



VACUUMATICS; Systematic Flexural Rigidity Analysis

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Abstract

The structural integrity of vacuumatics relies on the principle of prestressing unbound particles inside an enclosed membrane. By introducing a negative pressure (partial vacuum) inside this airtight flexible enclosure, the membrane is tightly wrapped around the outer particles, hence effectively bonding the particle filling to create (adaptable) load-bearing structures.

Analytical and numerical studies on the fundamental prestress derivation of vacuumatically prestressed structures have shown that the effective prestressing forces between the particles largely depend, apart from the differential in (air) pressure differential, on the elastic properties of the skin material. The flexural rigidity of vacuumatics is mainly determined by the material properties of the particles and membrane used. Variations in elasticity of the skin and particle filling, and with this the shape, size, compressiveness, roughness, and packing density of the individual particles, highly influence the structural behaviour of vacuumatic structures.

In order to explore the influence of different particle and skin characteristics (or parameters) on the flexural rigidity, experimental research has been carried out by means of four point bending tests. Different types of particles were used to discover behavioural trends dependent on the parameters varied. The results of this study provide an enhanced understanding of the true overall structural response of vacuumatics. By systematically elaborating the different parameters, we are able to determine what specific material properties are desired to design the ‘most efficient’ vacuumatic structure for every application.

Keywords: vacuumatics, particle filling, membrane, atmospheric (air) pressure, vacuum prestress, flexural rigidity.

1 Introduction

The principle of prestressing unbound particles in order to create load-bearing structures is not an entirely new phenomenon. In soil mechanics, for instance, this structural principle is very well known as it describes the structural behaviour of layers of soil (e.g. sand particles) under external loading. With soil mechanics, the particles are mainly subjected to external vertical forces while being prestressed multi-directionally by the adjacent particles due to their own weight. The structural strength and stiffness is largely determined by the way the particles are packed. A higher packing density leads to a stronger and more rigid particle structure.

When these multi-directionally prestressed particles are subjected to bending, however, as with vacuumatics, a rather different approach is required. Considering the fact that unbound particles are not able to withstand any tensile forces, in first instance the tensile bending stresses need to be taken up by the prestressing of the particles. Secondly, the enclosing membrane at the tensile zone of the structure will be activated (Fig. 1). The compressive bending stresses are gradually distributed through the closely packed particles at the compression zone of the structure, which results in contact forces between adjacent particles.

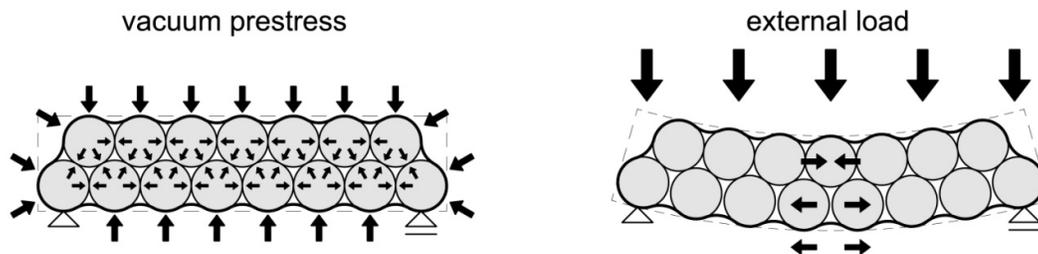


Fig. 1: compressive and tensile bending stresses with vacuumatics

Some similarities might be seen here with structural reinforced concrete. The (bonded) aggregates in concrete take up the compressive bending stresses, while the steel reinforcement takes up the tensile bending stresses at the tensile zone of the structure. It needs to be taken into account, however, that in contrast to unbound particles, concrete is able to withstand tensile stresses, to a certain extent, due to the chemical bonding of the aggregates.

The ‘vacuum prestressing’ of the particles is largely determined by the differential in air pressure (or ‘vacuum pressure’), as well as the elastic properties of the skin material. Self-evidently, a higher amount of vacuum pressure leads to a higher amount of prestress. Furthermore, a non-elastic enclosing membrane will also lead to a higher amount of prestress [1].

