Tensile Test Section for Monocure 3D

Tensile Graphs located at the end

1 Material Testing

As Flex100 is a new material on the market there is no property sheets available. This means material testing will be undertaken to find the best printing settings, UV exposure time and tensile testing to find Youngs modulus.

1.1 3D Printing Testing

The LCD printing process has 6 main settings which effect the print quality. Below is a list of them explaining what they do and how they affect the print quality:

1) Bottom Exposure Time: Is the amount of time the UV light is on and thus curing a thin layer of resin to the printing bed (or previous layer), that is pressed against an FEP sheet the separates the resin from touching the UV screen. It is usually up to 10 times as long as the normal exposure time due to needing to grip successfully to the printing bed. If it does not have successful adhesion to the bed, then it would cause the print to fall off and fail.
2) Bottom Layer Count: Is the number of layers that have the extended exposure time from 'Bottom Exposure Time'. This is normally less than 5 and helps ensure successfully bonding with the build plate.
3) Exposure Time: Is the amount of time that the rest of the required print layers will be exposed to UV lights. It is a lot less than the 'Bottom Exposure Time' as it is curing the resin to the previously cured layer. This is made easier as the UV lights can penetrate the resin into the previous layer assisting in strong bonds forming. Over exposure can cause geometry inaccuracies and under exposure can cause the same but also form weak layer adhesion.
4) Lifting Distance: Is the amount the build plate lifts in height between each layer to allow for fresh resin to settle underneath in preparation for the next layer. The build plate lowers down by, 'lifting distance minus

layer height' to allow accurate printing. If this is not the right height than the part may not separate from the FEP sheet and cause inaccurate printing.

5) Lifting Speed: Is the speed in which the build plate lifts to reach the required 'Lifting Distance'. If this is to fast it could create pully forces on the part and FEP and pull it off the build plate, cause layer separation, and stretch the FEP film.
6) Light Off Delay: Is the amount of time the light is off in between curing layers. Using this you can calculate the amount of time it takes to complete one cycle of lifting and lowering the print bed. From this it is possible to then increase that time allowing for a pause in between lowering back time and giving more time for the resin to settle. This helps with thick resins which if do not settle properly before the next layer can cause imperfections such as gaps and layer separation.

Due to the immense amount of printing options, dozens of test prints were conducted making minor changes between each one on individual settings. Below are the examples of some of the test prints used and the best printing settings that was found for different ratios of Flex100 mixed with Rapid resin.

1.1.1 Constants for testing

- 90% support base layer coverage was required to allow the flexible resin to have successful strength to be held up on the build plate.
- A raft was used to allow for strong bondage on the build plate and support structures.
- Same print layout and printing shapes.
- All parts 10mm in depth unless correct settings found a test at 40mm was conducted to finalise settings.
- A = 50 x 25mm, 1.5mm wall thickness.
- B = 50 x 2mm.
- C = 50 x 3mm.
- D = 50 x 4mm.
- E = 50mm diameter 2mm wall thickness.
- F = 25mm diameter, 1mm wall thickness.

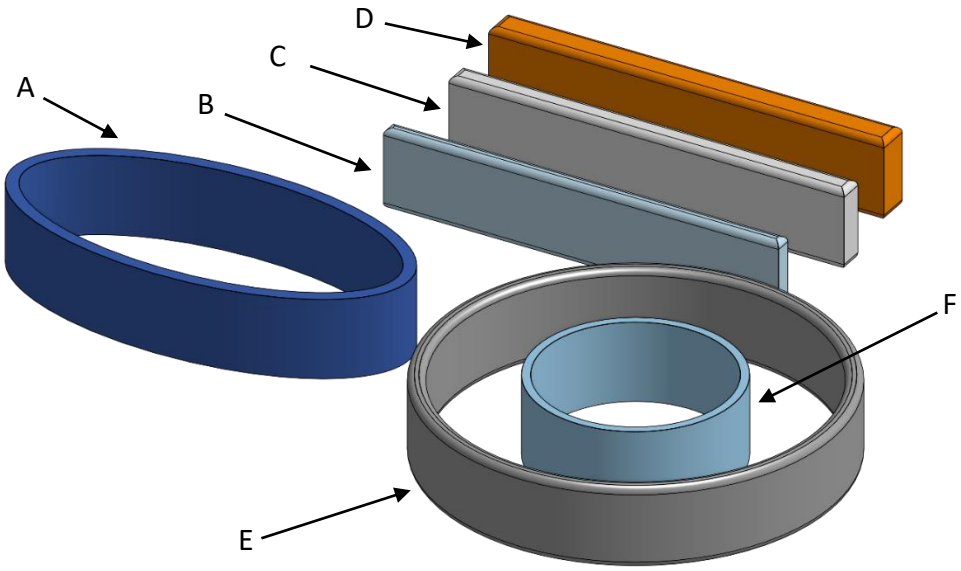


Fig 13: Parts for testing print settings *(Onshape)*

Fig 14: Examples of some of the test parts

1.1.2 Printing Settings

To successfully print a light off delay calculation was formulated to allow a custom length of time where the print head would pause before lowering back down onto the resin/FEP sheet. This is due to the thickness of the resin. An example of the formula for calculating the light off delay is below:

$$Light\ Off\ Delay = Lift\ Time + Retract\ time + Delay\ Wanted$$

$$Time = \frac{Distance}{Speed}$$

$$Time\ (Sec) = \left(\left(\frac{Lift\ Height}{Lift\ Speed}\right) + \left(\frac{Lift\ Height}{Retract\ Speed}\right)\right) \times 60(Min)$$

$$Time\ (Sec) = \left(\left(\frac{5}{50}\right) + \left(\frac{5}{90}\right)\right) \times 60(Min) = 9.3\ (Sec)$$

$$Light\ Off\ Delay = \ 9.3\ (Sec) + Delay\ Wanted = \ 9.3 + 2 = 11.3\ (Sec)$$

$$11.3 = 11.5\ (Sec, Rounded\ to\ nearest\ 0.5)$$

Equation 5: Light off delay for LCD printing

The larger the percentage of Flex100 the longer the 'Delay Wanted' had to be. For 100% Flex100 the minimum delay needed to allow the resin to settle properly was 2 seconds, for 90% and 70% it was 1.5 seconds, for 50% and 25% it was 1 second, and for 0% it was left at 1 second but was not actually needed.

Below are the settings that were found to be most suitable to achieve successful printing with such a flex resin and mixing it with a rigid resin:

<u>Flex100 = 100% : Rapid = 0%</u>

Layer Height:	0.05	mm	Bottom Lift Distance:	5	mm
Bottom Layer Count:	4		Lifting Distance:	5	mm
Exposure Time:	12	s	Bottom Lift Speed:	65	mm/min
Bottom Exposure Time:	60	s	Lifting Speed:	50	mm/min
Light-off Delay:	11.5	s	Retract Speed:	90	mm/min
Bottom Light-off Delay:	0	s			

Fig 15: 100% Flex100 settings

Flex100 90% : Rapid 10% and Flex100 70% : Rapid 30%

Layer Height:	0.05	mm	Bottom Lift Distance:	5	mm
Bottom Layer Count:	4		Lifting Distance:	5	mm
Exposure Time:	9	s	Bottom Lift Speed:	65	mm/min
Bottom Exposure Time:	60	s	Lifting Speed:	50	mm/min
Light-off Delay:	10.5	s	Retract Speed:	100	mm/min
Bottom Light-off Delay:	0	s			

Fig 16: 90% & 70% Flex100 settings

Flex100 50% : Rapid 50% and Flex100 25% : Rapid 75%

Layer Height:	0.05	mm	Bottom Lift Distance:	5	mm
Bottom Layer Count:	4		Lifting Distance:	5	mm
Exposure Time:	7	s	Bottom Lift Speed:	65	mm/min
Bottom Exposure Time:	60	s	Lifting Speed:	50	mm/min
Light-off Delay:	10	s	Retract Speed:	100	mm/min
Bottom Light-off Delay:	0	s			

Fig 17: 50% & 25% Flex100 settings

Flex100 0% : Rapid 100%

Layer Height:	0.05	mm	Bottom Lift Distance:	5	mm
Bottom Layer Count:	4		Lifting Distance:	5	mm
Exposure Time:	6	s	Bottom Lift Speed:	65	mm/min
Bottom Exposure Time:	60	s	Lifting Speed:	50	mm/min
Light-off Delay:	10	s	Retract Speed:	100	mm/min
Bottom Light-off Delay:	0	s			

Fig 18: 0% Flex100 settings

1.2 UV Exposure Testing

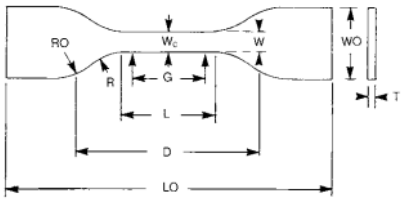
As the resin is cured by UV light, over exposure in direct sunlight will cause parts to continue to cure. This can lead to parts discolouring developing a yellow tinge and more brittle/rigid parts. The rigidity increase in the flexible resin causes splitting/layer separation when the shape is deformed. The timed over exposure testing led to a result of about 7 days behind a glass window with about 7 hours of sun exposure each day, totalling 49 hours. This is deemed to be acceptable as the end use is for deep sea applications where UV over exposure would not occur.

1.3 Tensile Testing

As this material is new to the market tensile testing was done to find out some of the main characteristics of different ratios of the material such as, elongation at break, ultimate tensile strength (UTS), and Young's Modulus. Testing is done in accordance with the requirements of 'ASTM D638 – 10 Standard Test Method for Tensile Properties of Plastics[1]'. It states that "Type IV specimen shall be used for testing nonrigid plastics with a thickness of 4 mm" *(D638)*.

