESV	0,702	2,240
AI2RP1	Rectangular Plate	20,54	4,635	50,70	8,565	4,268	10,866
AI2RP2	Rectangular Plate	19,82	4,840	50,22	8,419	4,273	12,714
AI2RP3	Rectangular Plate	20,78	4,755	50,52	8,651	4,580	16,502
AI2RP4	Rectangular Plate	20,45	4,835	50,87	8,828	4,726	
AI2RP5	Rectangular Plate	20,43	4,735	51,10	8,959	3,937	16,296
AI2RP6	Rectangular Plate	20,75	4,585	50,49	8,243	4,356	8,656
					AVERAGE	4,357	13,007
					STANDARD DESV	0,275	3,415

Table 6 Properties of rectangular plates - part 1

NAME	TYPE	WIDTH	THICKNESS	LENGTH	WEIGHT	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[mm]	[gr]	[MPa]	[MPa]
BI2RP1	Rectangular Plate	19,85	4,845	50,38	8,696	3,359	14,410
BI2RP2	Rectangular Plate	20,60	4,775	50,64	8,61	3,626	13,016
BI2RP3	Rectangular Plate	20,65	4,660	50,63	8,719	3,525	
BI2RP4	Rectangular Plate	20,03	4,870	51,05	8,737	3,941	11,870
BI2RP5	Rectangular Plate	19,85	4,710	50,19	8,303	3,242	8,593
BI2RP6	Rectangular Plate	19,81	4,910	49,88	8,459	4,519	14,808
					AVERAGE	3,702	12,539
					STANDARD DESV	0,467	2,495
CI2RP1	Rectangular Plate	19,88	4,805	49,55	8,272	7,949	15,051
CI2RP2	Rectangular Plate	20,50	4,695	50,76	8,506	7,632	
CI2RP3	Rectangular Plate	19,69	4,745	50,65	8,353	7,356	19,914
CI2RP4	Rectangular Plate	21,02	4,715	51,19	9,092	7,385	15,128
CI2RP5	Rectangular Plate	20,42	4,885	50,72	8,75	8,874	13,613
CI2RP6	Rectangular Plate	19,88	4,715	49,29	8,2132	7,887	18,936
					AVERAGE	7,847	16,528
					STANDARD DESV	0,560	2,734
U2RP1	Rectangular Plate	19,85	4,075	51,08	7,337	3,190	8,394
U2RP2	Rectangular Plate	19,76	4,745	49,75	8,305	3,453	8,742
U2RP3	Rectangular Plate	19,78	4,905	49,23	8,149	3,124	11,013
U2RP4	Rectangular Plate	19,93	4,810	49,36	8,01	2,219	8,716
U2RP5	Rectangular Plate	19,82	4,850	49,65	8,164	3,347	8,638
U2RP6	Rectangular Plate	19,89	4,845	50,91	8,76	3,418	9,864
					AVERAGE	3,125	9,228
					STANDARD DESV	0,462	1,013

Table 7 Properties of rectangular plates - Part 2

7.2 CIRCULAR PLATES

NAME	TYPE	DIAMETER	THICKNESS	WEIGHT	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[gr]	[MPa]	[MPa]
AI1CP1	Circular Plate	53,76	3,66	14,06	7,835	22,645
AI1CP2	Circular Plate	54,13	3,93	15,93	4,897	16,288
AI1CP3	Circular Plate	54,33	4,07	16,54		
AI1CP4	Circular Plate	52,65	3,80	14,04	4,670	15,072
AI1CP5	Circular Plate	53,70	4,00	16,07	10,354	19,391
AI1CP6	Circular Plate	54,12	3,86	15,07	4,445	15,023
				AVERAGE	6,440	17,684
				STANDARD DESV	2,587	3,293
BI1CP1	Circular Plate	53,78	3,83	14,95	6,672	14,065
BI1CP2	Circular Plate	54,30	3,94	16,54	6,978	16,230
BI1CP3	Circular Plate	54,32	3,82	16,34	7,364	16,820
BI1CP4	Circular Plate	51,15	3,87	13,34	5,524	20,472
BI1CP5	Circular Plate	54,15	4,05	16,56	5,908	14,836
BI1CP6	Circular Plate	53,89	3,91	15,33	4,304	
				AVERAGE	6,125	16,485
				STANDARD DESV	1,121	2,483

Table 8 Properties of circular plates - part 1

NAME	TYPE	DIAMETER	THICKNESS	WEIGHT	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[gr]	[MPa]	[MPa]
CI1CP1	Circular Plate	53,91	4,08	16,50	12,936	25,377
CI1CP2	Circular Plate	50,75	3,84	13,62	10,931	24,470
CI1CP3	Circular Plate	54,12	4,02	15,97	9,726	20,433
CI1CP4	Circular Plate	54,16	3,74	14,94	7,764	19,868
CI1CP5	Circular Plate	52,56	4,07	15,04	7,780	17,646
CI1CP6	Circular Plate	53,40	4,14	15,66	7,804	25,255
				AVERAGE	9,490	22,175
				STANDARD DESV	2,133	3,282
U1CP1	Circular Plate	53,69	3,54	13,42	2,1515	8,1483
U1CP2	Circular Plate	53,65	3,99	14,77	5,7917	9,7920
U1CP3	Circular Plate	54,28	3,76	15,59	4,2567	10,4942
U1CP4	Circular Plate	54,24	3,70	15,05	4,2120	
U1CP5	Circular Plate	54,02	3,87	14,70	4,5844	6,8876
U1CP6	Circular Plate	54,04	3,87	15,73	4,7742	9,4490
				AVERAGE	4,295	8,954
				STANDARD DESV	1,196	1,435
AI2CP1	Circular Plate	54,01	4,02	16,28	7,233	20,503
AI2CP2	Circular Plate	53,89	3,89	14,77	6,299	14,633
AI2CP3	Circular Plate	54,11	3,79	15,19	7,407	23,035
AI2CP4	Circular Plate	54,08	4,05	16,38	7,832	18,234
AI2CP5	Circular Plate	54,04	4,06	16,36	6,963	21,932
AI2CP6	Circular Plate	53,95	4,02	15,39	4,822	10,923
				AVERAGE	6,759	18,210
				STANDARD DESV	1,077	4,654
BI2CP1	Circular Plate	54,28	4,02	15,96	4,970	15,028
BI2CP2	Circular Plate	54,28	3,92	15,47	4,054	
BI2CP3	Circular Plate	54,00	4,01	15,89	6,210	13,705
BI2CP4	Circular Plate	53,96	4,04	15,69	4,739	12,395
BI2CP5	Circular Plate	54,30	4,01	15,69	5,484	17,365
BI2CP6	Circular Plate	53,82	4,03	15,43	4,877	15,162
				AVERAGE	5,056	14,731
				STANDARD DESV	0,729	1,852
CI2CP1	Circular Plate	54,23	4,11	16,31	10,021	23,332
CI2CP2	Circular Plate	54,09	4,28	16,89	8,796	24,013
CI2CP3	Circular Plate	54,02	3,97	15,65	12,604	27,125
CI2CP4	Circular Plate	54,00	4,18	16,51	10,835	26,762
CI2CP5	Circular Plate	54,16	3,92	15,64	10,475	23,719
CI2CP6	Circular Plate	53,85	3,84	14,75	11,282	21,059
				AVERAGE	10,669	24,335
				STANDARD DESV	1,274	2,276

Table 9 Properties of circular plates - part 2

NAME	TYPE	DIAMETER	THICKNESS	WEIGHT	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[gr]	[MPa]	[MPa]
U2CP1	Circular Plate	53,86	3,88	15,21	5,146	9,658
U2CP2	Circular Plate	53,69	3,96	15,14	3,171	
U2CP3	Circular Plate	53,92	3,94	15,28		4,077
U2CP4	Circular Plate	53,92	3,98	15,51	4,265	10,691
U2CP5	Circular Plate	54,39	4,03	16,02	5,674	9,998
U2CP6	Circular Plate	54,09	4,11	16,34	5,400	9,110
				AVERAGE	4,731	8,707
				STANDARD DESV	1,020	2,651

Table 10 Properties of circular plates - part 3

7.3 RECTANGULAR PLATES FROM CUBES

NAME	TYPE	WIDTH	THICKNESS	LENGTH	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[mm]	[MPa]	[MPa]
AI1CUB1-1	Rectangular Plate	19,77	3,71	49,70	3,818	10,159
AI1CUB1-2	Rectangular Plate	20,12	4,08	49,60	3,199	7,760
AI1CUB1-3	Rectangular Plate	20,41	4,05	49,71	2,799	6,983
AI1CUB1-4	Rectangular Plate	20,32	4,02	49,52	3,150	10,519
AI1CUB1-5	Rectangular Plate	20,42	4,01	49,59	3,212	5,299
AI1CUB1-6	Rectangular Plate	20,50	4,05	49,53	3,459	5,855
AI1CUB1-7	Rectangular Plate	20,39	3,96	49,51	2,999	7,706
AII1CUB2-1	Rectangular Plate	20,16	5,14	50,67	4,638	10,090
AII1CUB2-2	Rectangular Plate	20,16	5,14	50,67	3,159	7,234
AII1CUB2-3	Rectangular Plate	19,93	4,01	49,75	3,845	6,834
AII1CUB2-4	Rectangular Plate	20,06	3,96	49,82	3,142	6,216
AII1CUB2-5	Rectangular Plate	20,23	3,90	49,84	3,168	5,696
AII1CUB2-6	Rectangular Plate	20,29	3,79	49,78	2,776	4,202
AII1CUB2-7	Rectangular Plate	20,28	3,95	49,87	1,798	2,711
AII1CUB2-8	Rectangular Plate	20,38	4,45	49,81	2,214	4,653
AI2CUB3-1	Rectangular Plate	20,03	4,82	49,63	4,066	4,40
AI2CUB3-2	Rectangular Plate	20,15	4,05	49,54	4,083	9,61
AI2CUB3-3	Rectangular Plate	20,13	4,05	49,59	4,243	7,37
AI2CUB3-4	Rectangular Plate	20,17	3,99	49,62	3,129	6,68
AI2CUB3-5	Rectangular Plate	20,25	4,05	49,62	2,914	7,56
AI2CUB3-6	Rectangular Plate	20,25	4,03	49,56	3,231	4,54
AI2CUB3-7	Rectangular Plate	20,26	4,04	49,56	2,487	6,18
AI2CUB3-8	Rectangular Plate	20,28	4,00	49,39	0,831	4,19
AII2CUB4-1	Rectangular Plate	19,82	3,78	48,86	6,634	15,07
AII2CUB4-2	Rectangular Plate	20,01	4,09	48,82	4,357	7,57
AII2CUB4-3	Rectangular Plate	19,86	3,95	48,86	4,251	12,06
AII2CUB4-4	Rectangular Plate	20,05	4,09	48,83	3,192	7,18
AII2CUB4-5	Rectangular Plate	20,35	4,07	49,00	2,853	6,29
AII2CUB4-6	Rectangular Plate	20,25	4,00	48,87	2,555	7,08
AII2CUB4-7	Rectangular Plate	20,35	4,05	49,13	3,081	6,02
AII2CUB4-8	Rectangular Plate	20,33	3,98	49,05	3,415	6,29

Table 11 Properties of rectangular plates from cubes - part 1

NAME	TYPE	WIDTH [mm]	THICKNESS [mm]	LENGTH [mm]	FLEXURAL STRENGHT [MPa]	YOUNG MODULUS [MPa]
BI1CUB3-1	Rectangular Plate	19,73	3,61	49,72	5,187	14,292
BI1CUB3-2	Rectangular Plate	19,98	3,98	49,80	5,043	12,198
BI1CUB3-3	Rectangular Plate	20,07	4,01	49,84	4,551	7,252
BI1CUB3-4	Rectangular Plate	20,25	3,99	49,91	3,490	11,272
BI1CUB3-5	Rectangular Plate	20,30	3,94	49,91	3,684	7,393
BI1CUB3-6	Rectangular Plate	20,34	4,00	49,85	4,160	8,667
BI1CUB3-7	Rectangular Plate	20,42	4,43	49,83	3,005	4,468
BI1CUB3-8	Rectangular Plate	20,34	4,38	49,79	2,605	2,742
BI2CUB1-1	Rectangular Plate	19,96	5,70	50,61	3,622	9,993
BI2CUB1-2	Rectangular Plate	20,07	4,04	50,78	2,297	9,422
BI2CUB1-3	Rectangular Plate	20,13	4,05	50,89	2,615	8,474
BI2CUB1-4	Rectangular Plate	20,08	4,08	50,88	2,152	10,224
BI2CUB1-5	Rectangular Plate	20,16	3,87	50,86	0,160	0,675
BI2CUB1-6	Rectangular Plate	20,12	4,01	50,77	1,965	4,037
BI2CUB1-7	Rectangular Plate	20,05	4,06	50,58	2,720	7,913
BI2CUB1-8	Rectangular Plate	19,84	4,10	50,34	2,747	7,440
CI1CUB4-1	Rectangular Plate	19,96	4,13	49,81	6,959	16,601
CI1CUB4-2	Rectangular Plate	20,04	4,07	49,80	6,154	14,063
CI1CUB4-3	Rectangular Plate	20,11	4,08	49,87	6,894	14,691
CI1CUB4-4	Rectangular Plate	20,20	4,08	50,02	7,664	10,113
CI1CUB4-5	Rectangular Plate	20,20	4,05	50,10	3,037	7,554
CI1CUB4-6	Rectangular Plate	20,27	4,01	50,22	2,785	7,399
CI1CUB4-7	Rectangular Plate	20,30	4,03	50,35	3,162	7,161
CI1CUB4-8	Rectangular Plate	20,43	3,94	50,39	2,646	4,001
CI2CUB2-1	Rectangular Plate	20,10	5,38	50,56	7,317	17,732
CI2CUB2-2	Rectangular Plate	20,20	4,06	50,52	6,528	16,147
CI2CUB2-3	Rectangular Plate	20,28	4,11	50,53	4,561	8,119
CI2CUB2-4	Rectangular Plate	20,28	4,03	50,48	4,043	6,413
CI2CUB2-5	Rectangular Plate	20,34	3,93	50,46	3,014	5,904
CI2CUB2-6	Rectangular Plate	20,44	3,89	50,41	3,079	4,050
CI2CUB2-7	Rectangular Plate	20,43	4,05	50,32	2,975	4,550
CI2CUB2-8	Rectangular Plate	20,43	4,11	50,27	2,817	6,314

Table 12 Properties of rectangular plates from cubes - part 2

7.4 CIRCULAR PLATES FROM CYLINDERS

NAME	TYPE	DIAMETER [mm]	THICKNESS [mm]	FLEXURAL STRENGHT [MPa]	YOUNG MODULUS [MPa]
AI1CYL4-1	Circular Plate	53,99	4,49	7,106	21,763
AI1CYL4-2	Circular Plate	54,03	4,50	5,723	12,348
AI1CYL4-3	Circular Plate	54,05	4,34	5,771	10,435
AI1CYL4-4	Circular Plate	54,02	4,46	5,032	14,117
AI1CYL4-5	Circular Plate	53,99	4,36	4,035	8,791
AI1CYL4-6	Circular Plate	53,70	4,52	4,720	7,570

Table 13 Properties of circular plates from cylinders - part 1

NAME	TYPE	DIAMETER	THICKNESS	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[MPa]	[MPa]
AI2CYL1-1	Circular Plate	54,22	4,28	5,549	12,533
AI2CYL1-2	Circular Plate	54,27	4,44	4,570	11,808
AI2CYL1-3	Circular Plate	54,17	4,51	6,253	11,808
AI2CYL1-4	Circular Plate	54,14	4,45	3,772	12,714
AI2CYL1-5	Circular Plate	54,15	4,44	3,744	8,278
AI2CYL1-6	Circular Plate	54,13	4,71	3,490	8,476
AII1CYL2-1	Circular Plate	53,55	4,32	4,314	12,590
AII1CYL2-2	Circular Plate	53,37	4,38	3,744	10,862
AII1CYL2-3	Circular Plate	52,99	4,32	4,818	10,676
AII1CYL2-4	Circular Plate	52,00	4,42	4,679	10,963
AII1CYL2-5	Circular Plate	51,93	4,52	4,750	10,202
AII1CYL2-6	Circular Plate	51,99	4,40	4,472	8,263
AII2CYL2-1	Circular Plate	54,09	4,29	6,600	14,486
AII2CYL2-2	Circular Plate	54,20	4,49	5,974	12,533
AII2CYL2-3	Circular Plate	54,00	4,39	9,360	11,808
AII2CYL2-4	Circular Plate	53,95	4,20	3,979	12,714
AII2CYL2-5	Circular Plate	53,85	4,51	4,224	8,278
AII2CYL2-6	Circular Plate	53,92	4,55	4,025	8,476
BI1CYL1-1	Circular Plate	53,98	4,40	6,488	13,840
BI1CYL1-2	Circular Plate	53,83	4,58	5,010	10,578
BI1CYL1-3	Circular Plate	54,06	4,52	7,929	17,121
BI1CYL1-4	Circular Plate	54,16	4,37	6,970	16,403
BI1CYL1-5	Circular Plate	54,07	4,39	6,777	13,920
BI1CYL1-6	Circular Plate	54,00	4,47	8,051	18,322
BI2CYL4-1	Circular Plate	53,19	3,96	4,406	4,406
BI2CYL4-2	Circular Plate	53,46	4,32	4,689	4,689
BI2CYL4-3	Circular Plate	53,65	4,30	5,034	5,034
BI2CYL4-4	Circular Plate	53,83	4,44	4,320	4,320
BI2CYL4-5	Circular Plate	53,63	4,37	4,217	4,217
BI2CYL4-6	Circular Plate	53,41	4,41	4,872	4,872
BII2CYL3-1	Circular Plate	53,73	4,27	4,382	16,754
BII2CYL3-2	Circular Plate	53,95	4,44	4,371	13,098
BII2CYL3-3	Circular Plate	53,99	4,50	4,500	14,235
BII2CYL3-4	Circular Plate	54,01	4,55	4,557	12,381
BII2CYL3-5	Circular Plate	53,50	4,35	4,172	9,968
BII2CYL3-6	Circular Plate	53,45	4,38	4,316	9,757
CI1CYL3-1	Circular Plate	53,95	4,45	9,599	23,386
CI1CYL3-2	Circular Plate	54,01	4,52	8,522	20,460
CI1CYL3-3	Circular Plate	54,00	4,45	10,024	21,751
CI1CYL3-4	Circular Plate	54,00	4,42	6,805	14,403
CI1CYL3-5	Circular Plate	53,92	4,38	5,940	14,799
CI1CYL3-6	Circular Plate	54,01	4,43	4,591	8,716