In this paper the systematic fundamental research on the flexural rigidity of vacuumatics will be discussed, based on a series of four point bending tests. The aim of this experimental study is to discover behavioural trends, determined by varying specific characteristics (or parameters) of the particle filling and the enclosing membrane.



2 Parameters

The effect of the individual elements (particles and skin) on the bending stiffness of vacuumatics can be attributed to a number of parameters [2]. By carrying out several identical four point bending tests while varying only one of these parameters, the influence of this parameter on the flexural rigidity can be illustrated. Each test is carried out at least three times in order to ensure consistency of the results.

For these tests we used glass and aluminium particles (Table 1) and plastic and elastic films (Table 2).

Table 1: particles used in tests

Particle	Material	Young's modulus (E_{50} at 100kPa) [MPa]	Parameters		
			Size [mm]	Shape	Surface texture
GL2.5	glass	58	Φ 2.5	spherical	smooth
GL5.0	glass	58	Φ 5.0	spherical	smooth
GL10	glass	(58)	Φ 10.0	spherical	smooth
AL5.0s	APM*	(18)	Φ 5.0	spherical	coarse
AL5.0c	APM*	18	Φ 5.0 x 20	cylindrical	coarse

* Advanced Pore Morphology (APM) elements – foamed aluminium

The specific particle and skin parameters that are varied during this experimental research are:

1. particle size (spherical diameter range)
2. particle shape (spherical or cylindrical)
3. particle surface texture (smooth or coarse)
4. skin elasticity (determined by the type of skin material and the skin thickness)

The particles used are more or less chosen for their expected behaviour and availability. Glass particles (beads) are known to be perfectly spherical and have an extremely smooth surface texture, which will lead to an assumedly constant packing density. The variation in particle size will therefore not affect the way the particles are packed.

Foamed aluminium particles, on the other hand, have a more angular surface texture. This characteristic can enhance particle interlocking, which might lead to a different flexural behaviour of vacuumatics. In order to potentially illustrate the influence of the so-called elongation ratio (breadth divided by length), spherical as well as cylindrical aluminium elements are used. For practical reasons the shape parameters in this exploratory research are restricted to this specific characteristic.



The membranes used are similarly chosen for their expected behaviour and availability. Plastic films, like Low Density Polyethylene (LDPE2) are widely available and relatively strong, but also easy to weld. SBS, on the other hand, is a rubber-like material, which is assumed to have a high yield strain compared to plastic films.

Table 2: membranes used in tests

Membrane	Material	Young's modulus	Skin thickness	Parameters
		[MPa]	[μm]	Elasticity
LDPE2	Low Density Polyethylene	150	90	'low'
SBS	VB3371*	7	400	'high'

* based on Styrene-butadiene-styrene (SBS) – rubber-like material

In order to obtain additional insight in the behaviour of the individual elements under flexural stresses, the (material) properties of the membranes under tensile forces as well as the particle fillings under compressive forces have to be determined. This is done by carrying out additional experimental research on these individual elements, like discussed below.

2.1 Compression tests particles

The properties of the particle under compression are determined by carrying out a series of triaxial tests on cylindrical particle samples (conform BS 1377-7). Each specimen is enclosed vertically by a thin rubber membrane and on both ends by rigid surfaces. The sample is then placed in a pressure chamber under a predetermined confining (water) pressure, which is kept constant during testing. The axial deformation of each specimen is measured, while a deviator stress in axial direction is applied up to failure. Failure occurs when the vertical applied force reaches its maximum and remains constant afterwards, or shows some small additional increase or decrease. At this point sliding planes have occurred in the specimen, which indicates that the shear strength of the specimen is exceeded. The relation of the shear stresses and normal stresses can be illustrated by plotting Mohr diagrams. These Mohr circles are defined by the confining pressure and the maximum deviator stress at failure. By drawing a tangent to the Mohr circles of identical samples under different confining stresses, the consistency of the test results can be indicated.