1.3.1 Tensile Testing Standards/Preparation

- The dimensions for the test pieces are as follows:



TYPE IV

Specimen Dimensions for Thickness, *T*, mm (in.)[A]

Dimensions (see drawings)	7 (0.28) or under		Over 7 to 14 (0.28 to 0.55), incl	4 (0.16) or under		Tolerances
	Type I	Type II	Type III	Type IV[B]	Type V[C,D]	
W—Width of narrow section[E,F]	13 (0.50)	6 (0.25)	19 (0.75)	6 (0.25)	3.18 (0.125)	±0.5 (±0.02)[B,C]
L—Length of narrow section	57 (2.25)	57 (2.25)	57 (2.25)	33 (1.30)	9.53 (0.375)	±0.5 (±0.02)[C]
WO—Width overall, min[G]	19 (0.75)	19 (0.75)	29 (1.13)	19 (0.75)	...	+ 6.4 (+ 0.25)
WO—Width overall, min[G]	...	...	...	...	9.53 (0.375)	+ 3.18 (+ 0.125)
LO—Length overall, min[H]	165 (6.5)	183 (7.2)	246 (9.7)	115 (4.5)	63.5 (2.5)	no max (no max)
G—Gage length[I]	50 (2.00)	50 (2.00)	50 (2.00)	...	7.62 (0.300)	±0.25 (±0.010)[C]
G—Gage length[I]	...	...	...	25 (1.00)	...	±0.13 (±0.005)
D—Distance between grips	115 (4.5)	135 (5.3)	115 (4.5)	65 (2.5)[J]	25.4 (1.0)	±5 (±0.2)
R—Radius of fillet	76 (3.00)	76 (3.00)	76 (3.00)	14 (0.56)	12.7 (0.5)	±1 (±0.04)[C]
RO—Outer radius (Type IV)	...	...	...	25 (1.00)	...	±1 (±0.04)

Fig 19: ASTM D638 – 10 test dimensions *(D638)*

Conditions for tensile testing:

- All parts printed in the same orientation. (3 orientations were tested – face flat, edge printing, and 45-degree angle).
- All parts post cured with 405nm wavelength UV light for 10 minutes each side, totalling 20 minutes.
- All parts kept in shaded containers until testing time, so the post UV is maintained constant.
- 5 parts of each ratio were printed in case of defects, with the best 3 selected for testing.
- A test speed of 50mm/min as recommended in ASTM D638 – 10.