Table 14 Properties of circular plates from cylinders - part 2

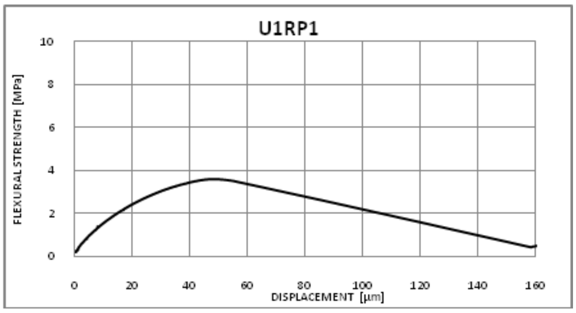
NAME	TYPE	DIAMETER	THICKNESS	FLEXURAL STRENGHT	YOUNG MODULUS
		[mm]	[mm]	[MPa]	[MPa]
CI2CYL5-1	Circular Plate	53,52	4,41	12,058	30,251
CI2CYL5-2	Circular Plate	53,69	4,47	9,166	24,233
CI2CYL5-3	Circular Plate	53,56	4,52	8,649	12,778
CI2CYL5-4	Circular Plate	53,85	4,46	5,394	12,700
CI2CYL5-5	Circular Plate	53,65	4,41	4,267	10,527
CI2CYL5-6	Circular Plate	53,65	4,49	5,146	11,029
CII2CYL6-1	Circular Plate	53,77	4,47	11,019	25,936
CII2CYL6-2	Circular Plate	53,73	4,51	12,473	24,981
CII2CYL6-3	Circular Plate	53,82	4,48	9,102	18,218
CII2CYL6-4	Circular Plate	53,99	4,45	5,895	15,185
CII2CYL6-5	Circular Plate	53,98	4,38	5,566	13,151
CII2CYL6-6	Circular Plate	53,85	4,52	4,850	9,264

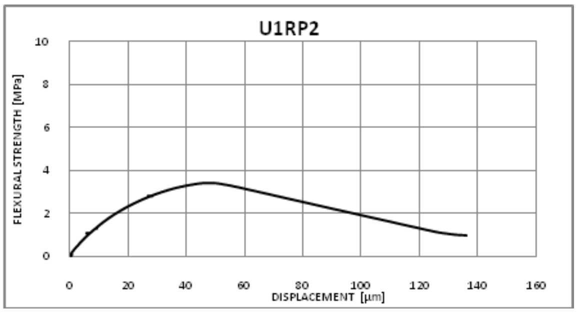
Table 15 Properties of circular plates from cylinders - part 3

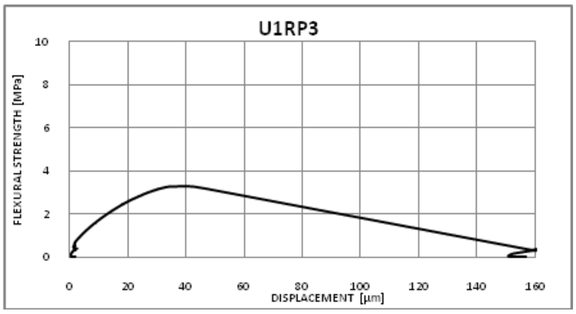
8. ANNEX B – GRAPHICS STRENGTH VS DEFORMATION

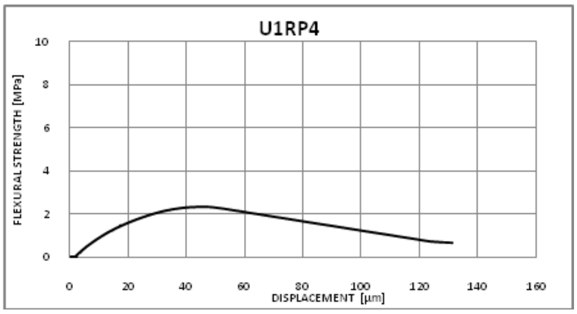
8.1 UNIDIRECIONAL BENDING TEST (THREE POINTS)

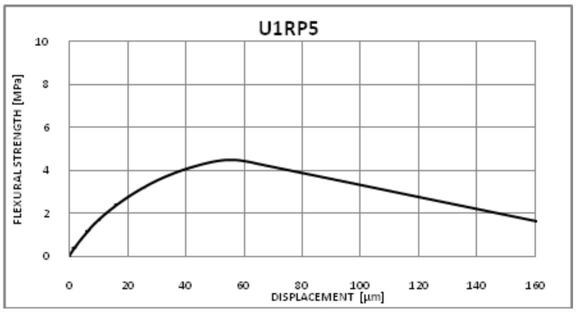
8.1.1 Untreated rectangular plates

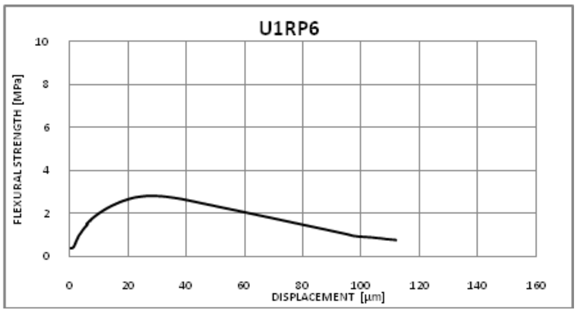


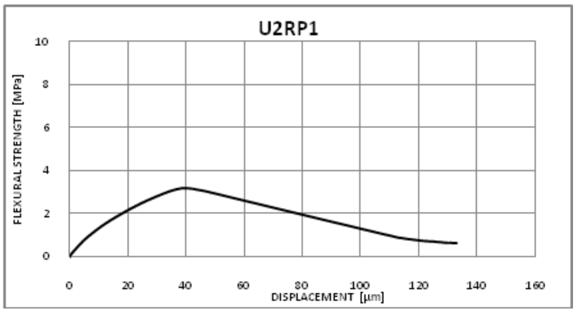


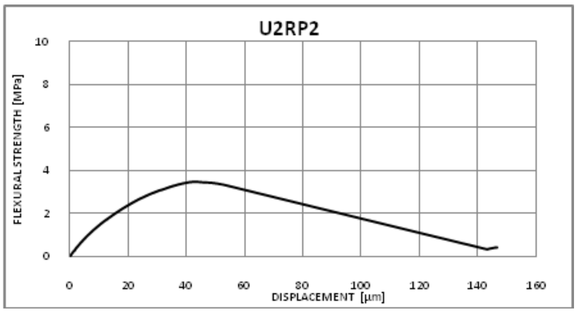












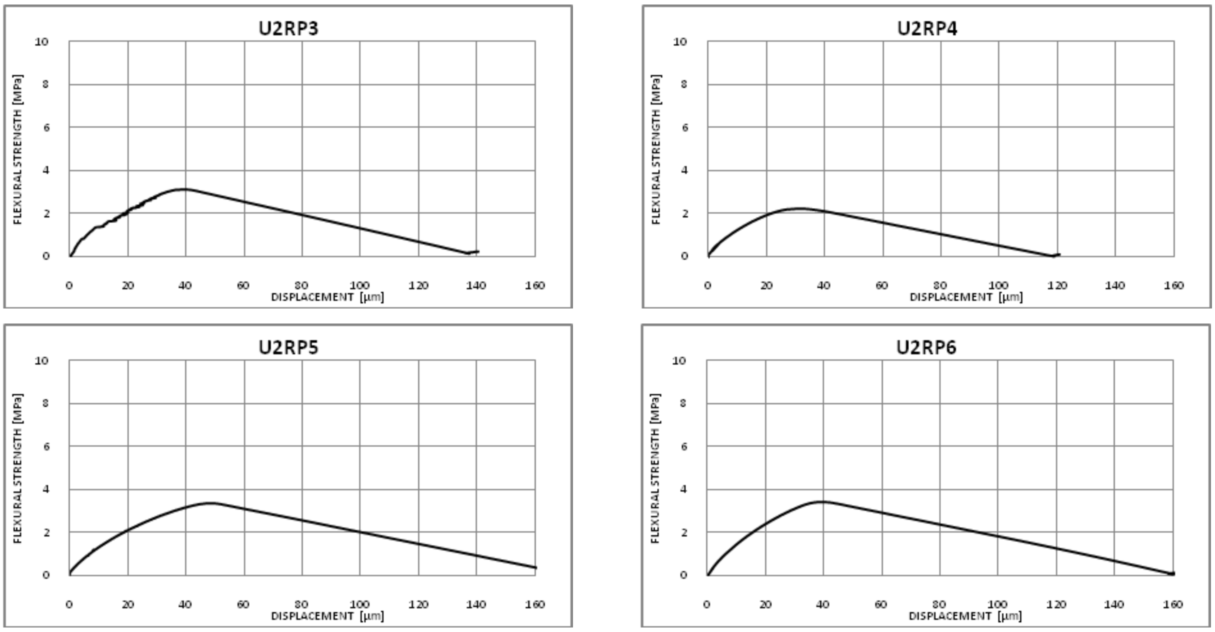
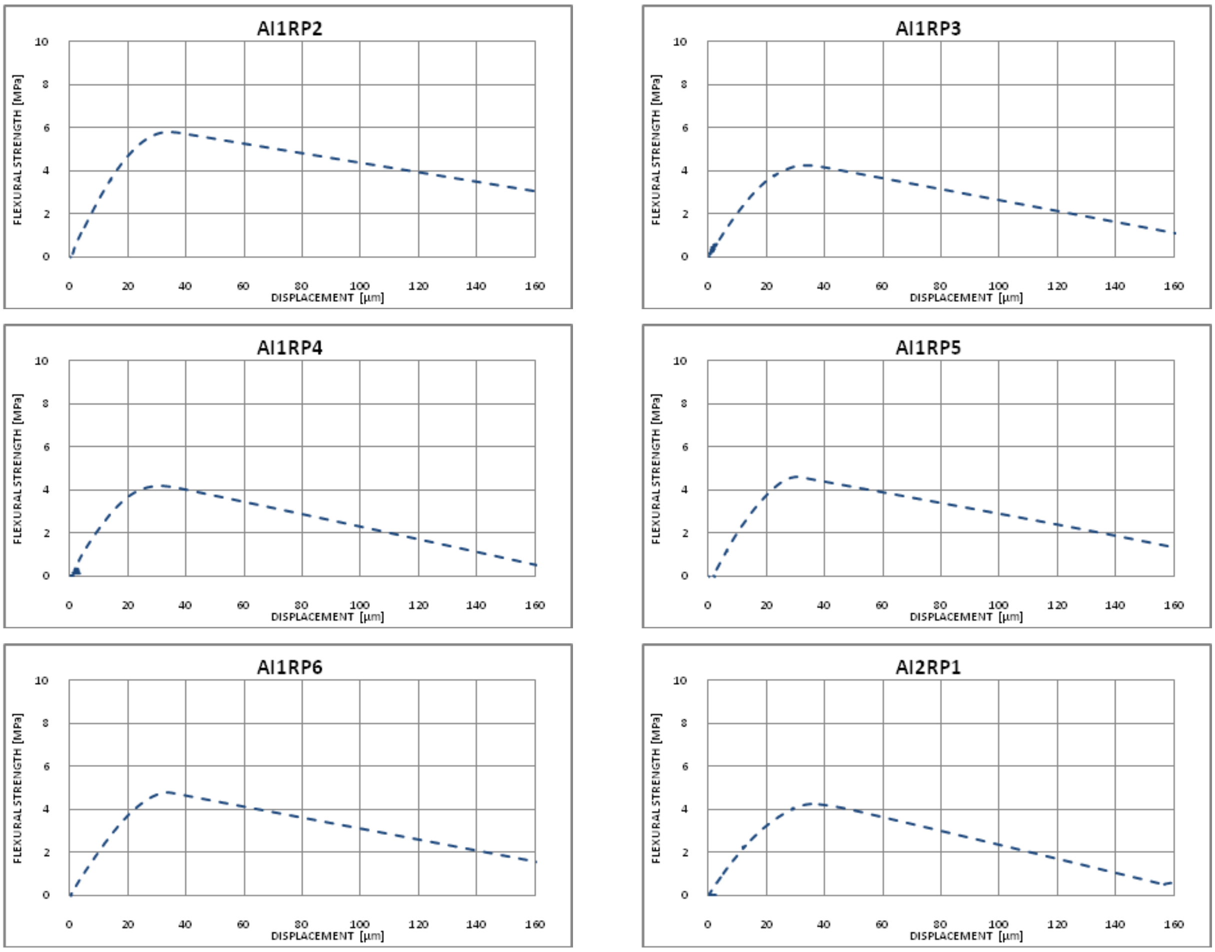


Figure 66 Strength vs deformation of untreated rectangular plates

8.1.2 Treated rectangular plates with product A



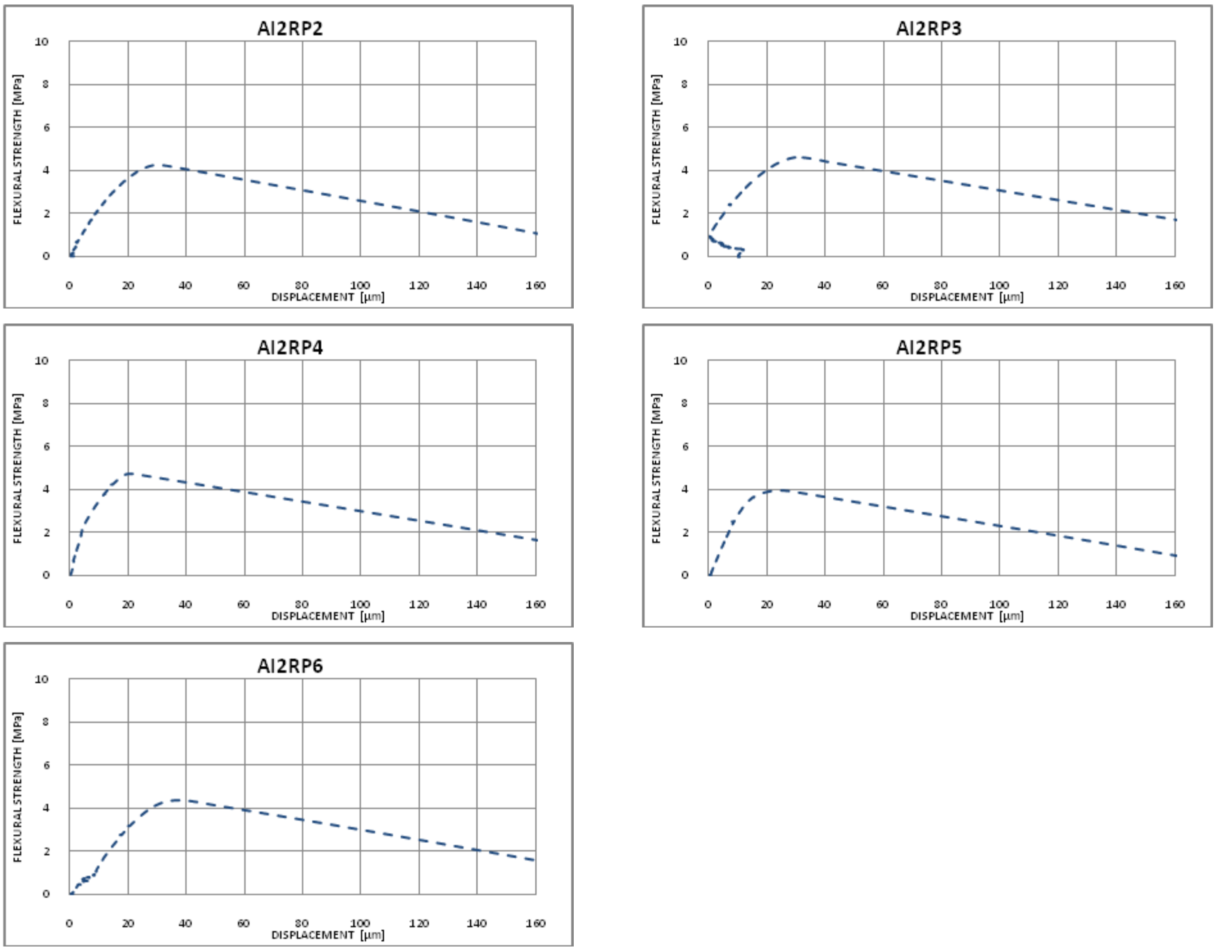
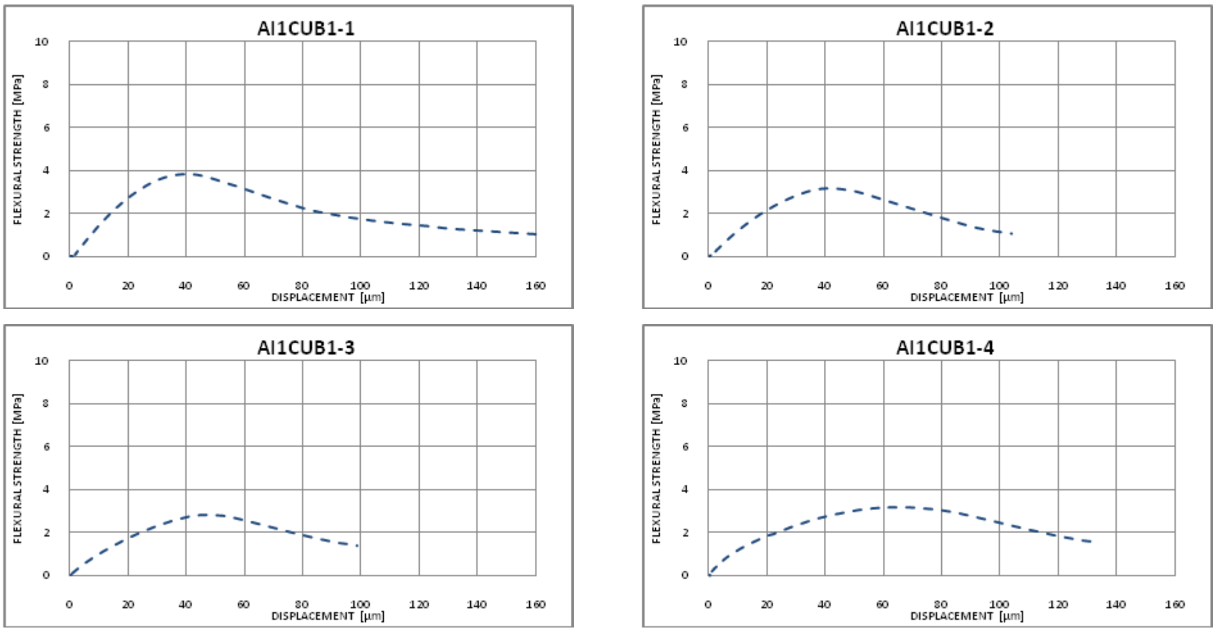
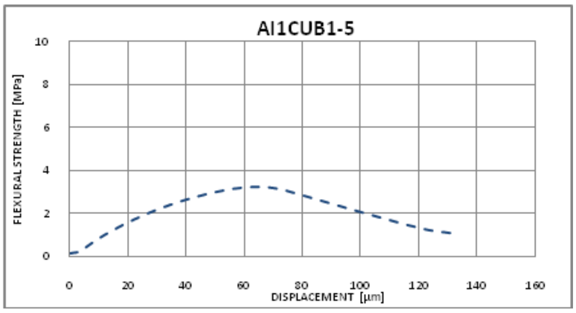
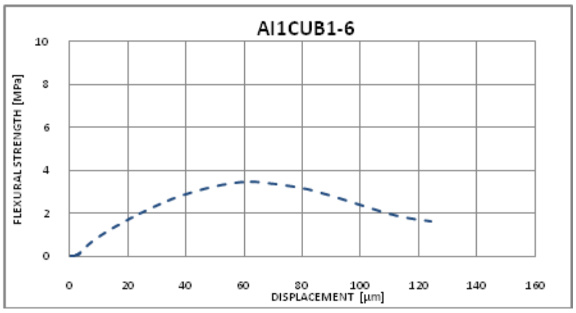