In case of the spherical glass particles, the tangent of all the Mohr circles illustrates not only that the results are consistent, but also that the specimen strength is independent of the particle size (Fig. 2). For this reason it might be expected that the particle size has also no effect on the flexural rigidity of vacuumatics. This will be discussed later.

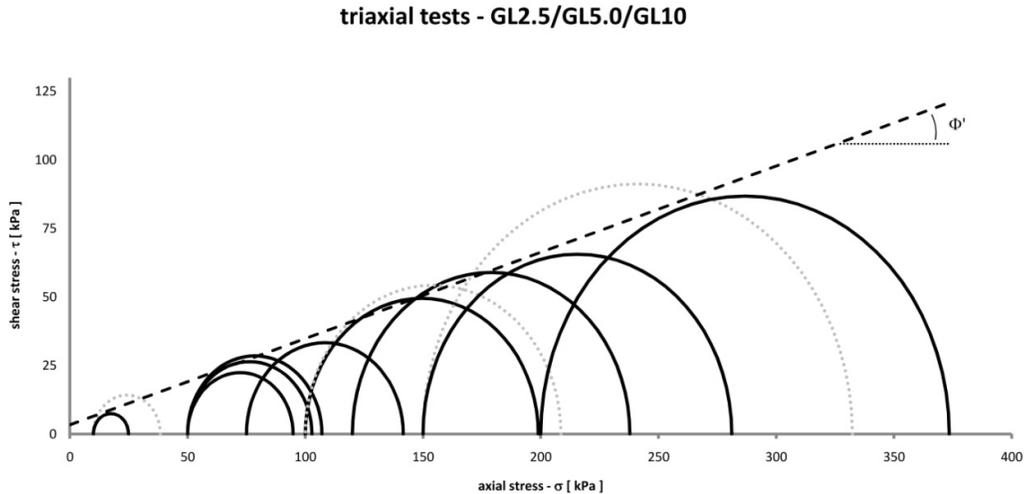


Fig. 2: Mohr diagrams of all triaxial tests on particles GL2.5, GL5.0 and GL10

The average Young's modulus (E_{50}) of each particle filling can be determined by plotting the stress-strain curve of the triaxial tests at 100kPa confining pressure, which corresponds to maximum 'vacuum pressure' (Fig. 3). It must be noted that no triaxial test has been carried out at 100kPa on glass particles GL10. It might be assumed that the compressive rigidity of GL10 is comparable to GL2.5 and GL5.0 at a confining pressure of 100kPa. Similar tests at a confining pressure of 50kPa illustrate that the (initial) rigidity of GL10 is indeed comparable (Fig. 3).

In case of the aluminium particles, it must be noted that the test at 100kPa confining pressure lead to very large particle stresses and deformations. This particular specimen even failed before a maximum deviator stress could have been reached, due to particle failure (crushing of the particles), as well as membrane puncture (Fig. 4). Similar tests at a confining pressure of 10kPa confirm, however, that the compressive rigidity of AL5.0s is comparable to AL5.0c (Fig. 4).

The above mentioned tests imply that the compressive rigidity is independent of the particle shape (i.e. the elongation ratio) as well as the particle size. However, the shape does seem to have a big influence on the strength of the specimens. With cylindrical particles, failure occurs at much higher deviator stresses.

Furthermore, a comparison between the tests with glass and spherical aluminium particles (GL5.0 and AL5.0s) illustrates that the frictional properties of the particles also have a big influence on the specimen strength. With the more coarse aluminium particles a higher failure load is achieved.