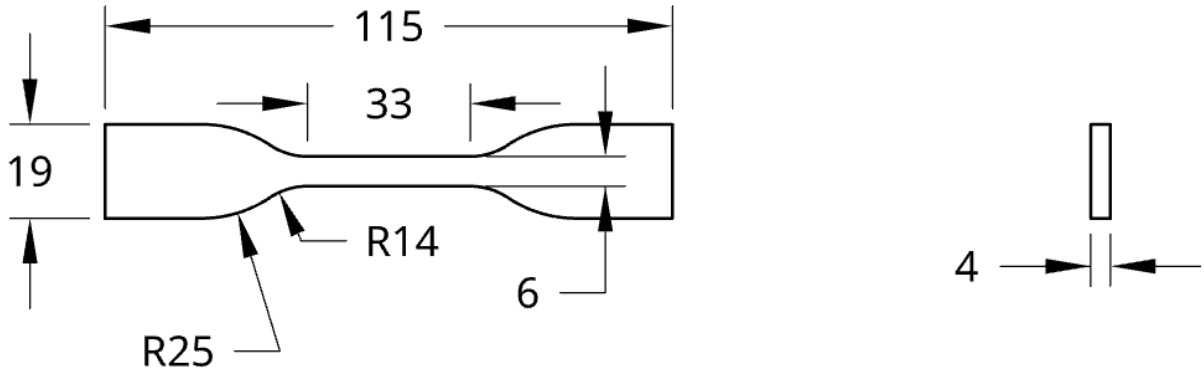


Fig 20: Designed drawing dimensions for testing *(Onshape)*

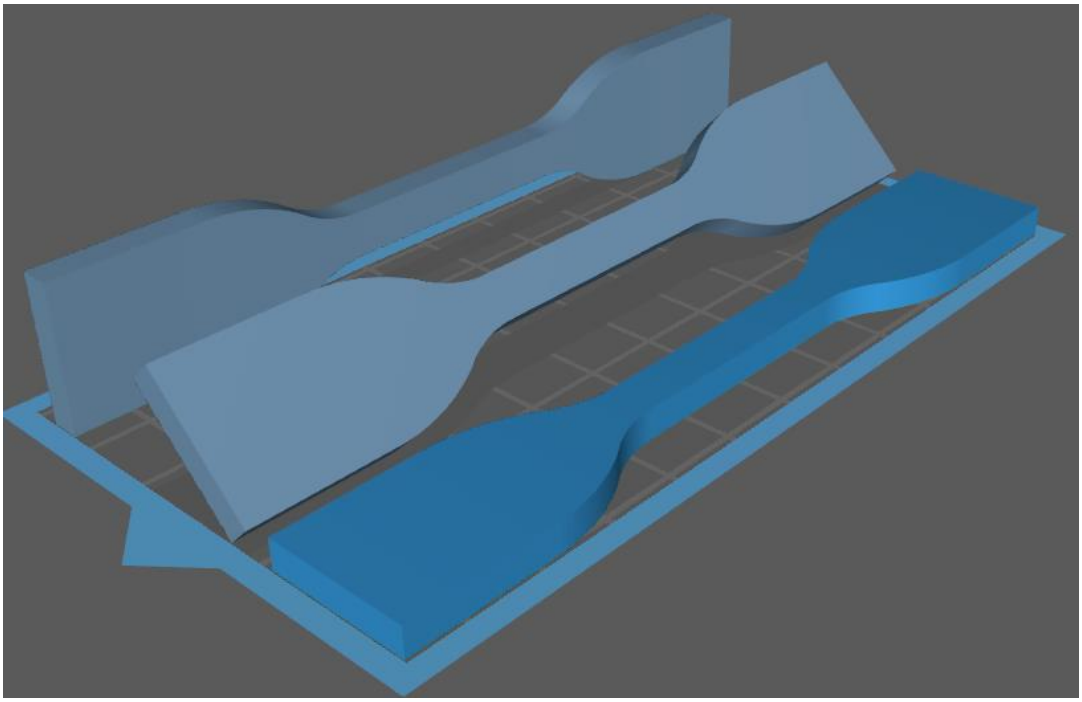


Fig 21: Printing orientation, On Edge, 45 Degree, and Face Flat *(Chitubox)*

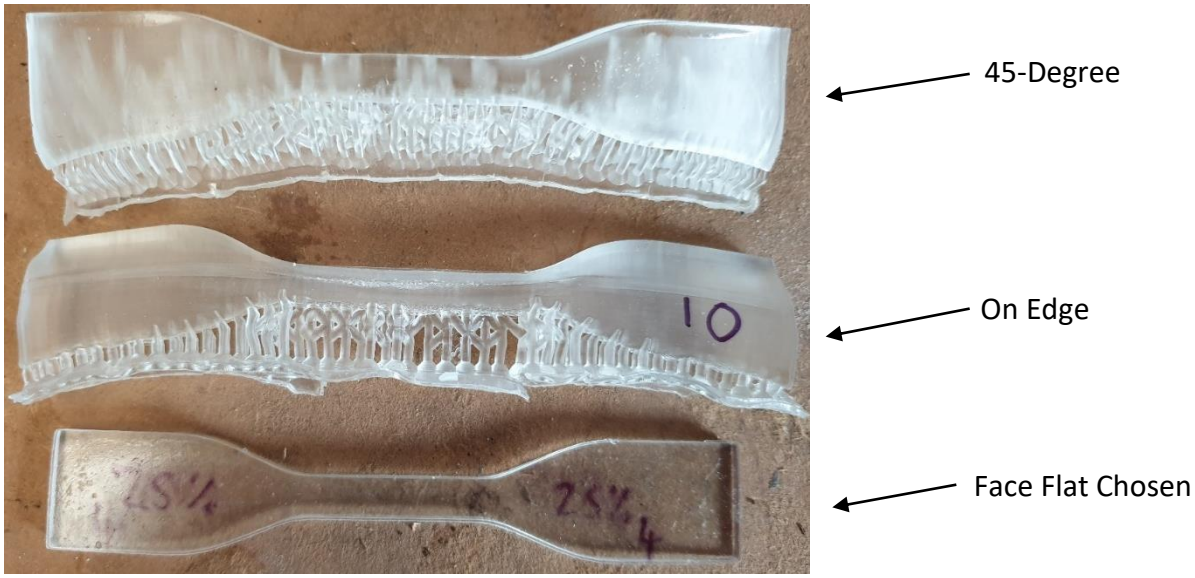


Fig 22: Orientation testing

Fig 23: 405nm UV curing chamber

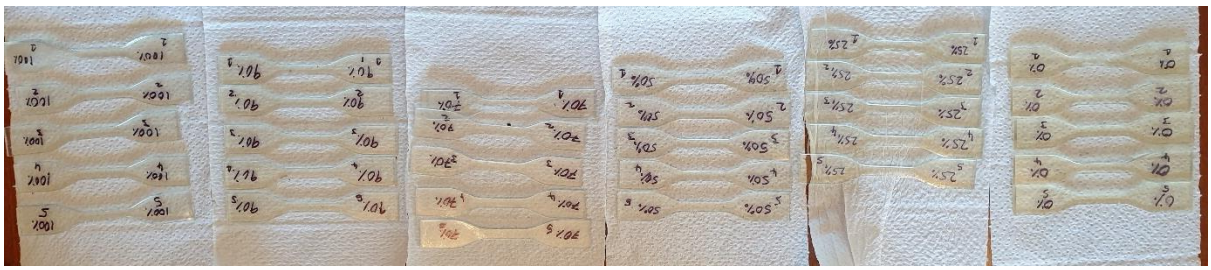


Fig 24: All prepared test pieces

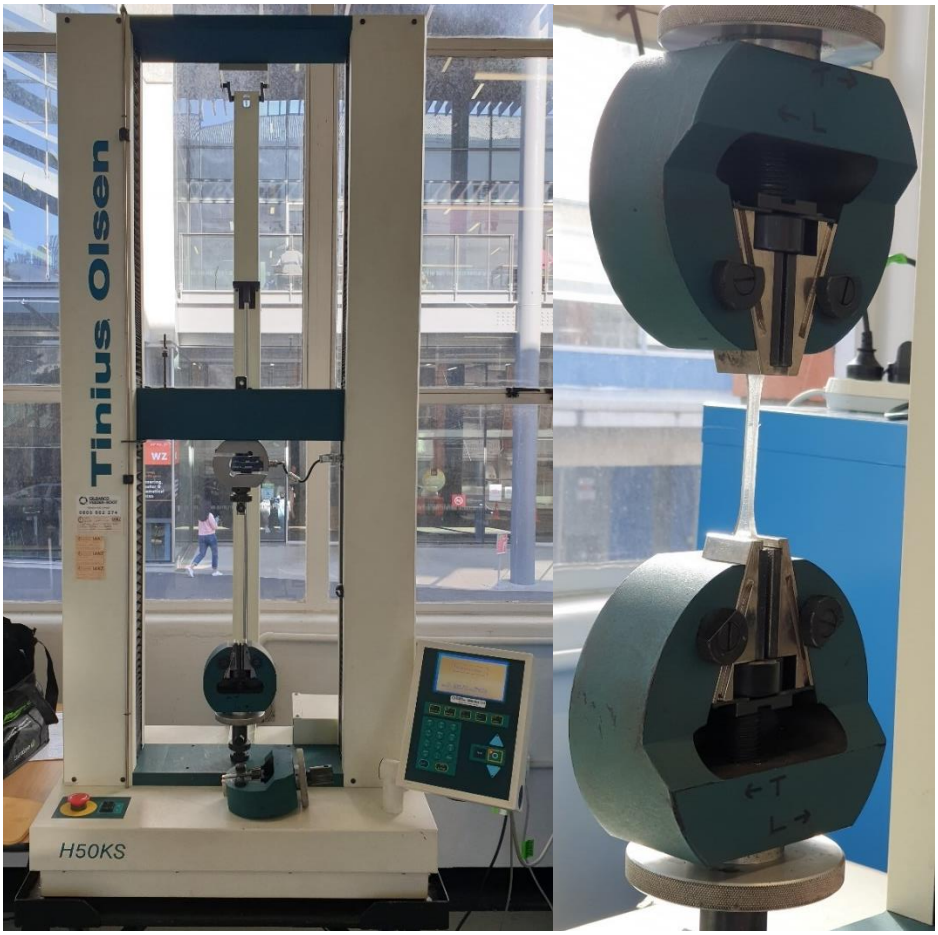


Fig 25: Tinius Olsen tensile test machine

1.3.2 Tensile Test Results (Graphs on page 57)

All cross-sectional areas were measured for each test sample before testing. This data plus the data provided by the tensile testing graphs gives enough data to be to calculate the Young's modulus. Below is an example calculation and its corresponding graph, followed by tables showing the full results. It is important to note that the initial length used is the length of the test section which is 33mm. Some of the more flexible ratios had some 'stretch' outside of this test region but it was minimal, and the testing equipment only gave the overall extension. This means these are only close estimations and should not be taken as exact figures.

$$Young's\ modulus\ E = \frac{Stress\ \sigma}{Strain\ \epsilon}$$

$$E = \frac{F \times L}{A \times \Delta L}$$

$$E = \frac{530.666N \times 0.033m}{(0.0064m \times 0.00379m) \times (11.47 \times 10^{-6}m)} = 62.94\ MPa$$

Equation 6: Young's modulus

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	530.666	-5.666	11.470	-5.666	0.000	0.000	0.000	0.000