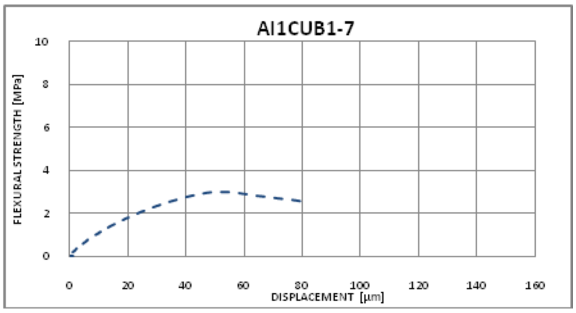
Figure 67 Strength vs deformation of treated rectangular plates with product A

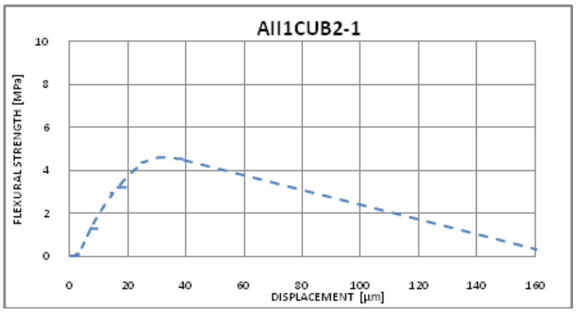
8.1.3 Treated cubes with product A

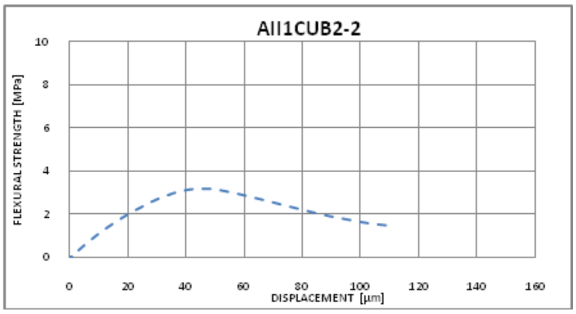


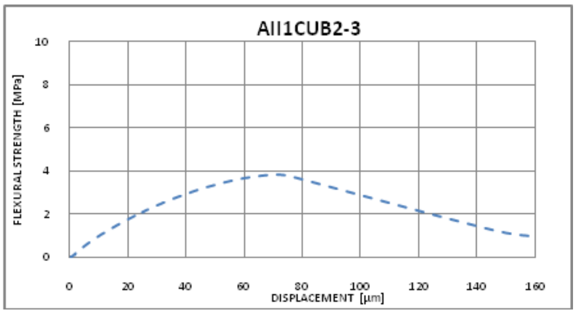

AI1CUB1-5
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]

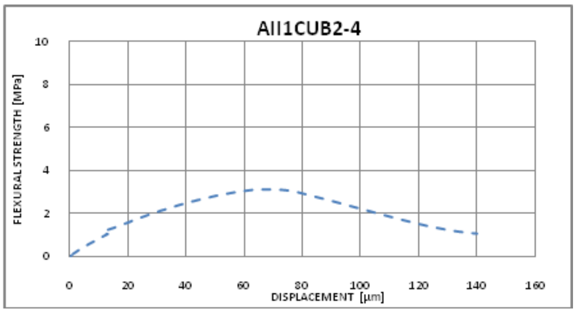

AI1CUB1-6
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]

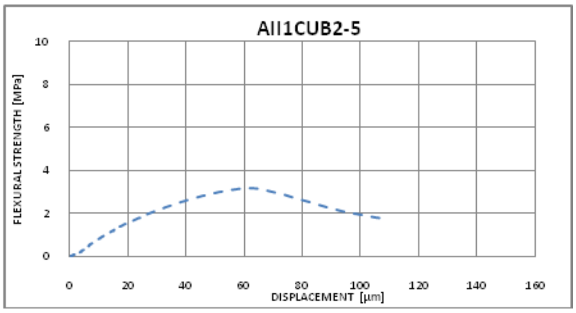

AI1CUB1-7
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-1
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-2
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-3
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-4
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-5
FLEXURAL STRENGTH [MPa]
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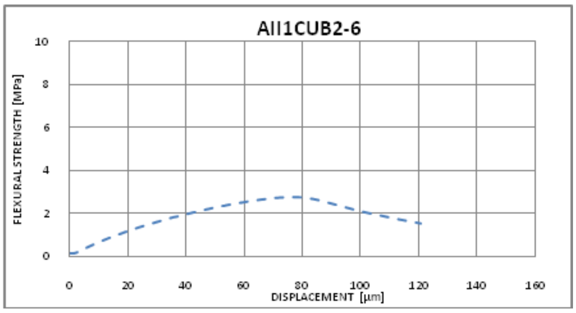
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-6
FLEXURAL STRENGTH [MPa]
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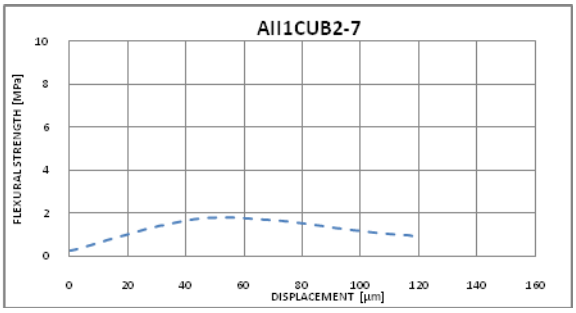
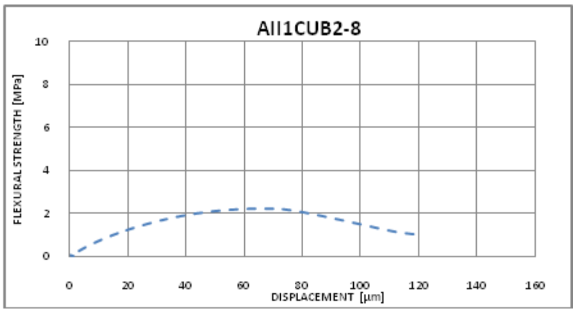
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-7
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [μm]


AII1CUB2-8
FLEXURAL STRENGTH [MPa]
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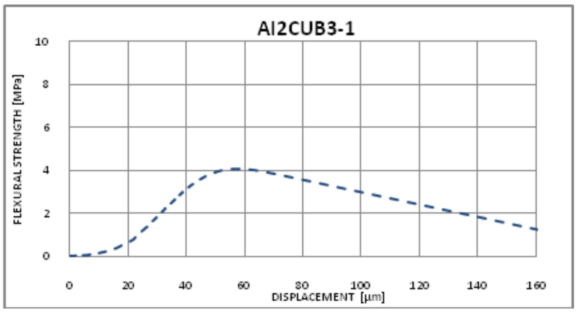
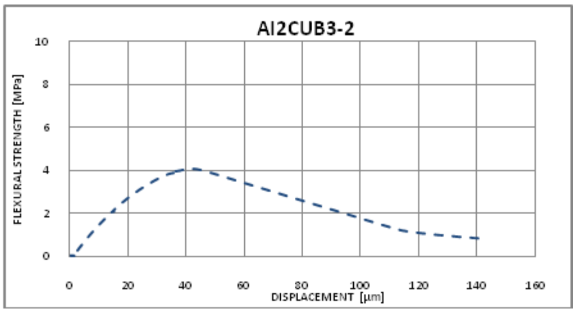
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-1
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-2
FLEXURAL STRENGTH [MPa]
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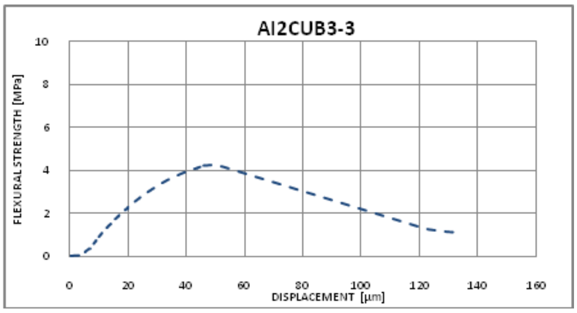
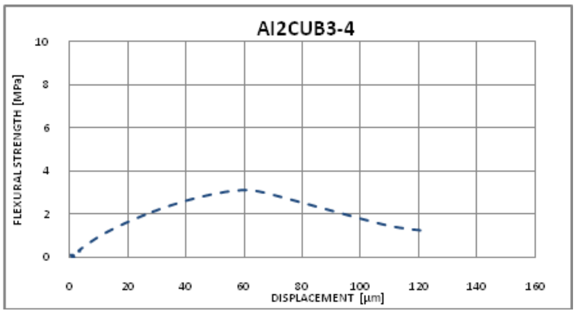
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-3
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-4
FLEXURAL STRENGTH [MPa]
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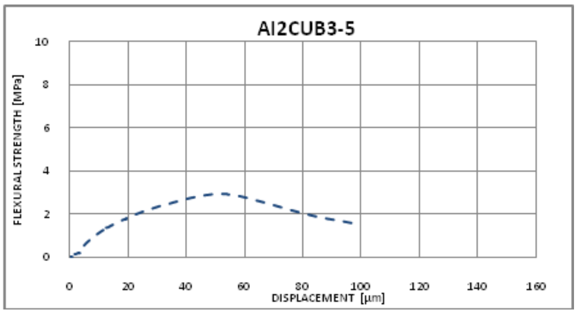
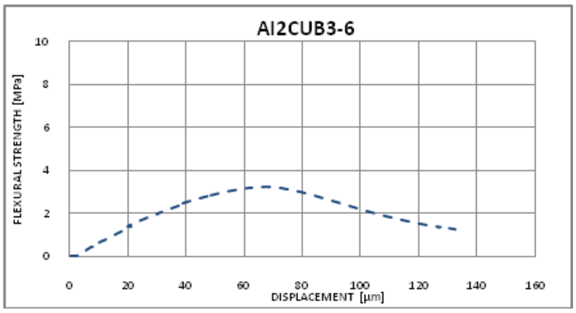
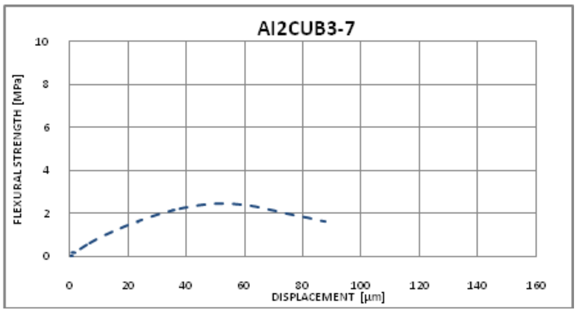
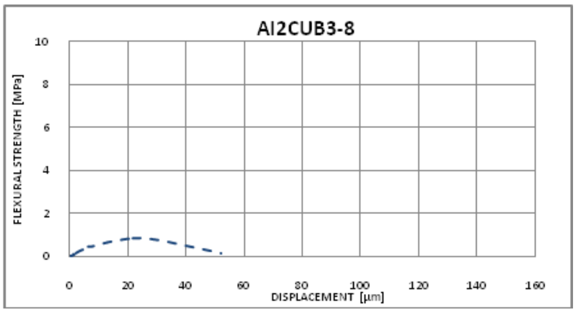
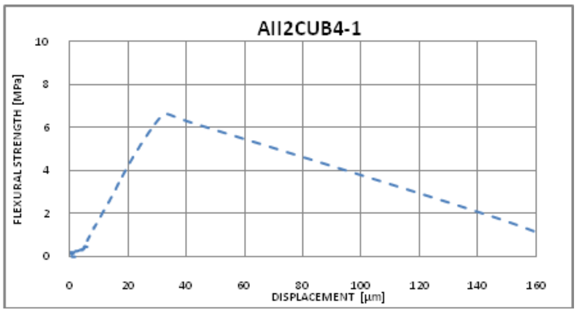
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-5
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-6
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-7
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AI2CUB3-8
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]


AII2CUB4-1
FLEXURAL STRENGTH [MPa]
0 2 4 6 8 10
0 20 40 60 80 100 120 140 160
DISPLACEMENT [µm]

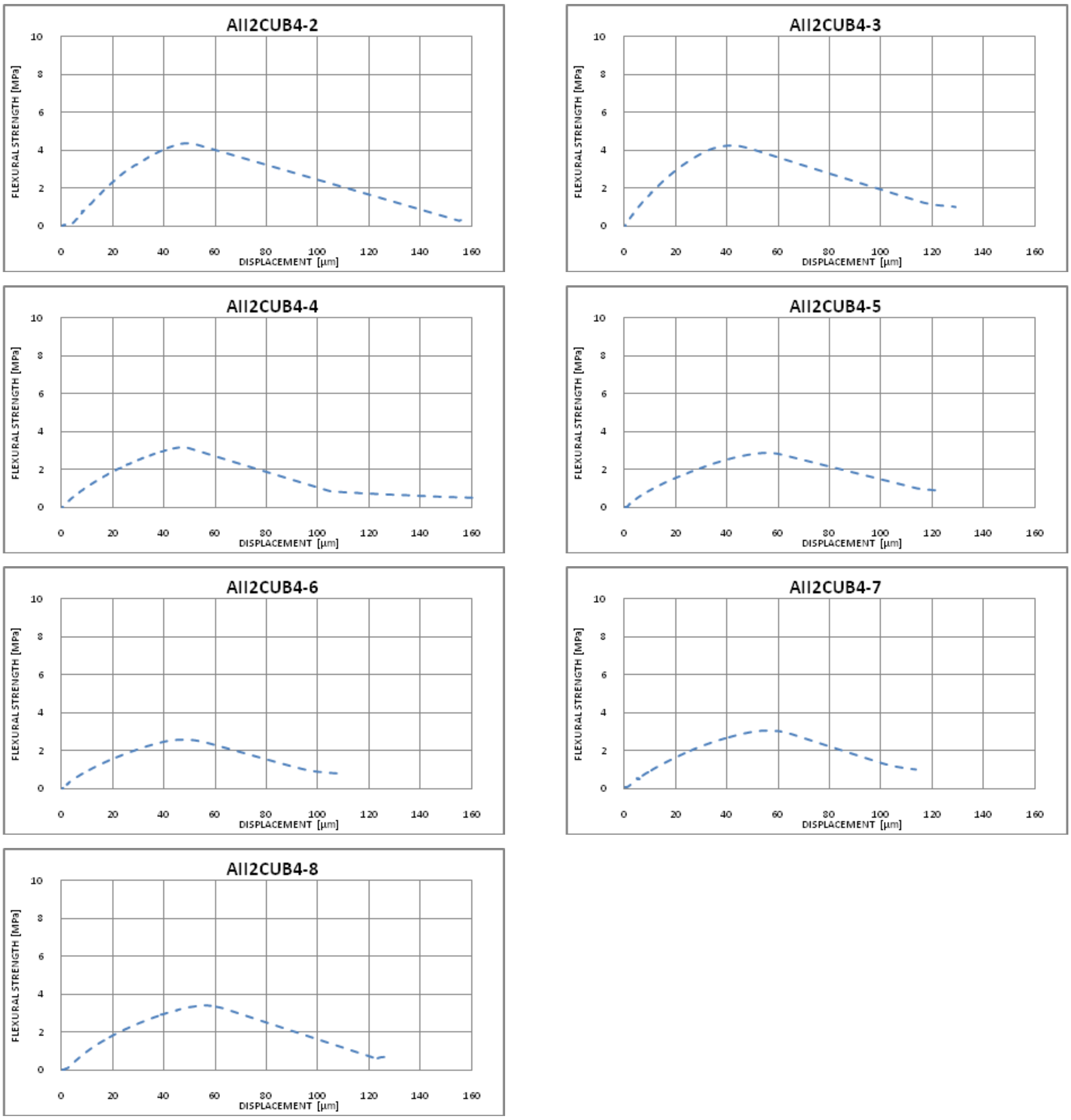
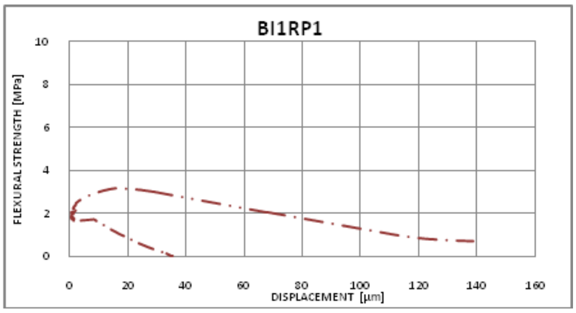
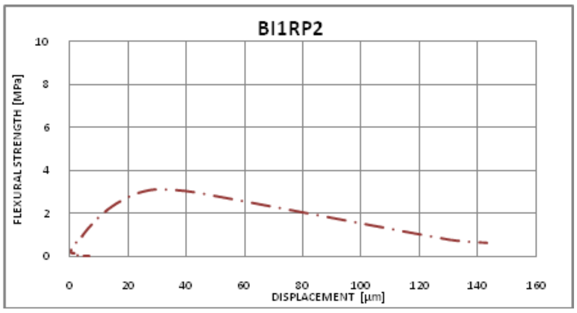
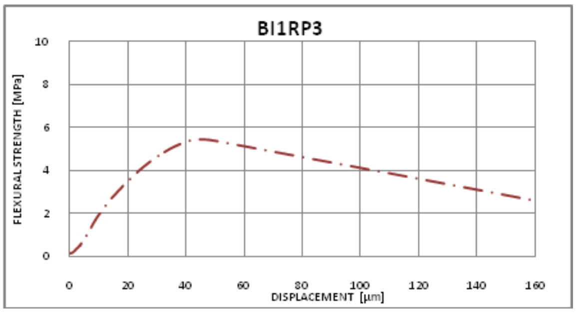