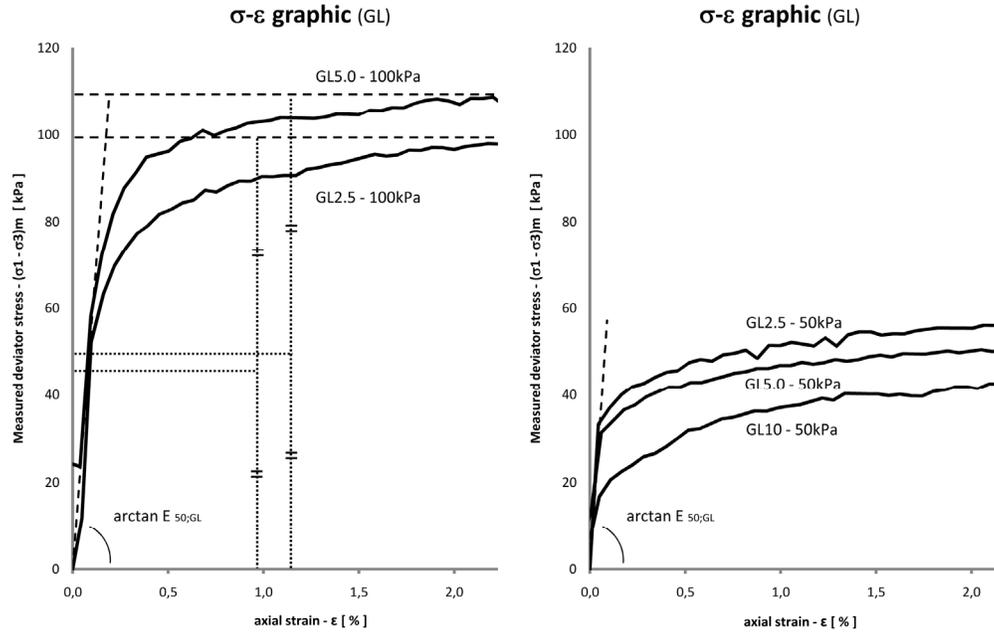


Fig. 3: stress-strain curves of particles GL2.5, GL5.0 and GL10

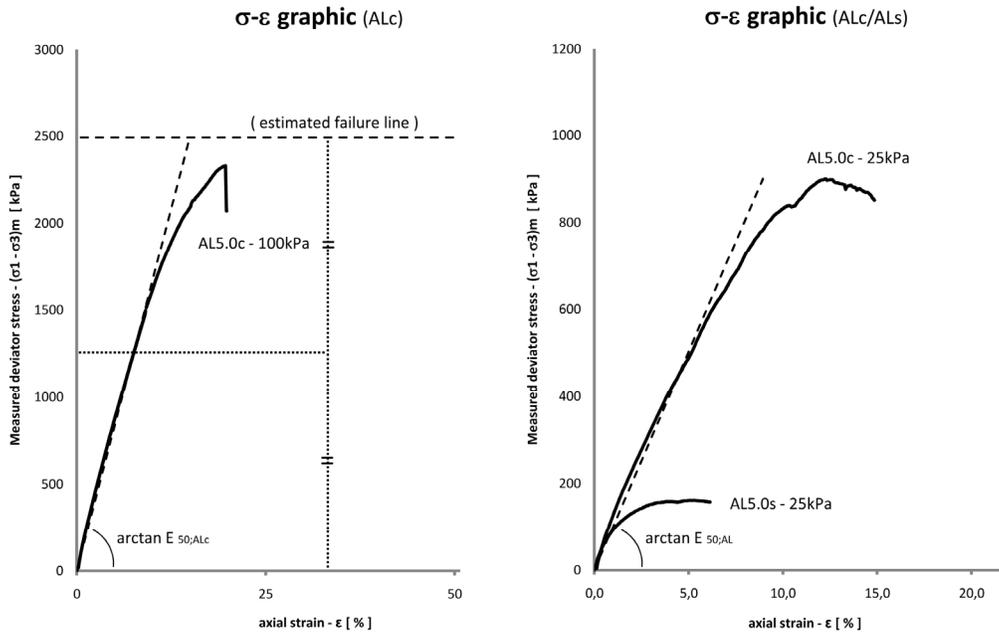


Fig. 4: stress-strain curves of particles AL5.0c and AL5.0s



2.2 Tensile tests membranes

The skin elasticity of each type of membrane used is determined by carrying out tensile tests on small strips of film (conform ASTM D882-91 and ISO 527). The orientation of these strips is identical to the longitudinal direction of the film under flexural strain when a vacuumatic structure is subjected to bending.