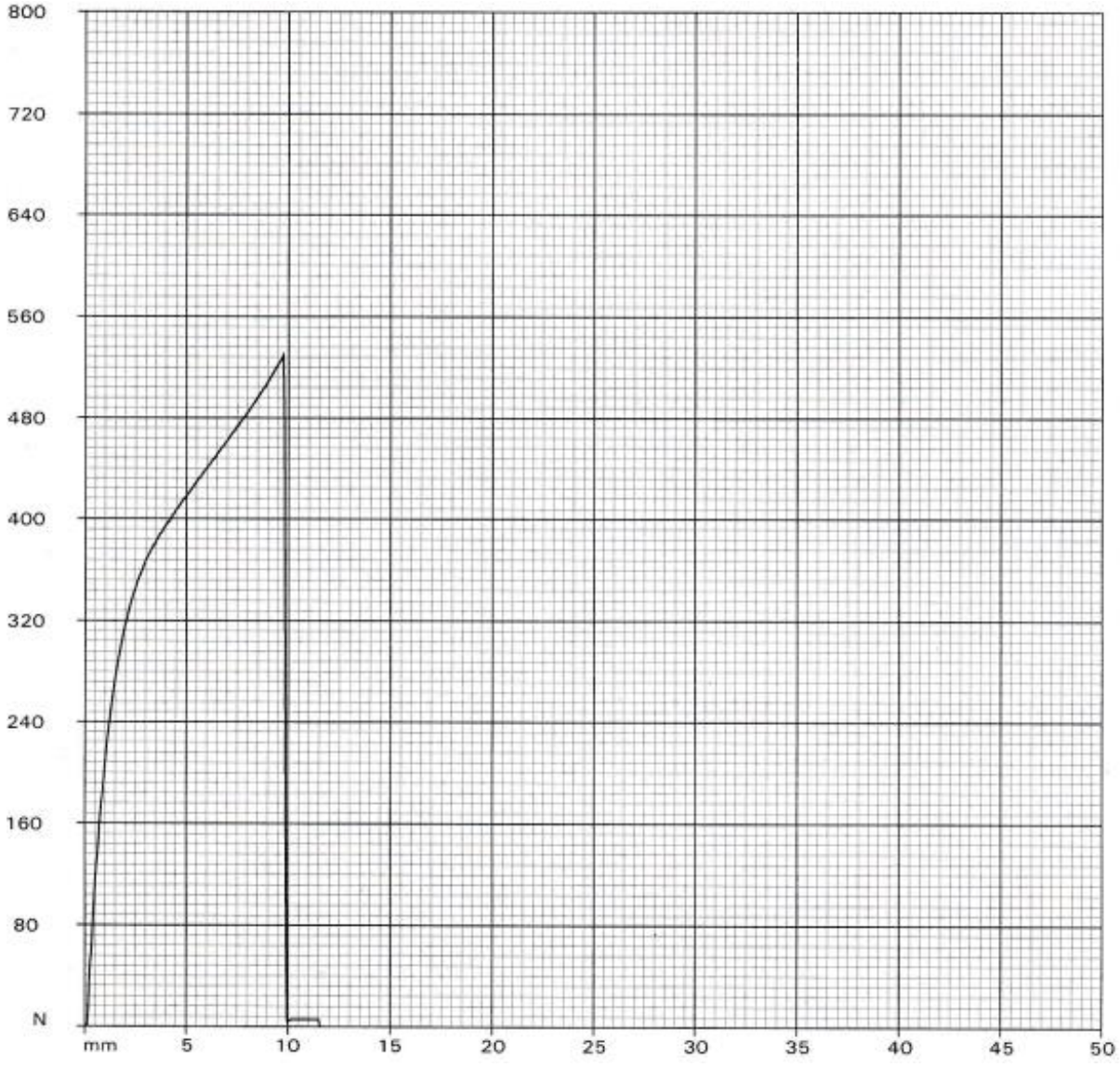


Fig 26: Tinius Olsen tensile graph print out 25% No.1

Flex100 %	Sample No.	Width (mm)	Thick (mm)	Area (mm^2)	Length (mm)	ΔLength (mm)	UTS (N)
100%	4	6.41	3.96	25.38	33.00	31.22	14.67
	3	6.51	3.78	24.61	33.00	38.56	20.00
	2	6.52	3.88	25.30	33.00	32.63	18.33
90%	3	6.49	3.79	24.60	33.00	15.83	28.00
	2	6.19	3.73	23.09	33.00	15.27	27.67
	1	6.20	3.80	23.56	33.00	14.73	25.67
70%	3	6.34	3.89	24.66	33.00	13.75	63.67
	2	6.37	3.81	24.27	33.00	17.62	83.00
	1	6.19	3.84	23.77	33.00	16.17	80.00
50%	5	6.57	3.90	25.62	33.00	14.12	163.33
	3	6.36	3.82	24.30	33.00	17.44	196.67
	1	6.38	3.78	24.12	33.00	19.71	207.00
25%	3	6.49	3.77	24.47	33.00	10.23	513.33
	2	6.39	3.79	24.22	33.00	10.26	493.33
	1	6.40	3.79	24.26	33.00	11.47	530.67
0%	5	6.37	3.76	23.95	33.00	5.19	552.67
	4	6.51	3.77	24.54	33.00	5.91	640.00
	3	6.39	3.68	23.52	33.00	4.50	504.33