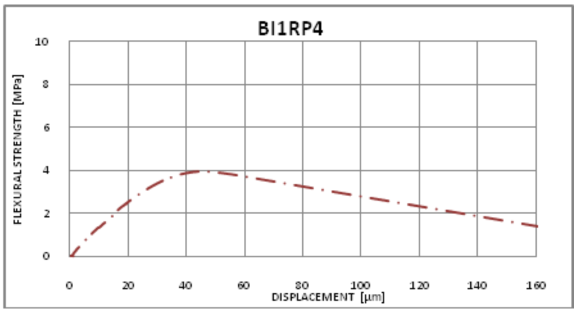
Figure 68 Strength vs deformation of plates extracted from treated cubes with Product A

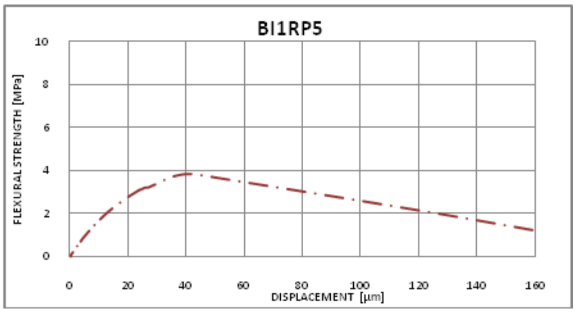
8.1.4 Treated rectangular plates with product B

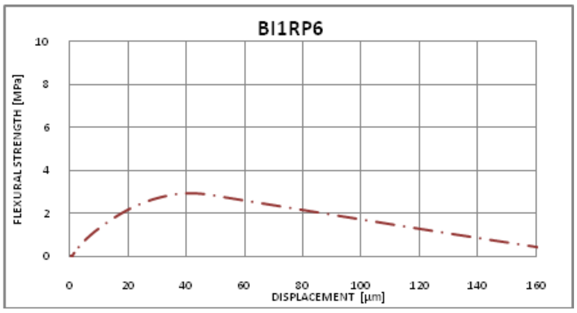


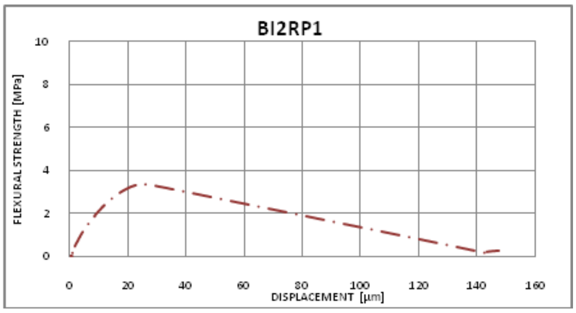


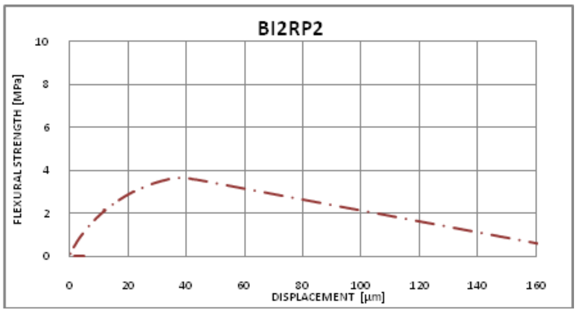


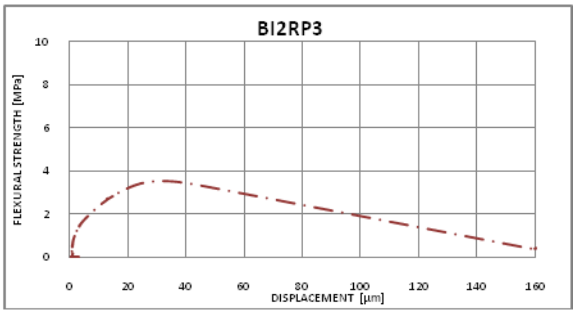


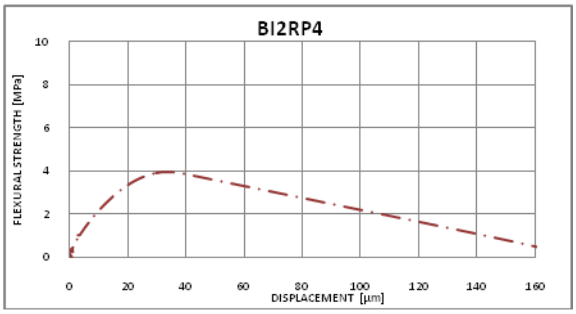












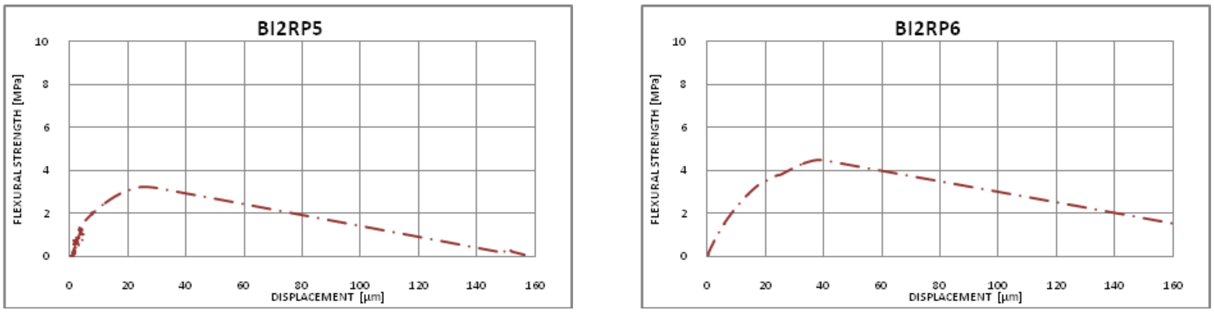
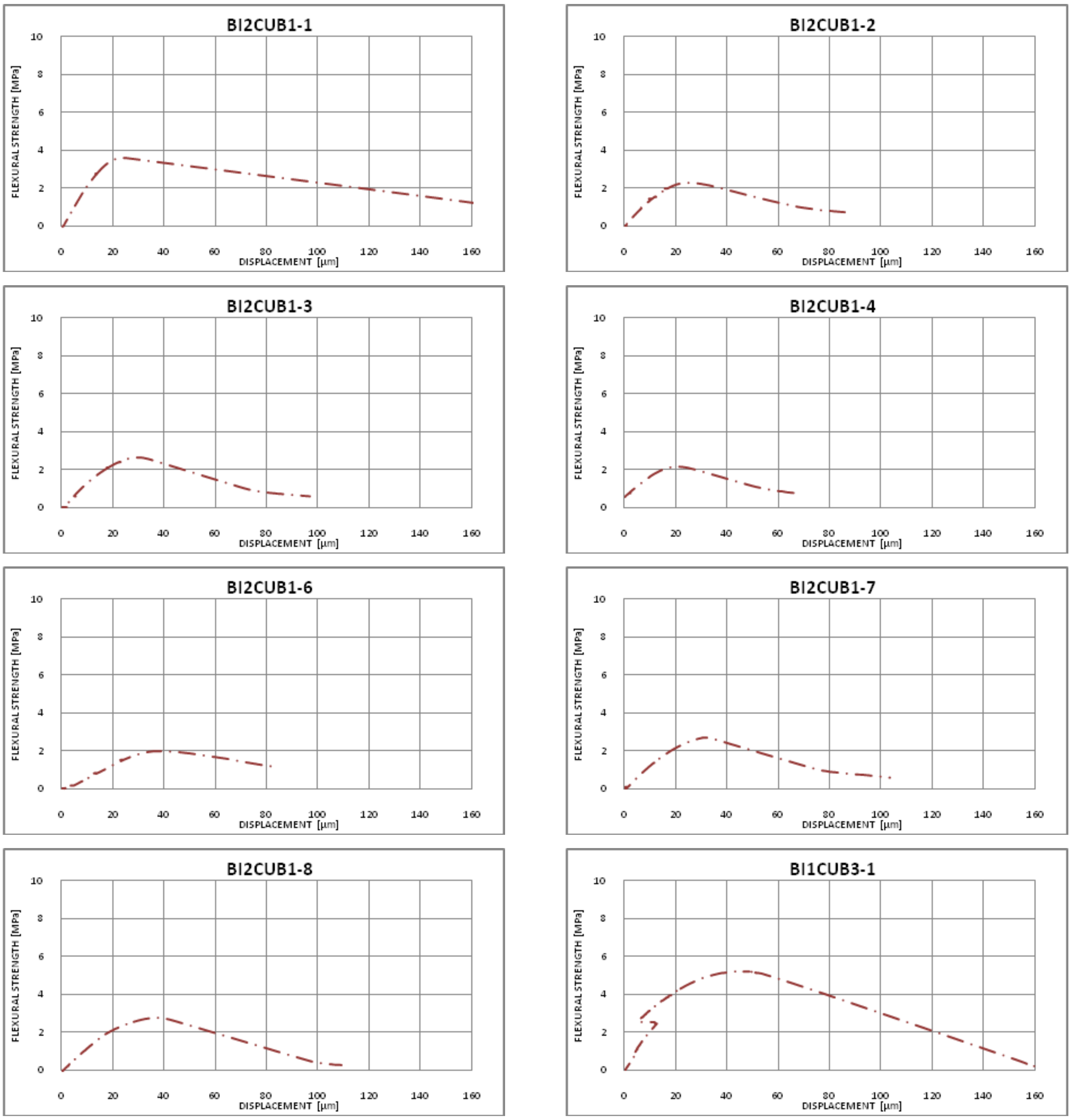


Figure 69 Strength vs deformation of treated rectangular plates with product B

8.1.5 Treated cubes with product B



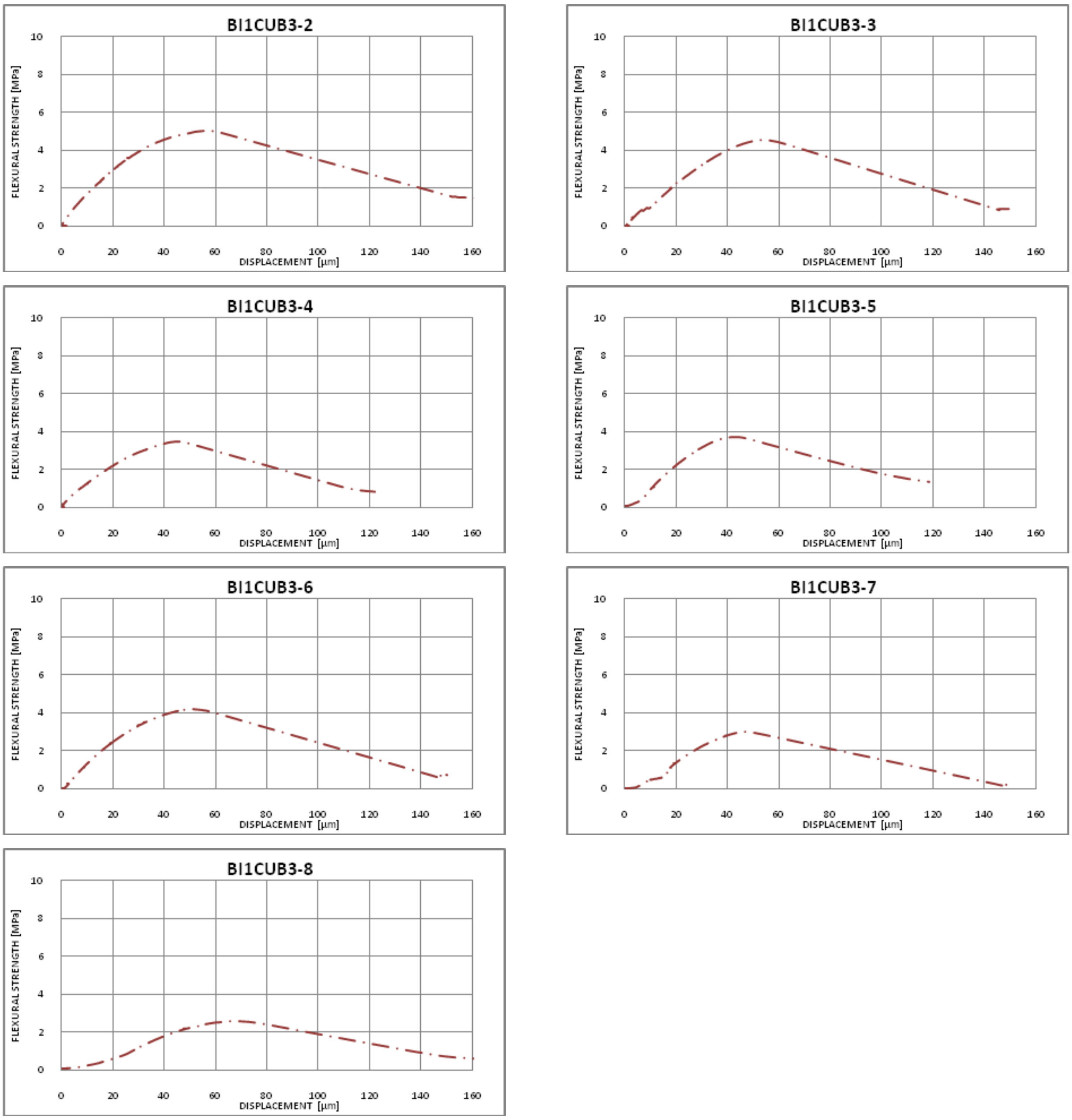
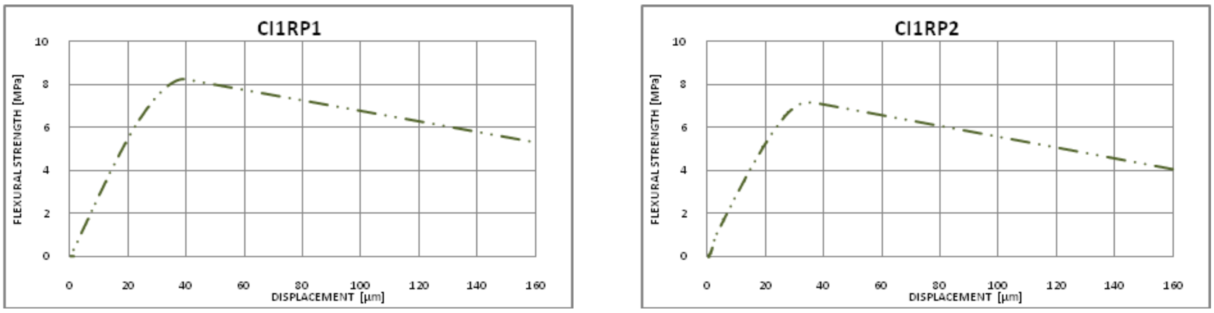


Figure 70 Strength vs deformation of plates extracted from treated cubes with product B

8.1.6 Treated rectangular plates with product C



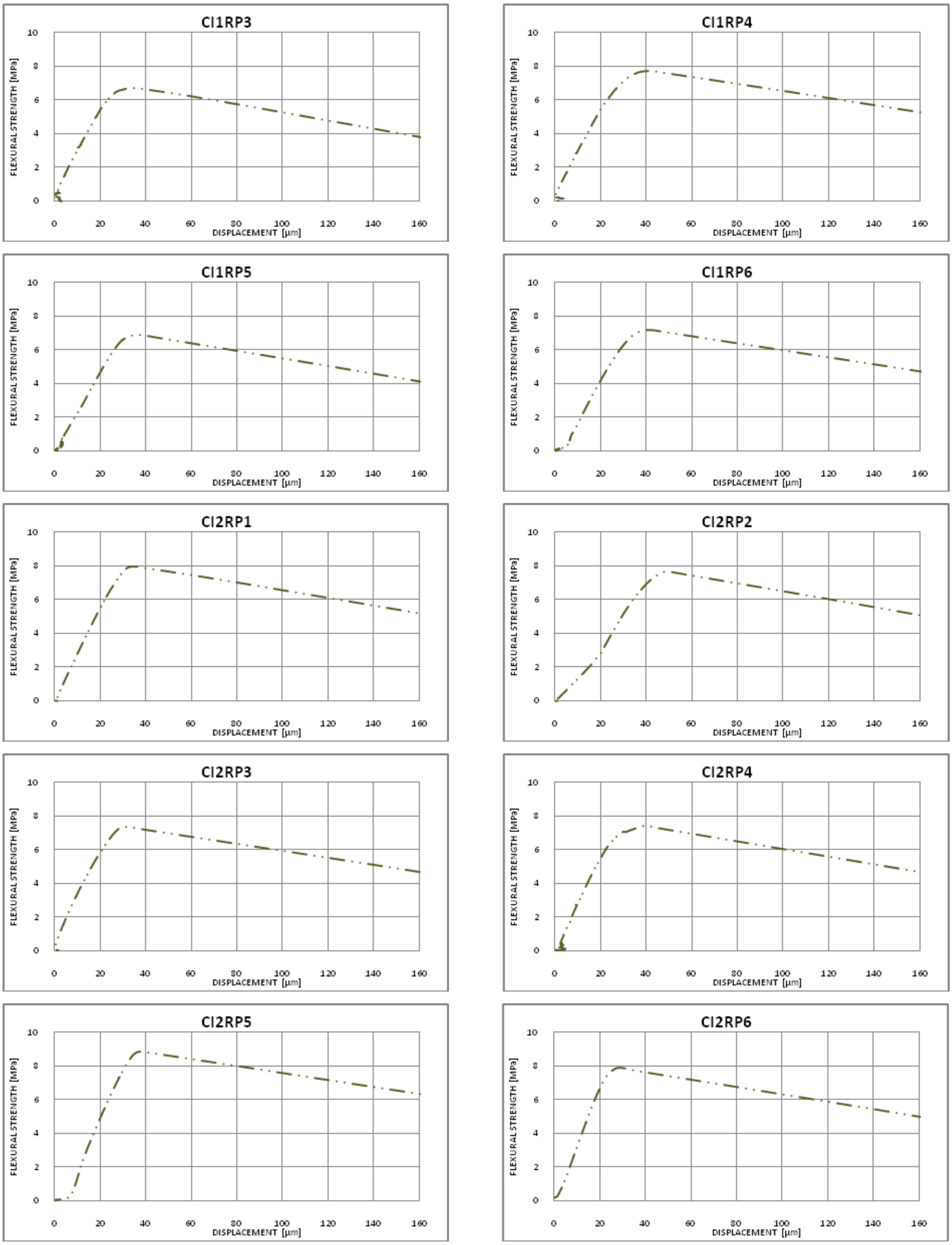
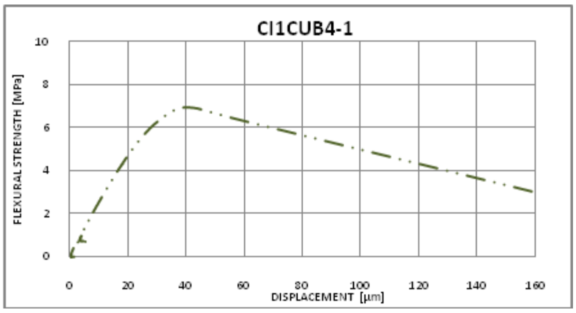
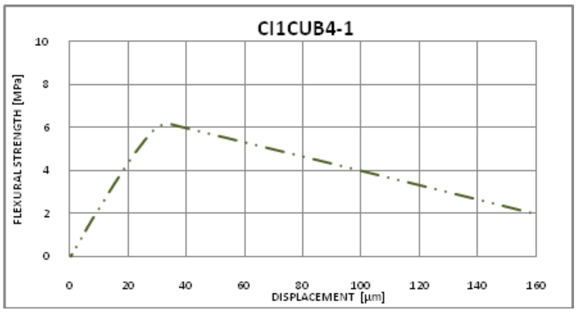
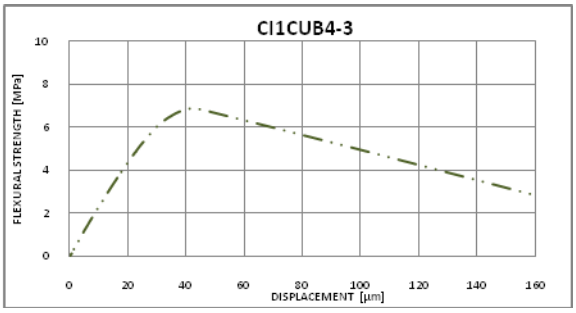