The initial linear part of the stress-strain curves of these skin materials show that the SBS film has a far lower elasticity than LDPE, yet a much higher yield strain (Fig. 5). This would imply a difference in flexural rigidity when applied in vacuumatics.

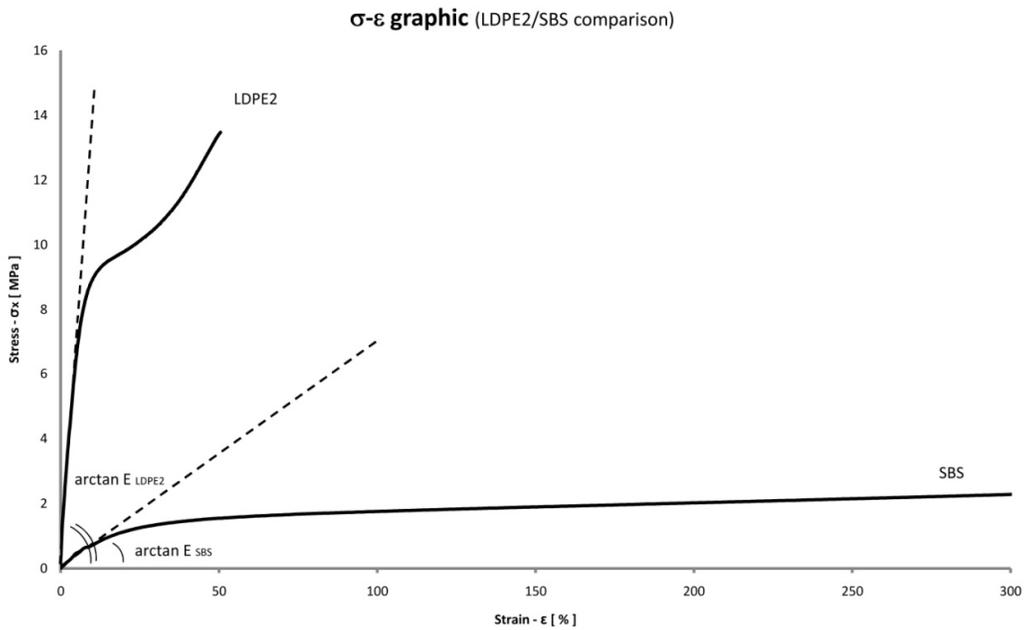


Fig. 5: stress-strain curve of membranes LDPE2 and SBS



3 Four point bending tests

The four point bending tests are conducted on beam-like specimens, which are simply supported on two outer points (spanning 500mm) and deformed by driving two concentrated loads downwards (Fig. 6). The advantage of doing four point bending tests is that in between the loads a uniform bending moment is produced without any shear forces. By measuring the vertical deformation of at least three points in between the loads, the bending deformation and therefore the flexural rigidity of the beam structure can be determined.

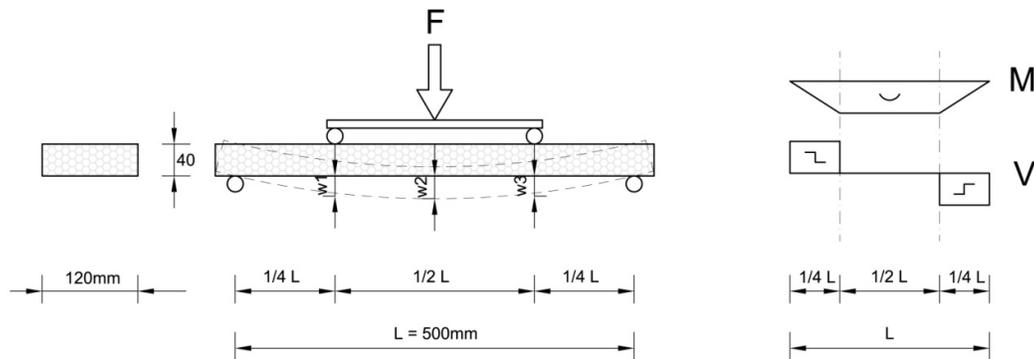


Fig. 6: four point bending test setup for vacuumatics beam, with bending moment (M) and shear force (V) diagrams