Table 1: Flex100 tensile test data

Young's Modulus (N/mm^2)	Young's Modulus (N/m^2)
0.61	610794.55
0.70	695523.16
0.73	733023.06
2.37	2372751.65
2.59	2589195.93
2.44	2440751.59
6.20	6197354.03
6.41	6405401.67
6.87	6867386.13
14.90	14895726.69
15.32	15321482.67
14.37	14373127.90
67.67	67665383.18
65.49	65493378.71
62.94	62943748.23
146.77	146774105.68
145.71	145706233.71
157.38	157383703.85

Table 2: Flex100 % ratio Young’s modulus

Flex100 %	Avg UTS (N)	Avg Young's Modulus (MPa)
100%	17.67	0.68
90%	27.11	2.47
70%	75.56	6.49
50%	189.00	14.86
25%	512.44	65.37
0%	565.67	149.95

Table 3: Flex100 average UTS and Young's modulus

1.4 Material Conclusion

From this we can conclude that Flex100 has some very promising properties with 100% Flex100 stretching up to 38mm in the tensile test, however applying the properties in a functional way is difficult. It all comes down to the geometry of the shape guiding which ratio of resin to use. The more flexible the part the harder it is to print larger shapes with high levels of detail, especially those with detail where support would be required. This is due to the high level of support needed to keep the part stable during printing as the stress of separating from the FEP sheet can deform or cause the part to fail if adequate support is not available. Accuracy of print is also a factor as the flexible properties cause geometry inaccuracies during printing. The more Rigid resin that is added the more accurate the printing becomes. The rigid resin has very high stress potential applications, reaching a Young's modulus of 149.95 MPa at 0% Flex100 (or 100% Rigid), compared to the 100% Flex100 of 0.68 MPa. It would make it a very good choice for any mechanical moving parts that would be undergoing excessive strain or stress.

2 Tensile Test Graphs

100%, 2

6.52 x 3.88

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Hounsfield
Test Report
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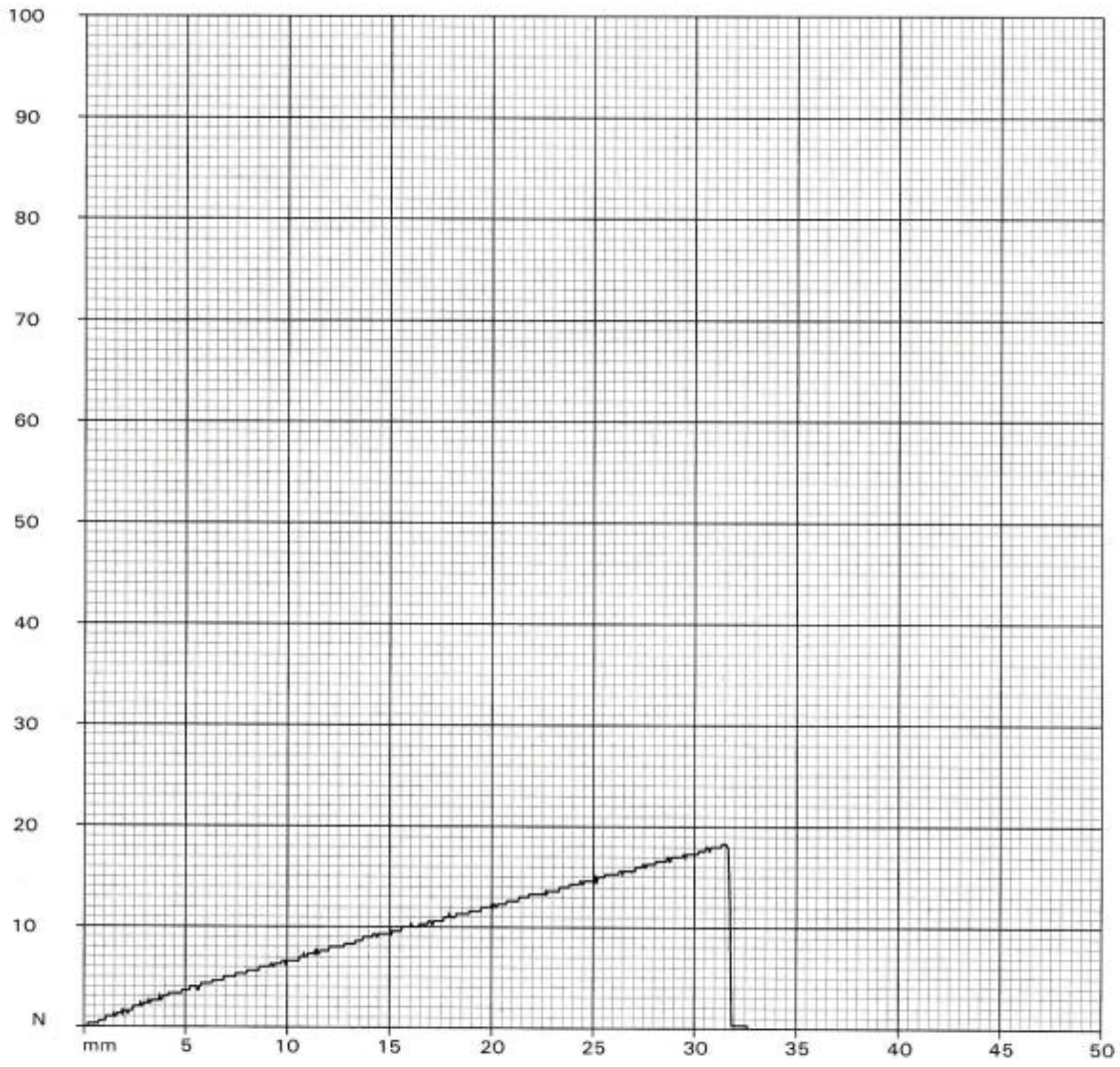
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	18.333	-0.333	32.625	6.666	0.000	0.000	0.000	0.000