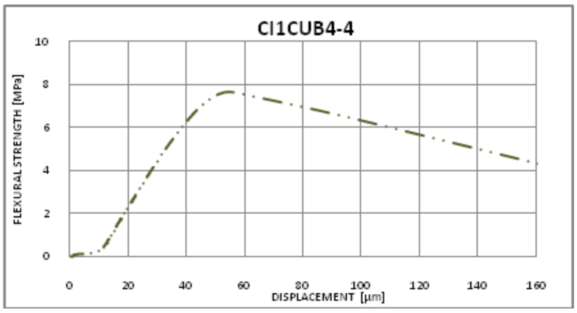
Figure 71 Strength vs deformation of treated rectangular plates with product C

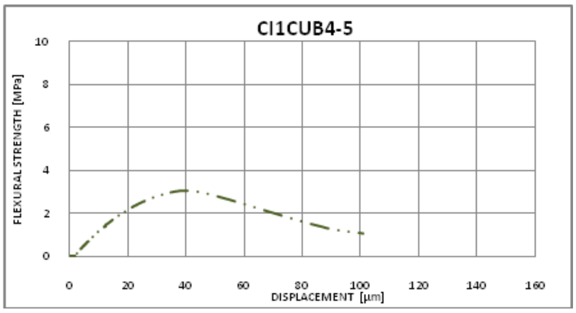
8.1.7 Treated cubes with product C

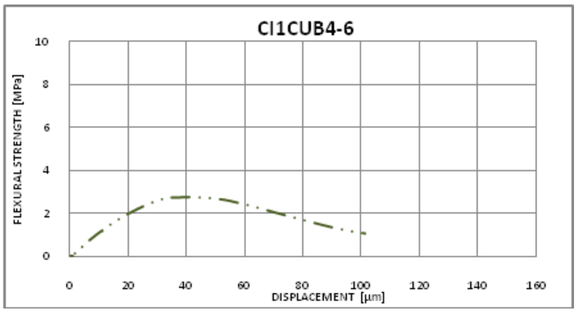


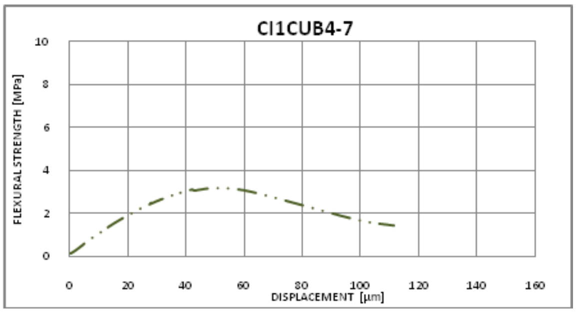


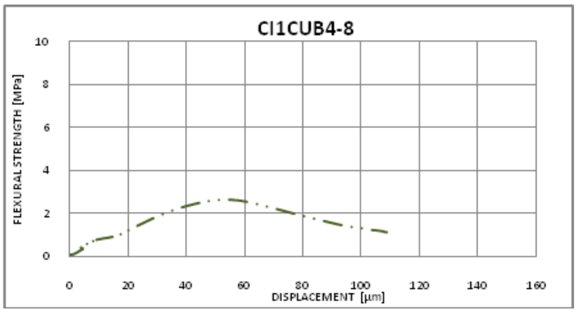


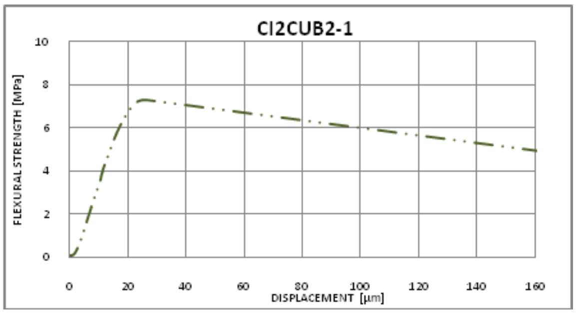


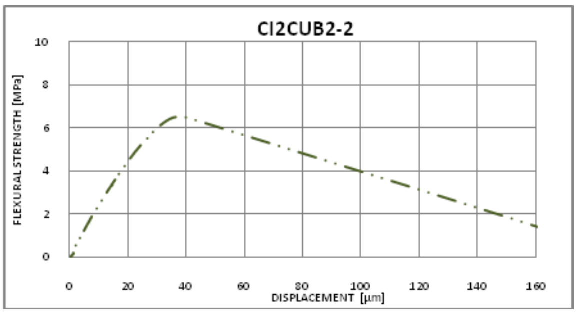












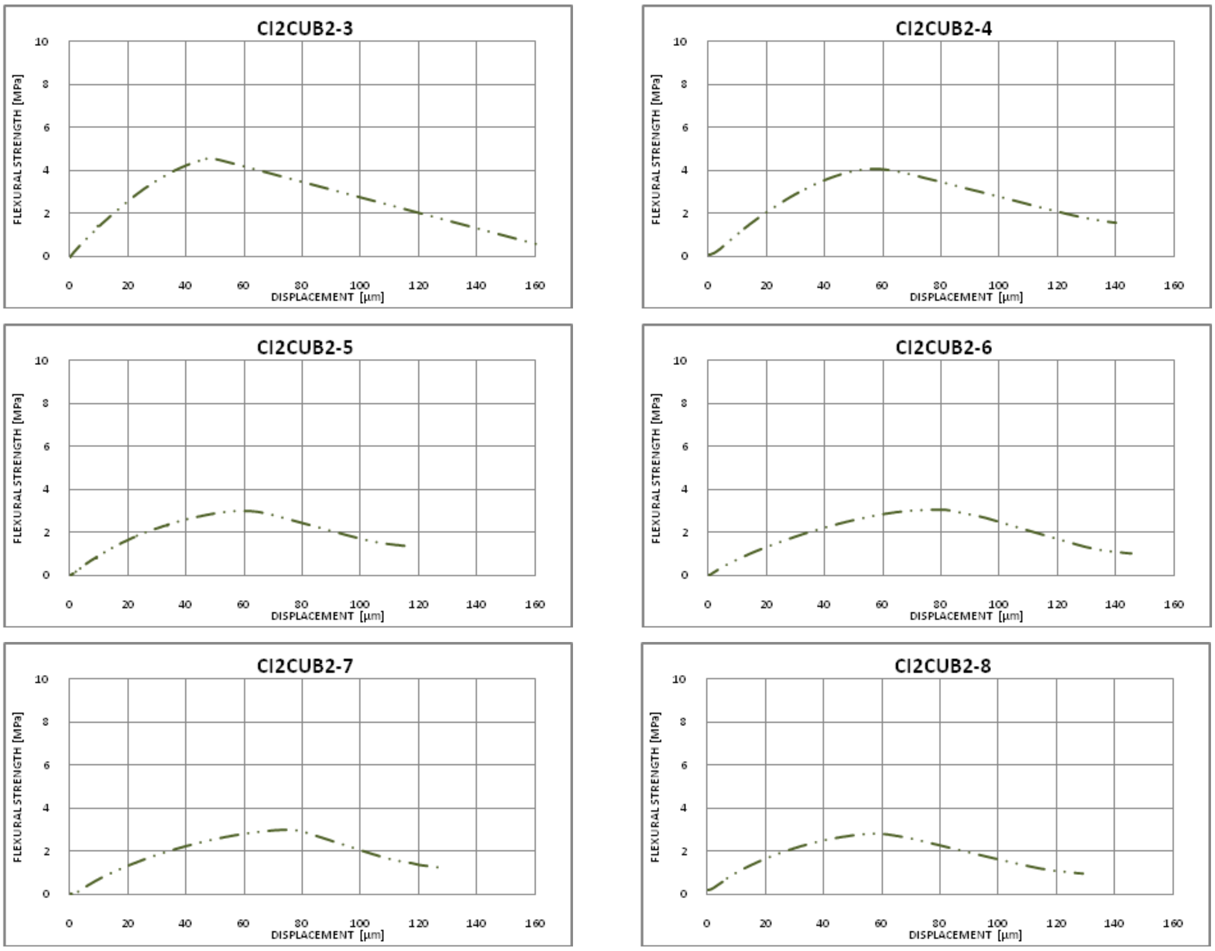
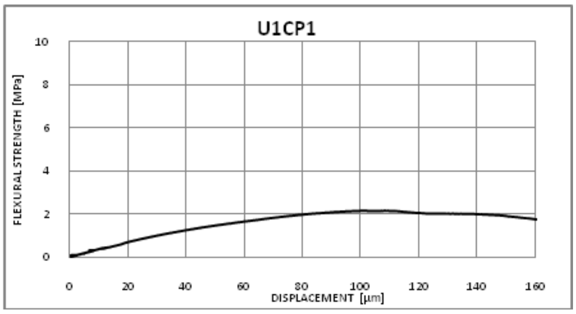
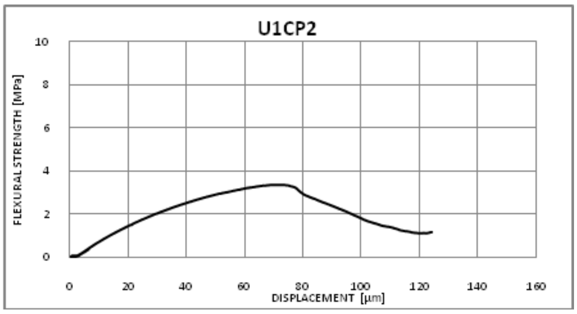


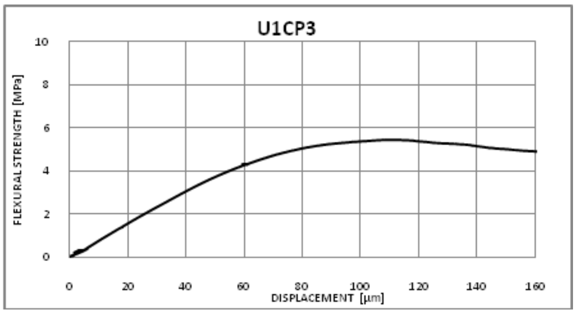
Figure 72 Strength vs deformation of plates extracted from treated cubes with product C

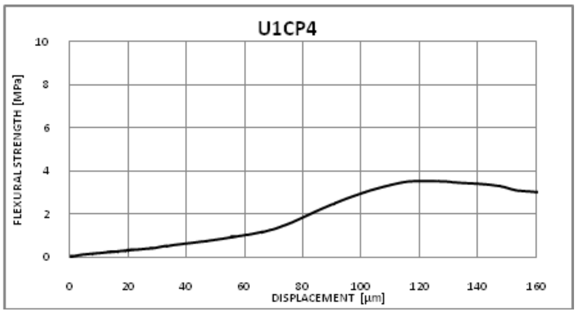
8.2 BIDIRECIONAL BENDING TEST (RING - RING)

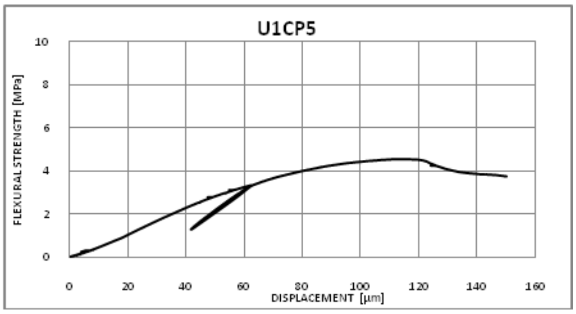
8.2.1 Untreated circular plates

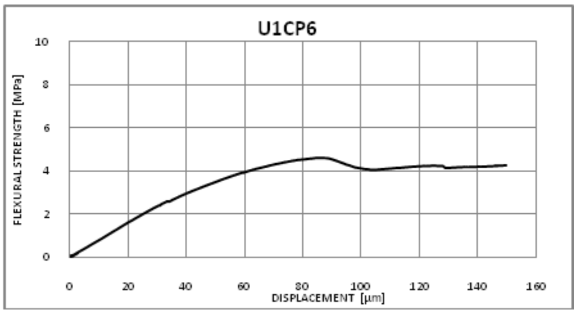


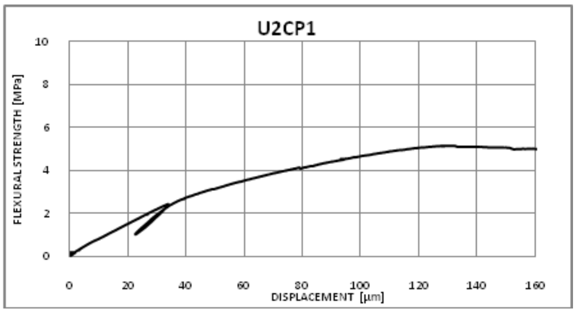


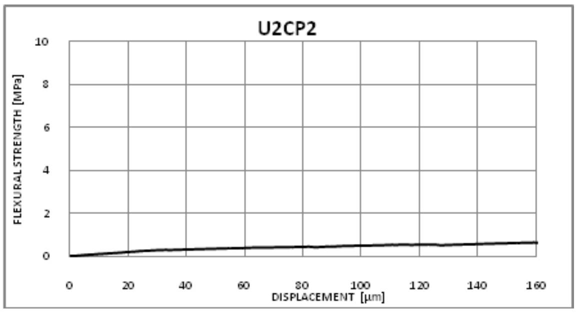












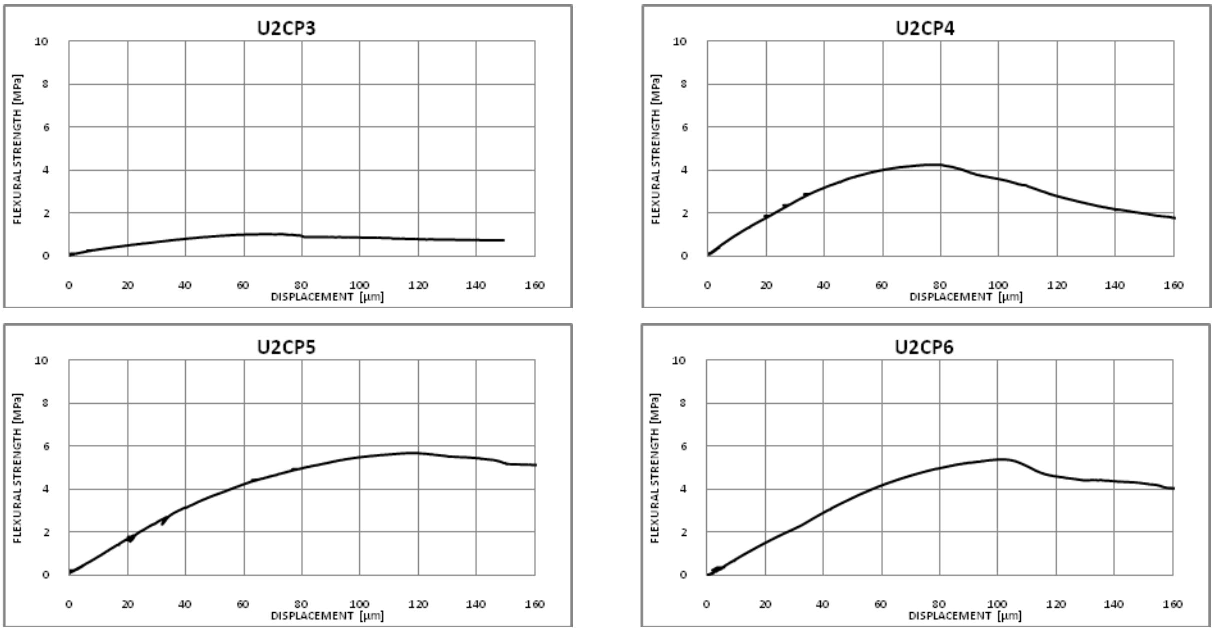
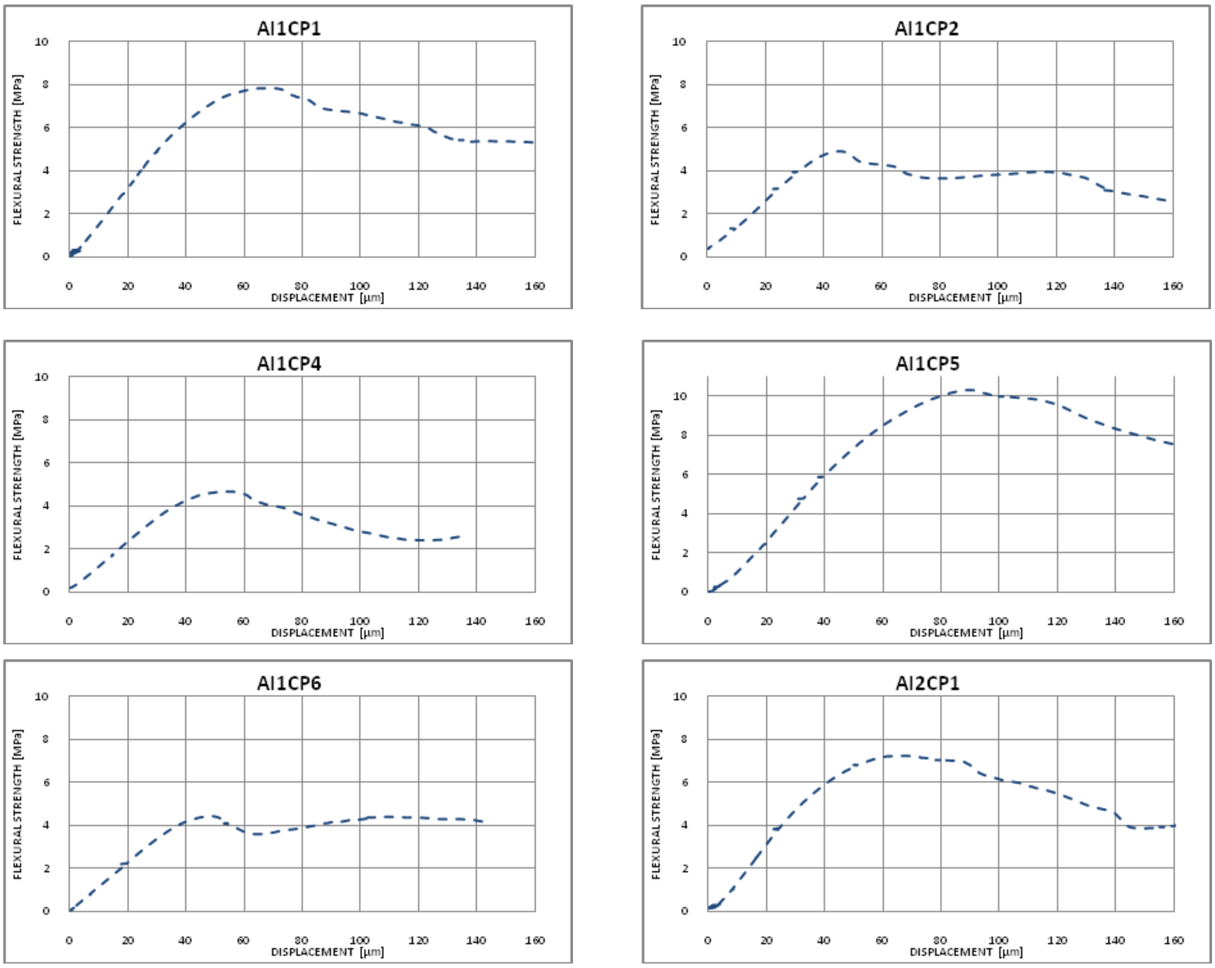