3.1 Test specimens

The beam elements are produced by pouring particles into the flexible membrane enclosure, which is positioned in a rectangular ‘beam-shaped’ counter mould, measuring approximately 120x40x600mm. The particles are consolidated by tapping the mould to ensure an optimal packing density. The bulk density (and thus the packing density) is measured by weighing and measuring each specimen. The deviation in packing density has proved to be of major influence on the flexural rigidity. Since this parameter is very difficult to direct, we are aiming for a constant packing density per particle type throughout the tests.

The introduced vacuum pressure (approximately 100kPa) stabilises the particle packing and ‘freezes’ the beam-like shape of the specimen. This process is repeated for each specimen. Because the level of vacuum pressure is of influence on the amount of prestressing (and therefore on the flexural rigidity) the vacuum pressure is measured and kept constant throughout the tests.



4 Results

In order to find behavioural trends in bending stiffness, the force-deformation graphics indicating the deformation at mid-span, are used as a qualitative indicator. It must be noted, that the overall deformation is shown in these graphics. This includes any deformation due to shear forces. Through visual observation of the test specimens (Fig. 7), we can assume that plane sections remain plane and normal to the longitudinal axis during deformation (Euler-Bernoulli beam theory). For this reason, the influence of the shear deformation on the overall deformation can be regarded as minimal. Therefore, the use of the force-deformation graphs as a qualitative indicator for difference in flexural rigidity is validated in this exploratory stage of the research.

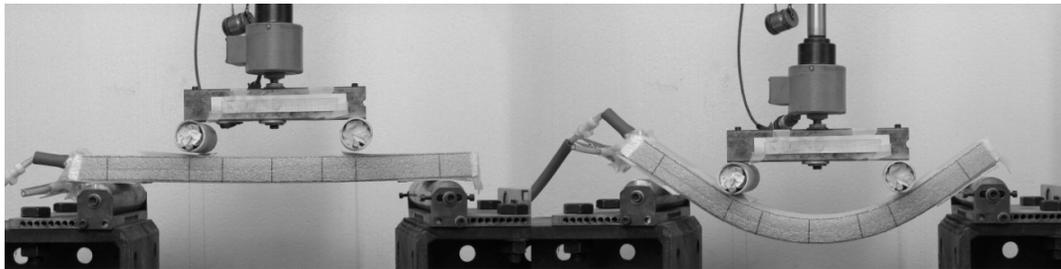


Fig. 7: four point bending test specimen (confirming the Euler-Bernoulli beam theory)

4.1 Parameter 1: particle size

When we look at the force-deformation graphic with LDPE2 (Fig. 8) as well as SBS (Fig. 9), it can be seen that the curves of the glass particles (GL2.5, GL5.0 and GL10) are more or less identical, which indicates a comparable flexural rigidity, in particular in the first part of the deflection curve. This is in agreement with the results obtained from the triaxial tests on glass particles, indicating that the rigidity is independent of particle size. A small trend that can be observed from these results, however, is that particles GL10 tend to result in a relatively lower flexural rigidity. This might be explained by the fact that the specimen height (40mm) is only four times the particle size (10mm). An adequate stress distribution throughout the particles during deformation might therefore be disrupted.

4.2 Parameter 2: particle shape

The force-deformation graphs indicate a comparable structural behaviour for both the aluminium particles, although the cylindrical particles (AL5.0c) seem to result in a slightly higher flexural rigidity. This might be explained by the increase in the number of contact surfaces, which benefits the interlocking potential of the particles.