Figure 73 Strength vs deformation of untreated circular plates

8.2.2 Treated circular plates with product A



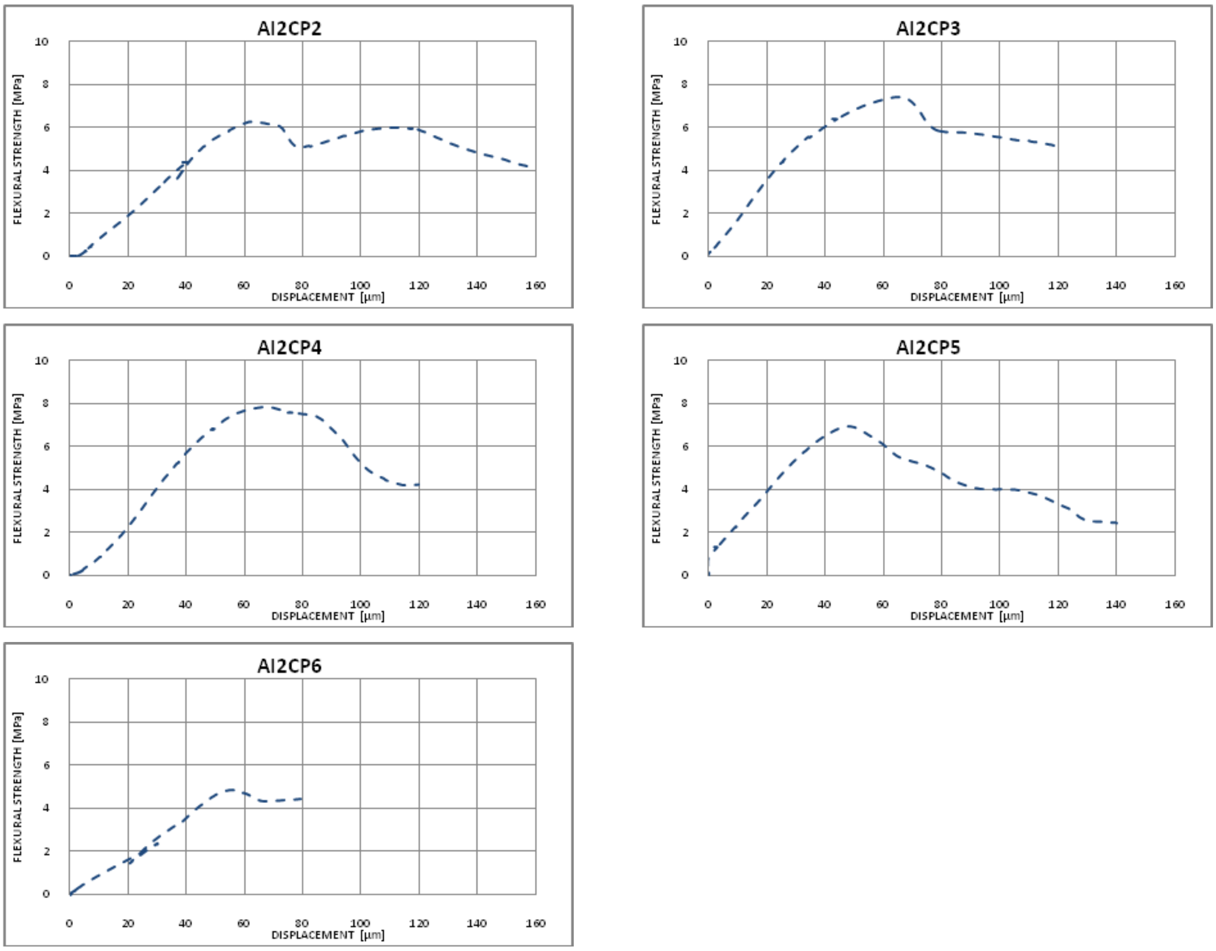
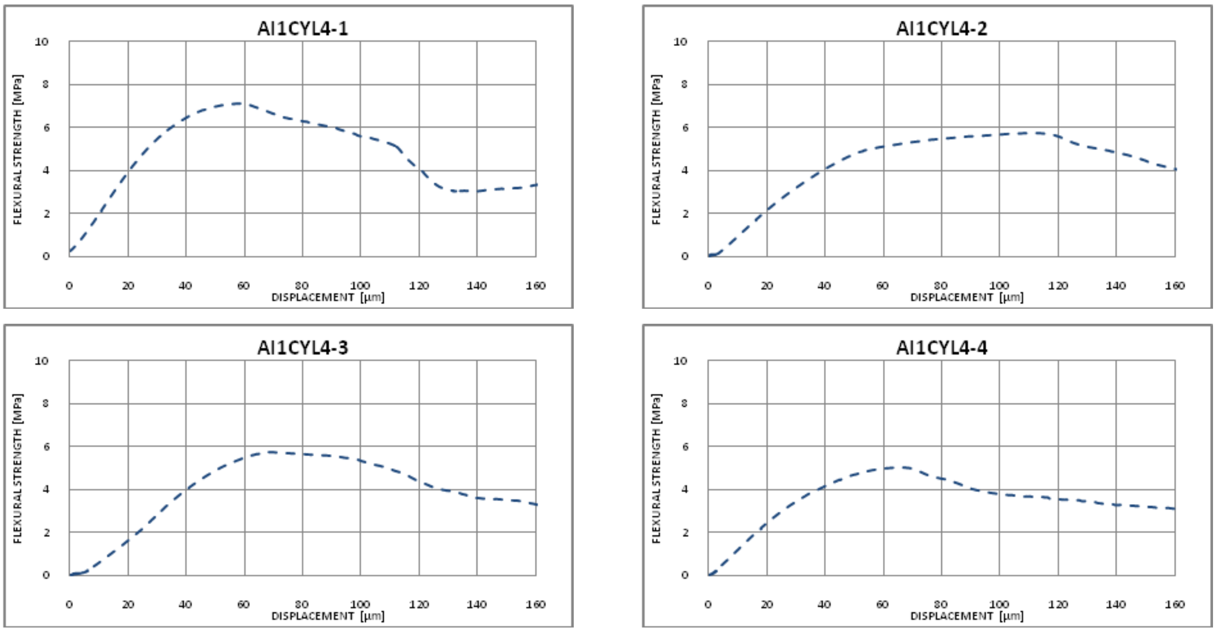
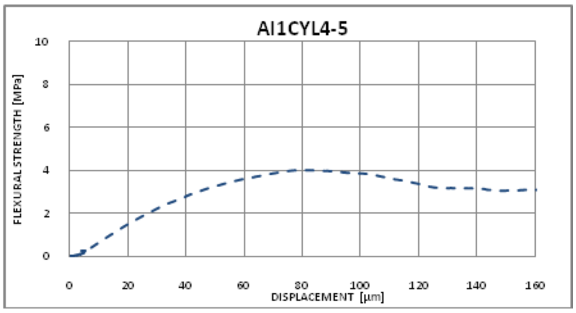
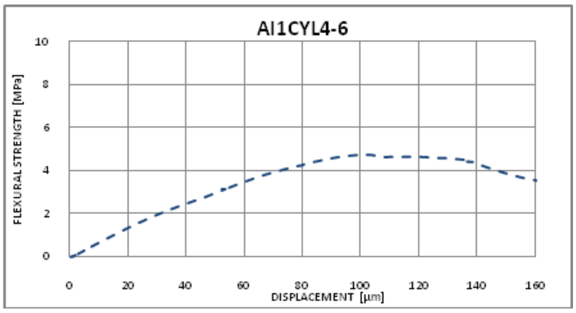


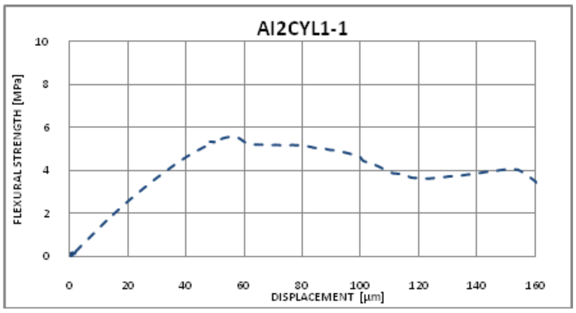
Figure 74 Strength vs deformation of treated circular plates with product A

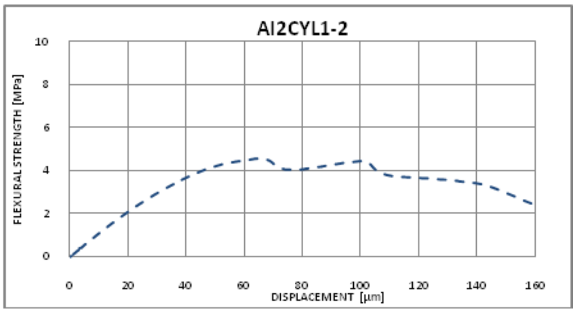
8.2.3 Treated cylinders with product A

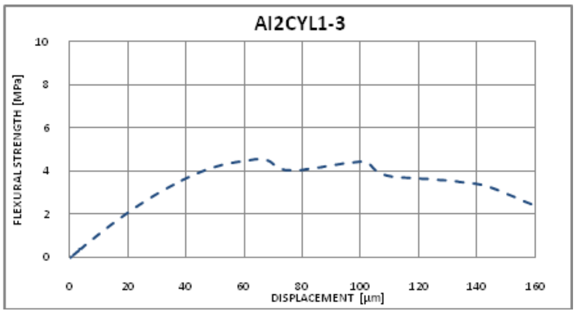


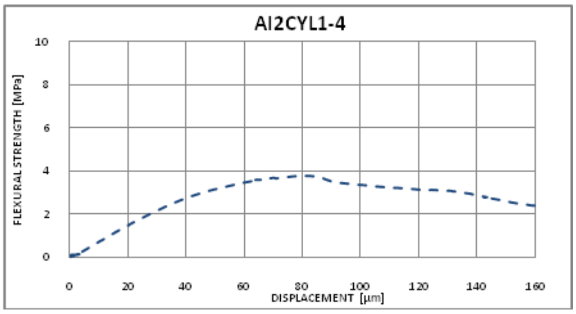

AI1CYL4-5
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

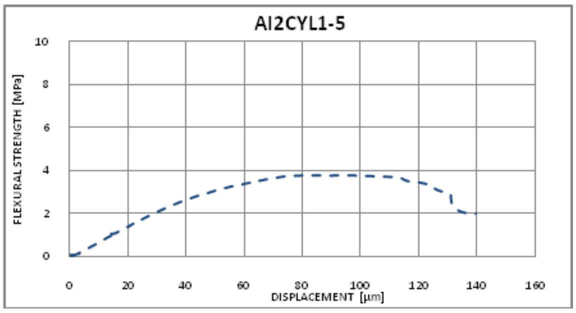

AI1CYL4-6
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

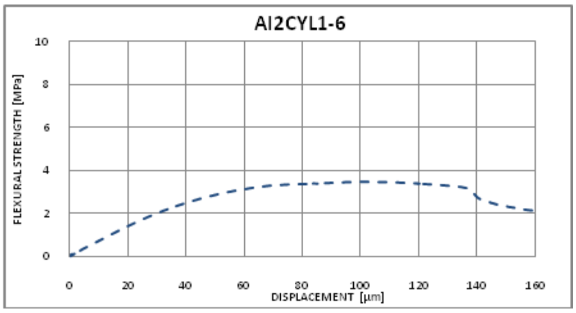

AI2CYL1-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

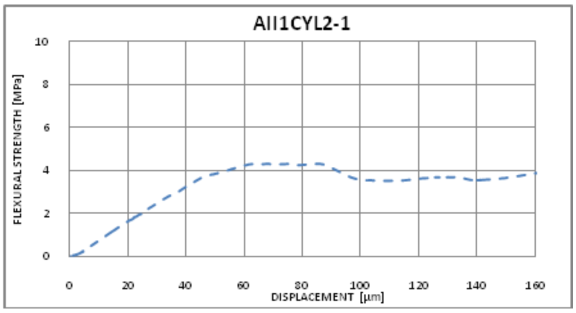

AI2CYL1-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

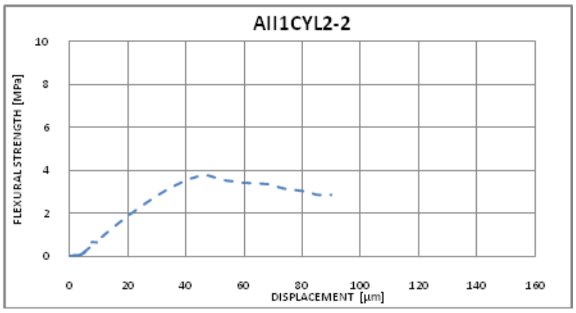

AI2CYL1-3
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


AI2CYL1-4
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


AI2CYL1-5
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


AI2CYL1-6
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


AII1CYL2-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


AII1CYL2-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

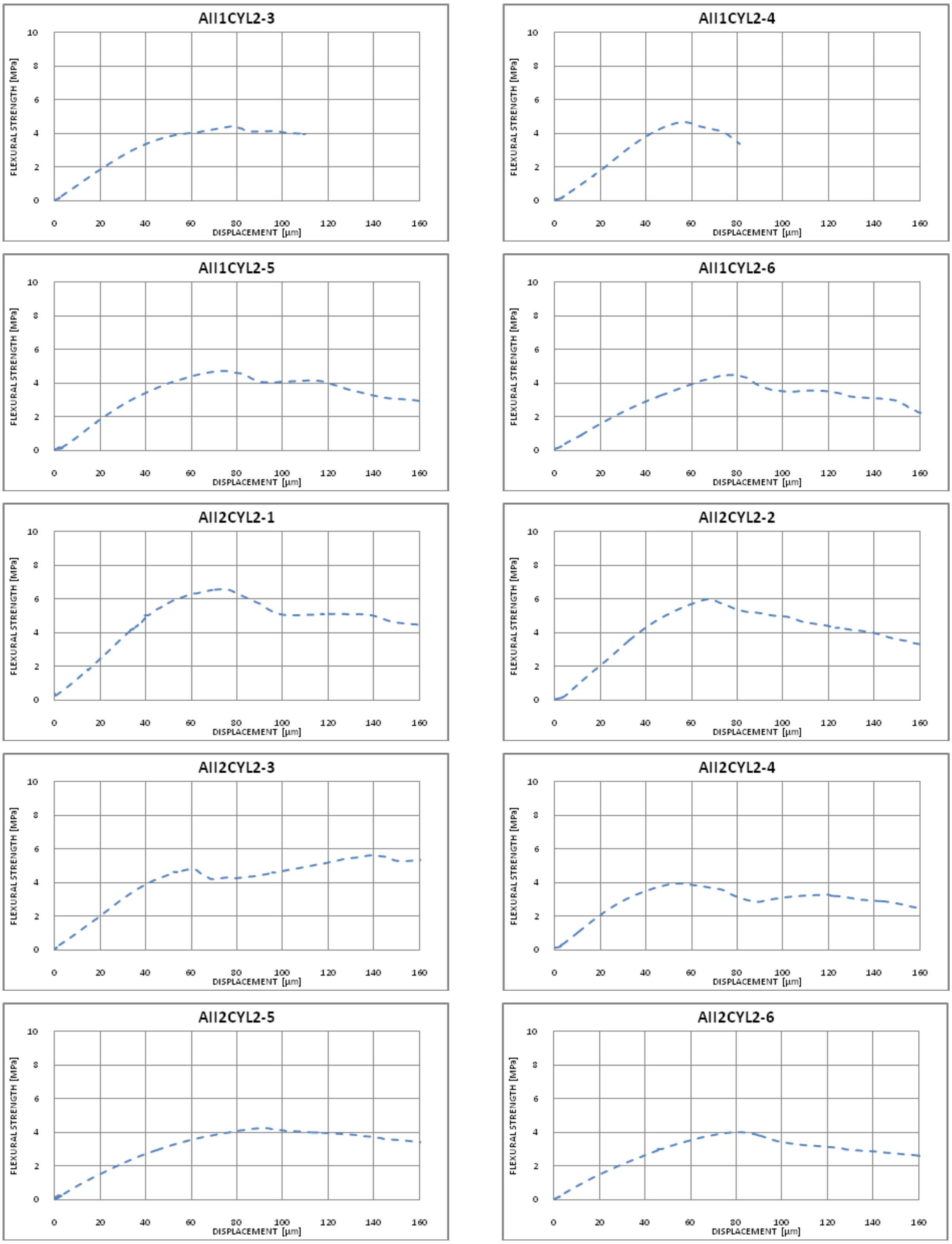
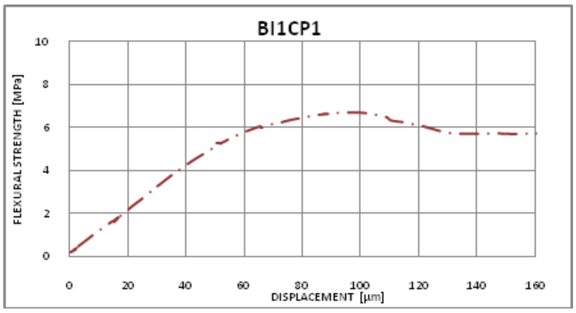
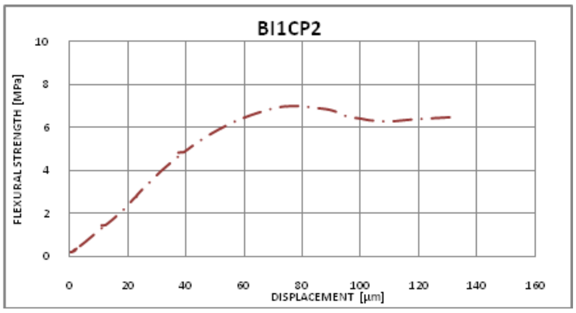
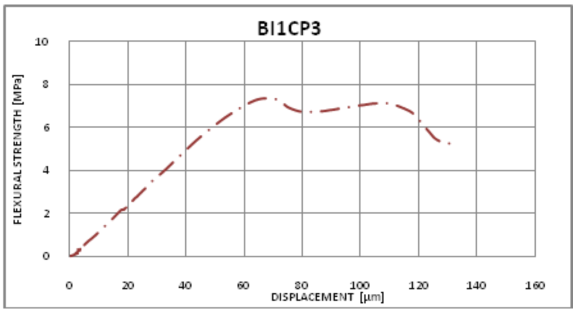