4.3 Parameter 3: particle surface texture

The force-deformation graphs also clearly show that with both types of membrane the use of the foamed aluminium particles (AL5.0s as well as AL5.0c) result in a higher flexural rigidity than the glass particles (Fig. 8 and 9). This might be attributed to the textured surface, which enables an enhanced interlocking of the particles. A similar conclusion might be drawn from the results of the triaxial tests, where failure of the aluminium particles occurs at a much higher deviator stress. The relatively higher initial rigidity of the specimen with glass particles can be explained by the fact that these particles are already closely packed before externally loaded. This will self-evidently result in a higher Young's modulus. When externally loaded, glass particles tend to slide over one another due to their smooth surface texture. With aluminium particles, cylindrical as well as spherical, the angular surface texture hinders this 'sliding' motion of the particles, resulting in relatively higher shear strength and therefore a higher deviator stress at failure.

4.4 Parameter 4: skin elasticity

When focussing on the different types of membrane, the graphs of the four point bending tests indicate that a lower skin elasticity (and thus a higher Young's modulus), as well as a low yield strain, leads to a higher flexural rigidity (Fig. 8 and 9). This can be explained by the fact that the particles at the tensile zone of the structure are more constrained by the membrane when submitted to tensile bending stresses.

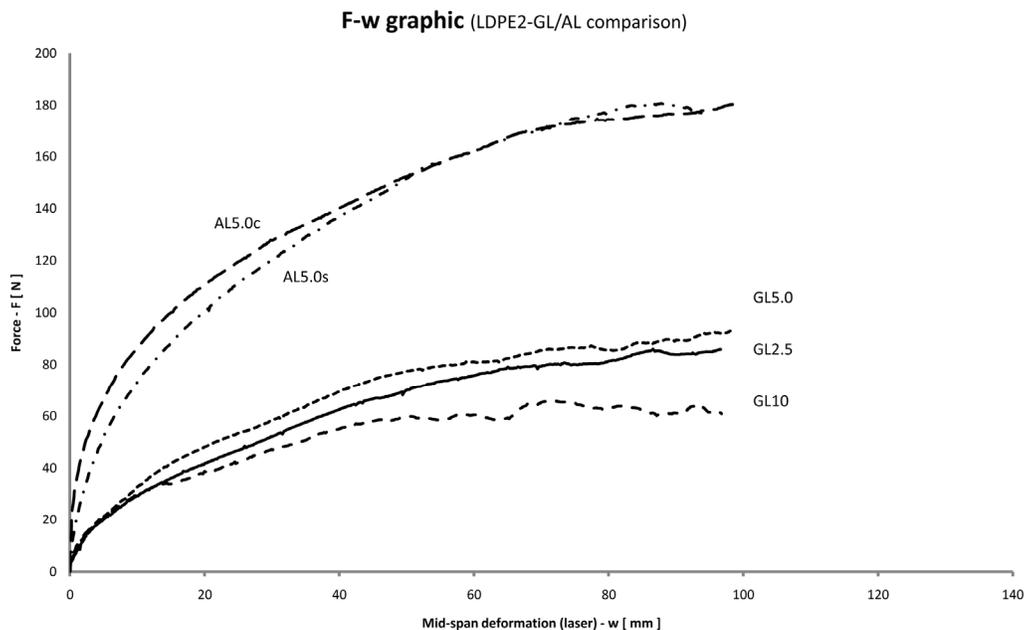


Fig. 8: comparison of glass and aluminium particles (GL2.5, GL5.0, GL10, AL5.0c and AL5.0s) with LDPE2 membrane