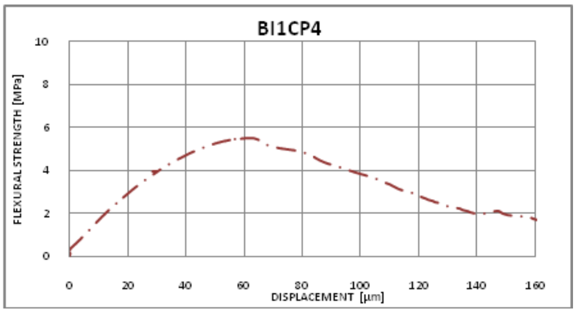
Figure 75 Strength vs deformation of plates extracted from treated cylinders with product A

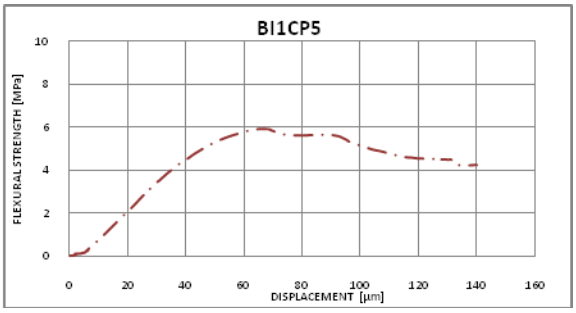
8.2.4 Treated circular plates with product B

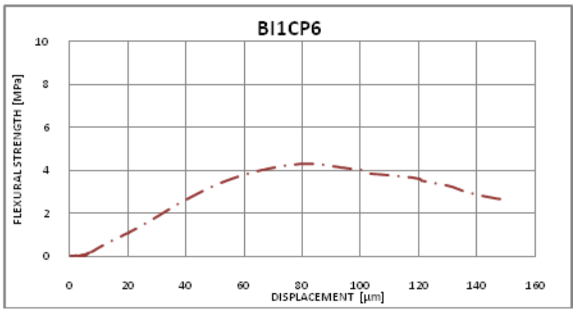


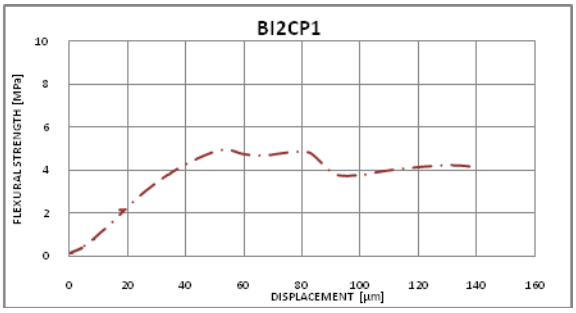


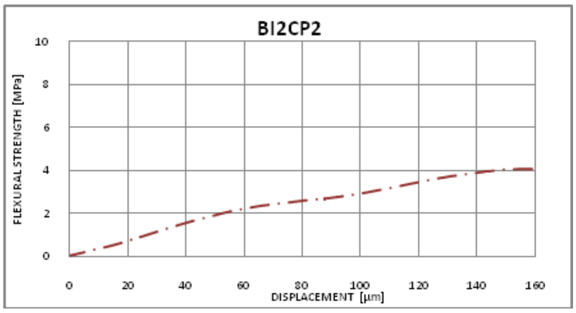












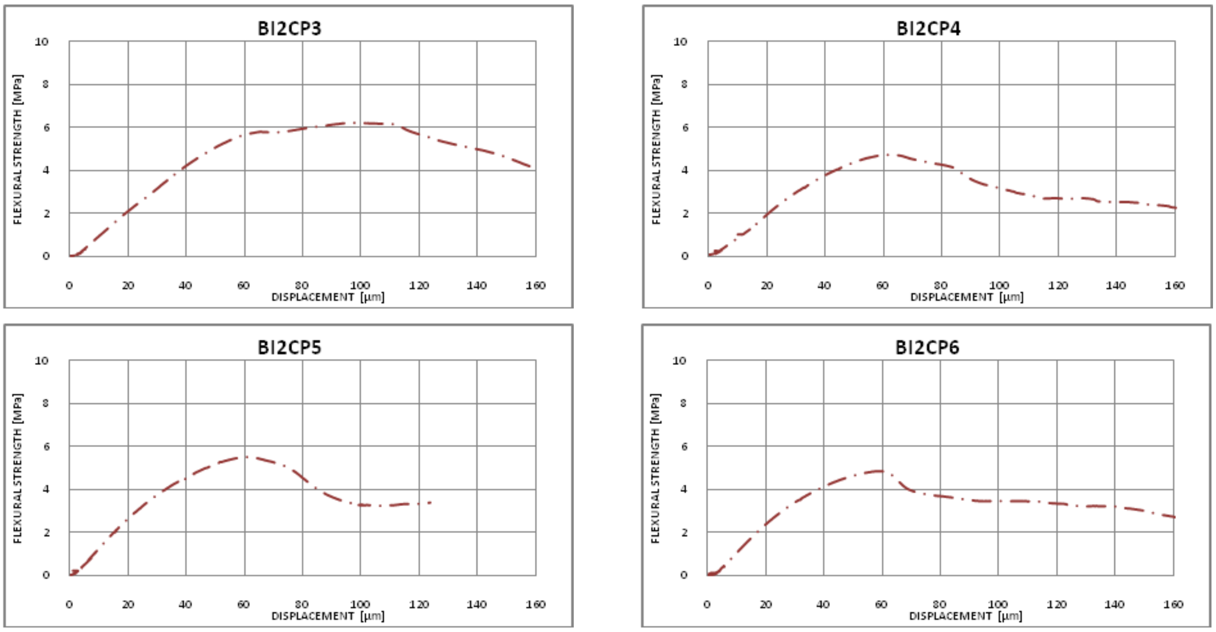
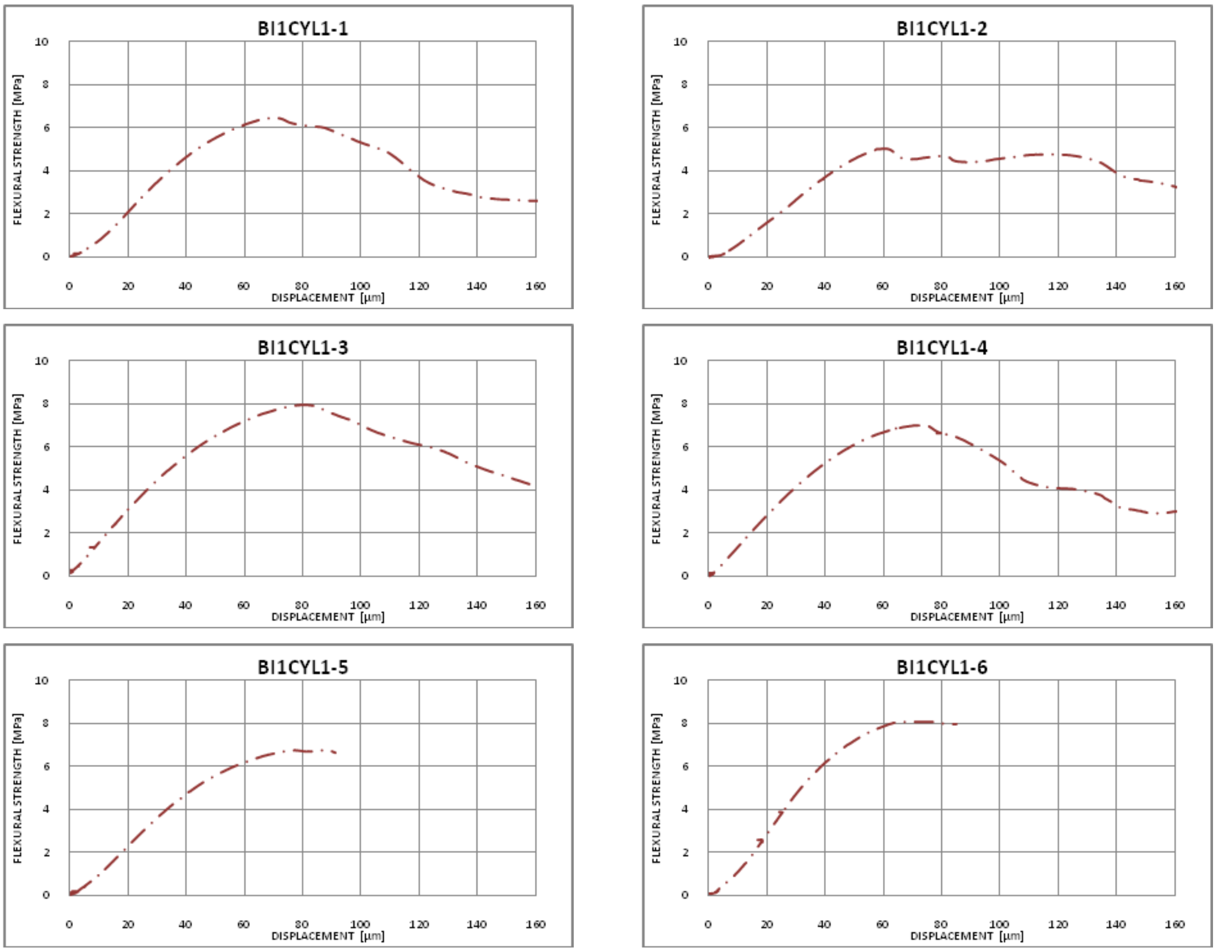
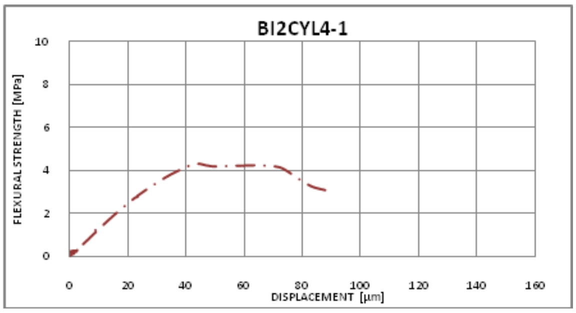
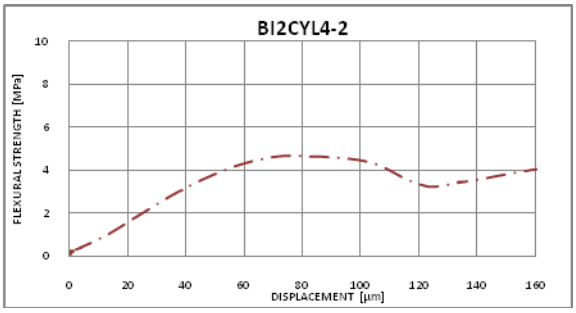


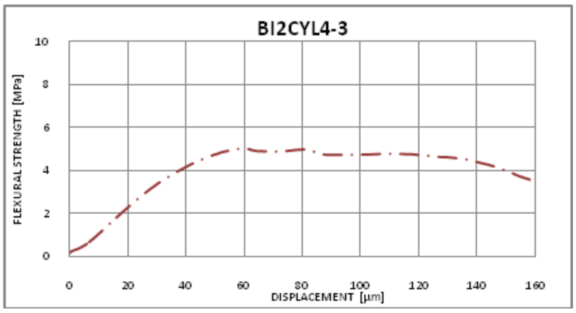
Figure 76 Strength vs deformation of treated plates with product B