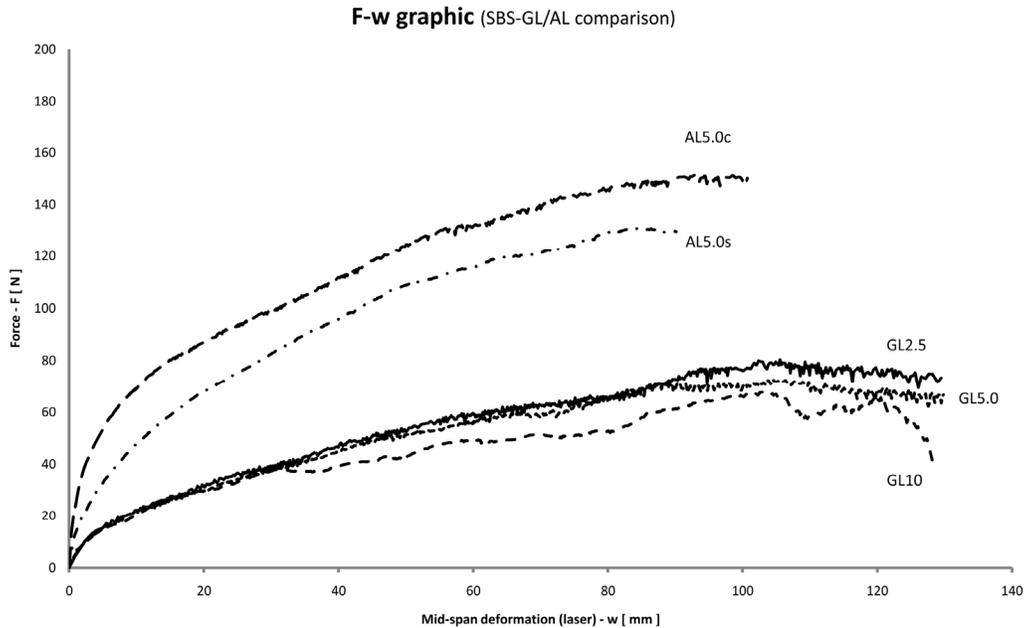


Fig. 9: comparison of glass and aluminium particles (GL2.5, GL5.0, GL10, AL5.0c and AL5.0s) with SBS membrane

5 Conclusions

Insight in the behavioural trends of vacuumatic structures are obtained by varying specific characteristics (or parameters) of the particles and membranes used.

The flexural rigidity of vacuumatics is aided by an enclosing skin with a low elasticity and a low yield strain, as well as a particle filling that has a large interlocking potential. Although a low elasticity of the particle filling (or a low compressiveness) is beneficial for a higher bending stiffness, the interlocking of the particles seems to play an even greater role with respect to the rigidity. Therefore, particles with a high frictional surface texture are desired to enhance the flexural rigidity.

The triaxial tests and the bending test of vacuumatics with spherical particles imply that the compressive rigidity as well as the flexural rigidity is independent of the particle size.



6 Discussion and future work

It must be stressed that with these types of structures, rather large deformations occur. This is not beneficial for the practical application of vacuumatics. However, at this exploratory stage of our research, we are not so much interested in the absolute numbers of strength and stiffness, but more in the behavioural trends that can be discovered.

Our aim is to apply vacuumatics as a fully adaptable 3D formwork system to create geometrically complex shapes and customised surface textures in concrete [3]. For this specialised application, the vacuumatically prestressed structure ‘only’ needs to (temporarily) withstand the concrete mortar pressure until the concrete is sufficiently hardened.

As an addition to the tests described in this paper, we are aiming to obtain insight into the stress distribution of vacuumatics when submitted to bending moments by explicitly monitoring and measuring the flexural strain of the top and bottom part of each specimen during testing. Furthermore, ways of increasing the flexural rigidity are being explored.

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References

- [1] Huijben F, van Herwijnen F. Vacuumatics: Vacuumatically Prestressed (Adaptable) Structures. *6th International Conference on Computation of Shell & Spatial Structures*. IASS-IACM 2008 Spanning Nano to Mega, Ithaca NY (USA), 2008.
- [2] Huijben F, van Herwijnen F, Lindner G. Vacuumatic Prestressed Flexible Architectural Structures. *III International Conference on Textile Composites and Inflatable Structures*. Structural Membranes 2007, Barcelona (ESP) 2007; 197-200.
- [3] Huijben F, van Herwijnen F, Nijssen R. Vacuumatics 3D-Formwork Systems: Customised Free-Form Solidification. *IV International Conference on Textile Composites and Inflatable Structures*. Structural Membranes 2009, Stuttgart (DEU) 2009.