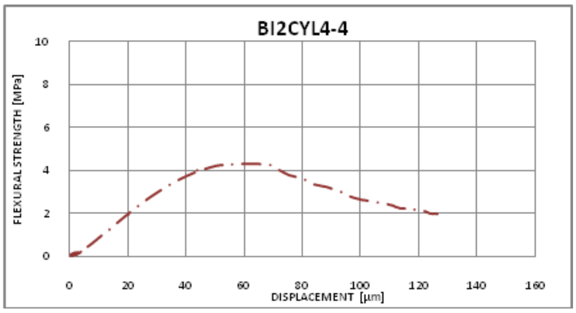
8.2.5 Treated cylinders with product B

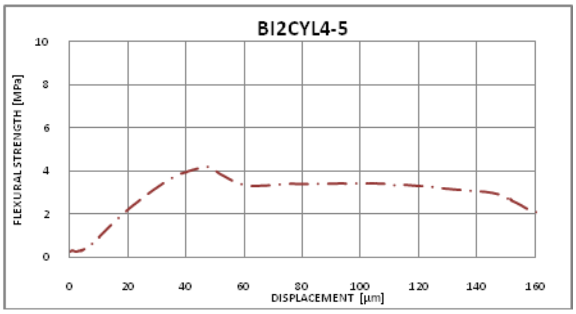


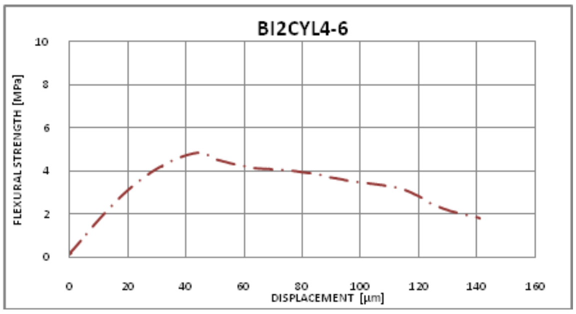

BI2CYL4-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

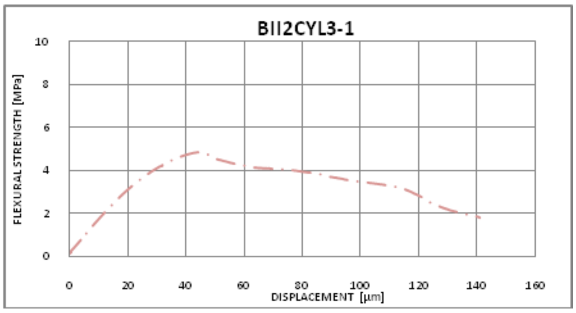

BI2CYL4-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

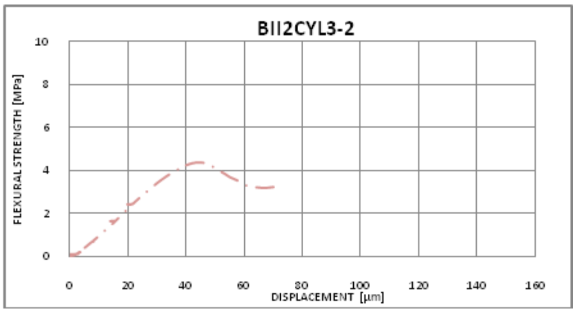

BI2CYL4-3
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

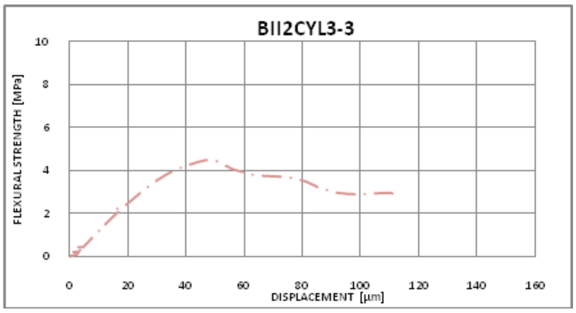

BI2CYL4-4
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

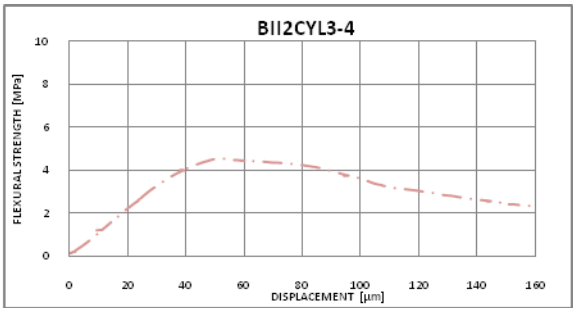

BI2CYL4-5
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


BI2CYL4-6
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


BII2CYL3-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


BII2CYL3-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


BII2CYL3-3
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


BII2CYL3-4
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

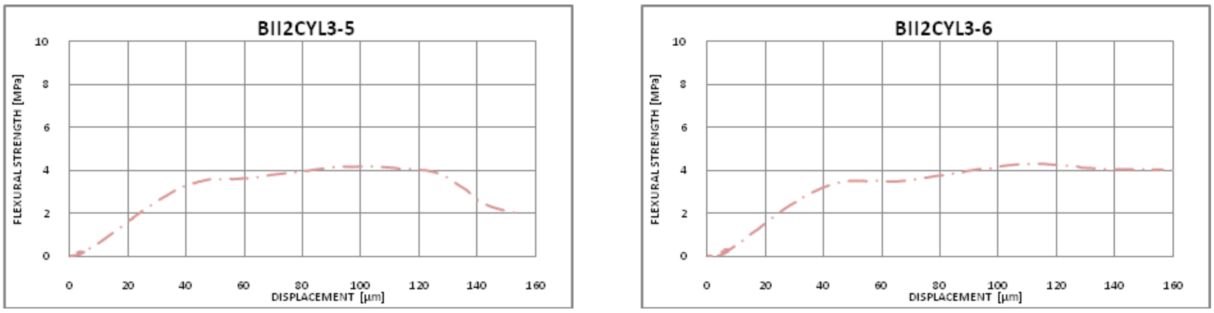
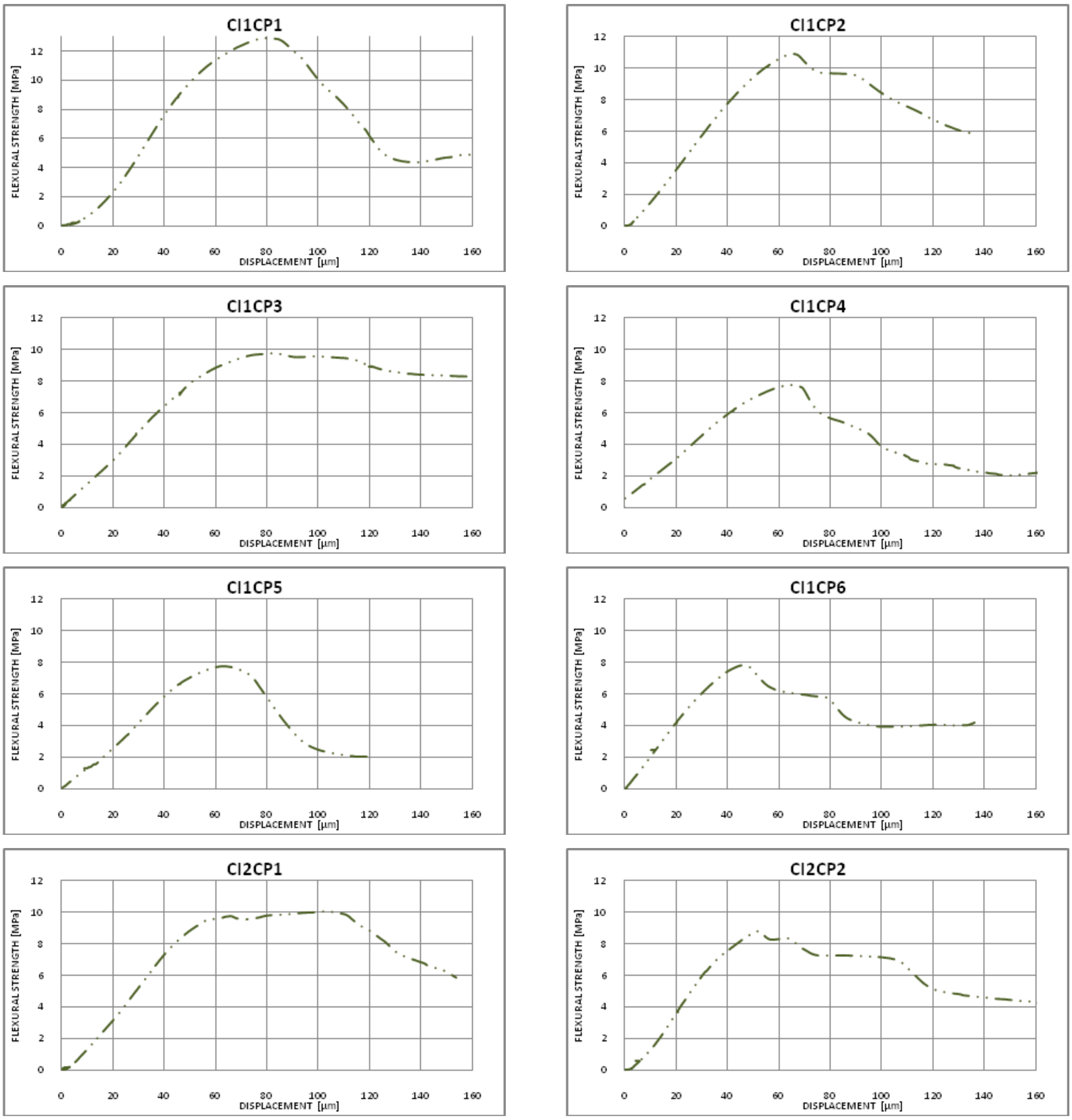


Figure 77 Strength vs deformation of plates extracted from treated cylinders with product B

8.2.6 Treated circular plates with product C



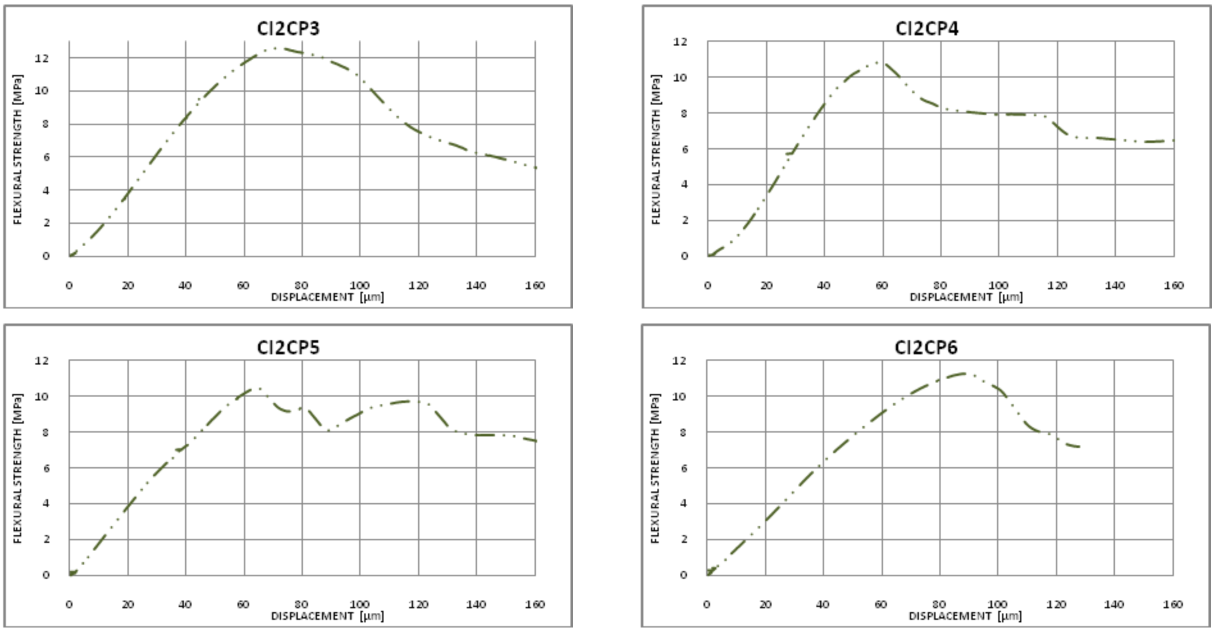
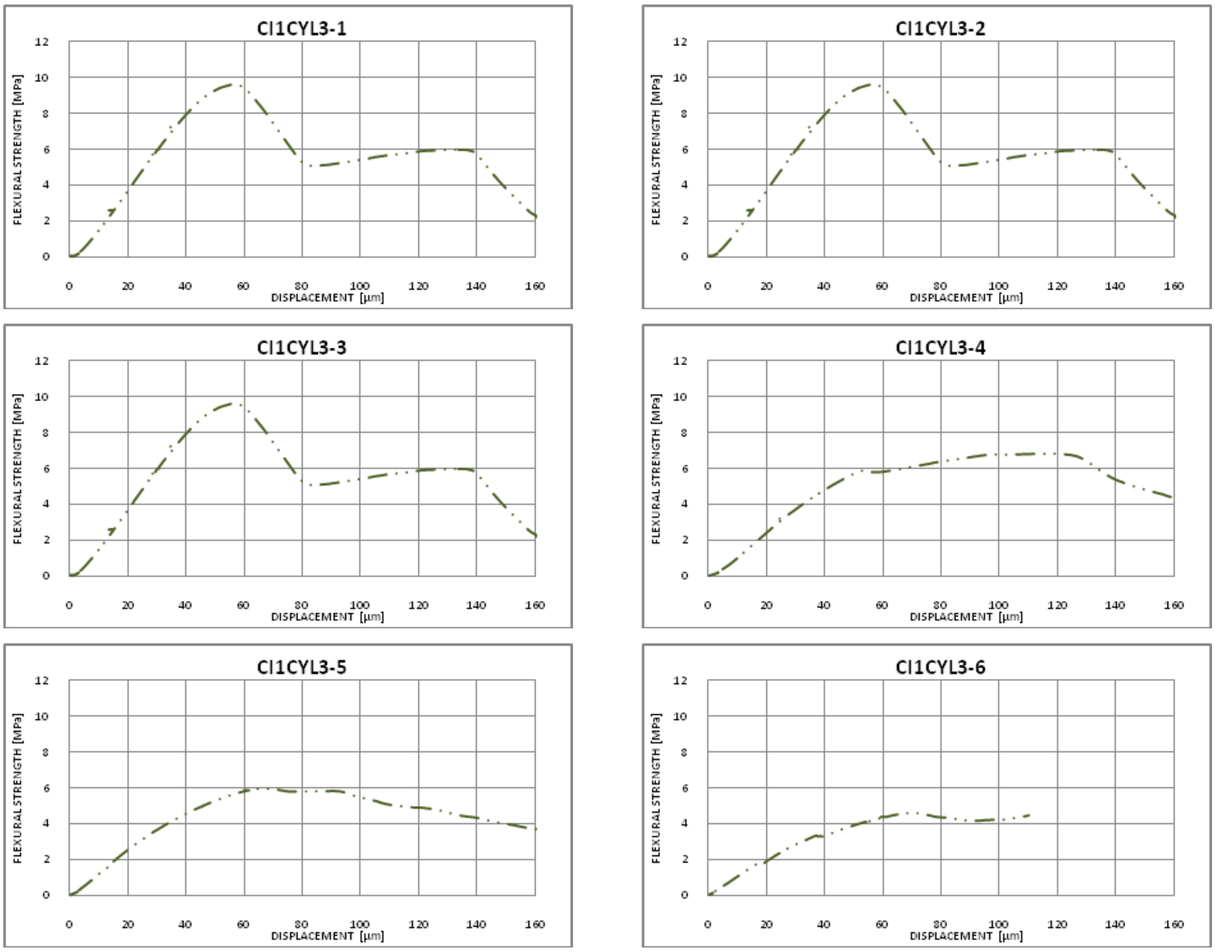
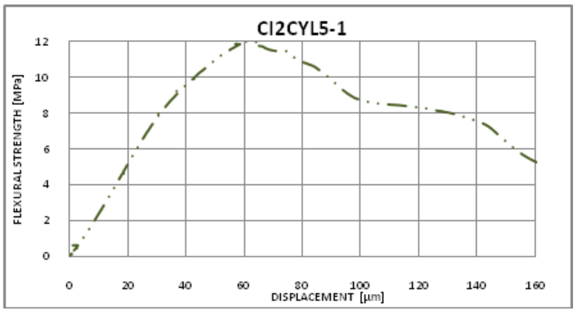
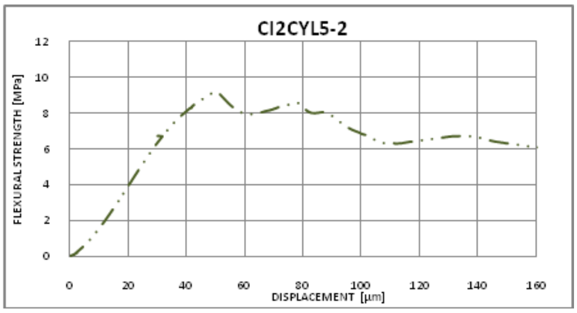


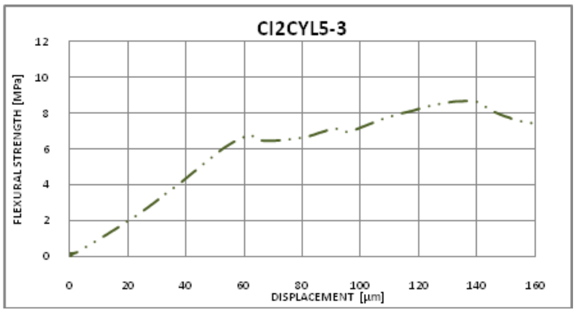
Figure 78 Strength vs deformation of treated plates with product C

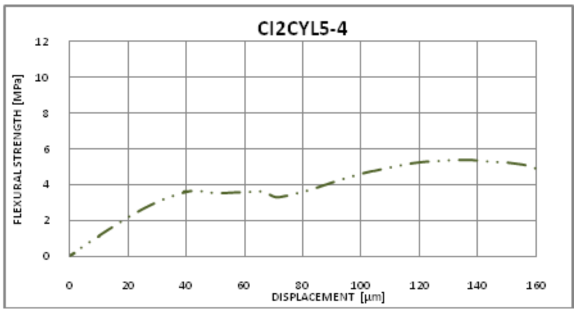
8.2.7 Treated cylinders with product C

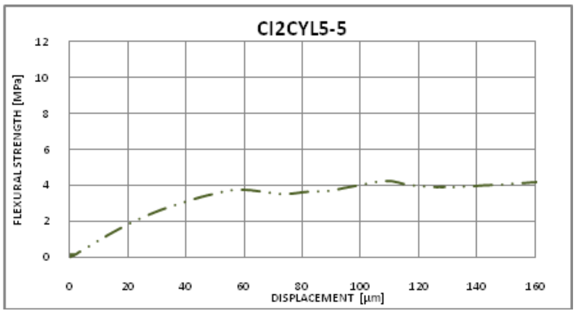


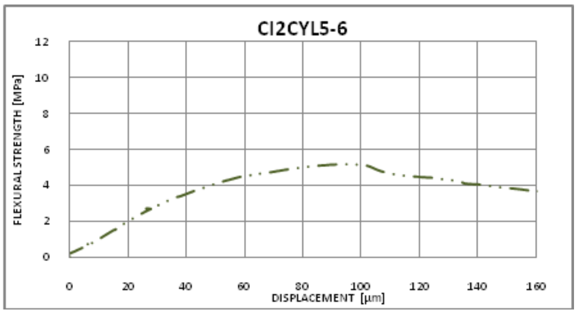

CI2CYL5-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

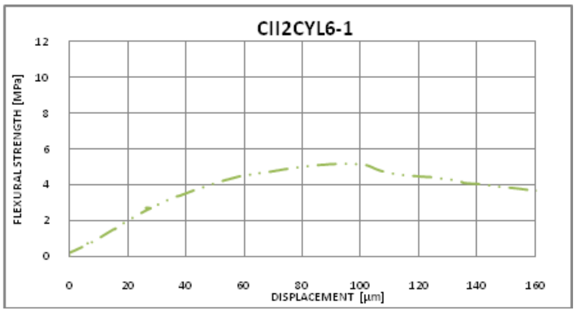

CI2CYL5-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

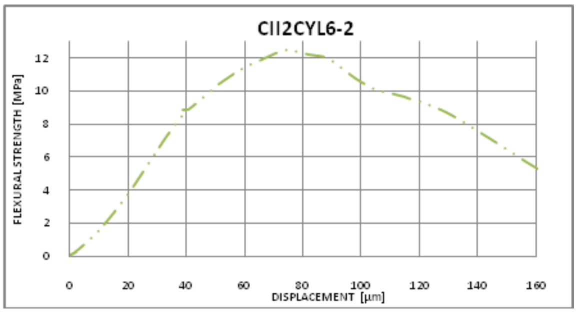

CI2CYL5-3
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

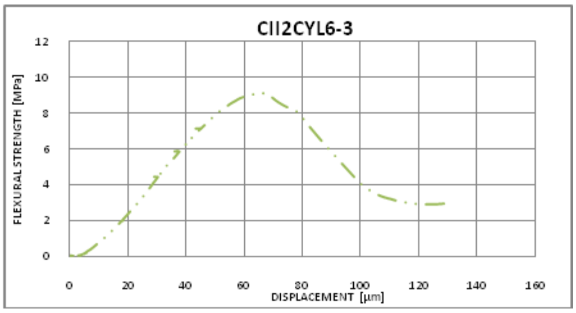

CI2CYL5-4
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

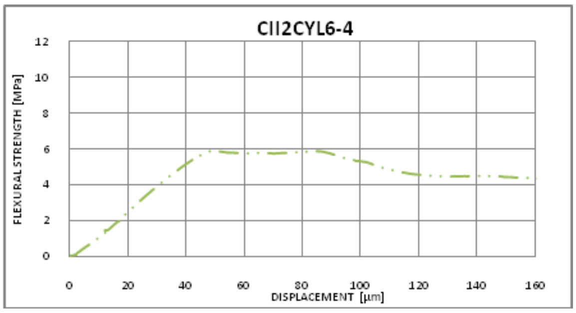

CI2CYL5-5
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


CI2CYL5-6
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


CII2CYL6-1
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


CII2CYL6-2
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


CII2CYL6-3
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]


CII2CYL6-4
FLEXURAL STRENGTH [MPa]
DISPLACEMENT [µm]

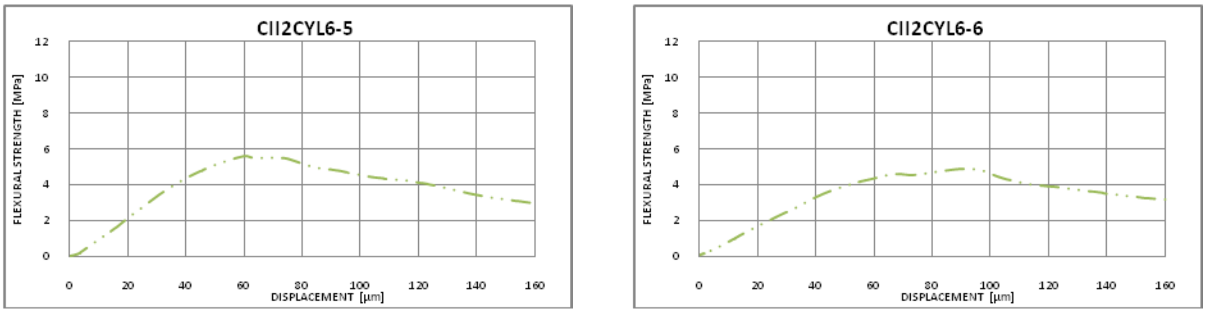


Figure 79 Strength vs deformation of plates extracted from treated cylinders with product C.