100%, 3

6.51 x 3.78

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Hounsfield
Test Report
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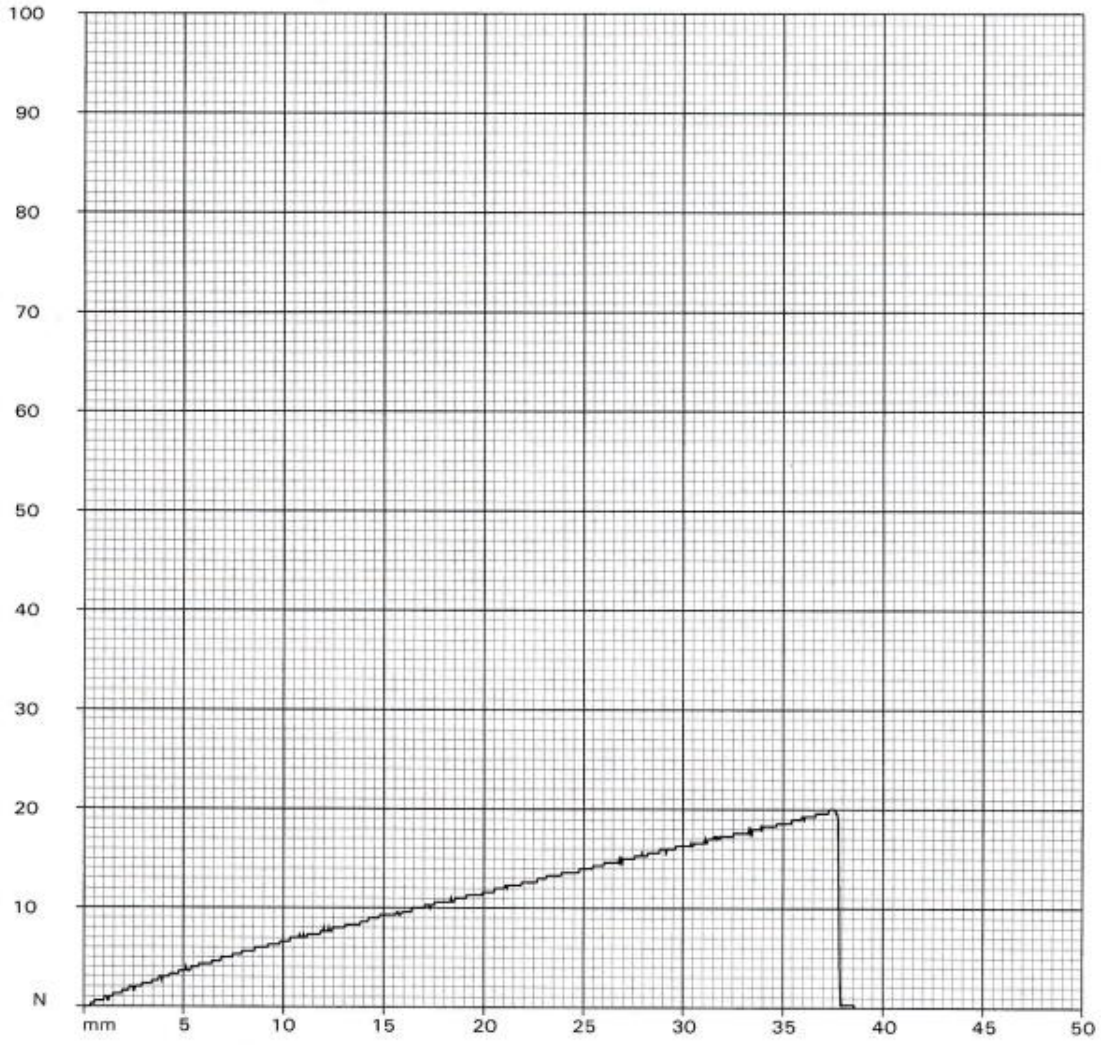
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator ......:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	20.000	0.333	38.562	6.666	0.000	0.000	0.000	0.000



100%, 4
6.41 x 3.96

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Hounsfield
Test Report
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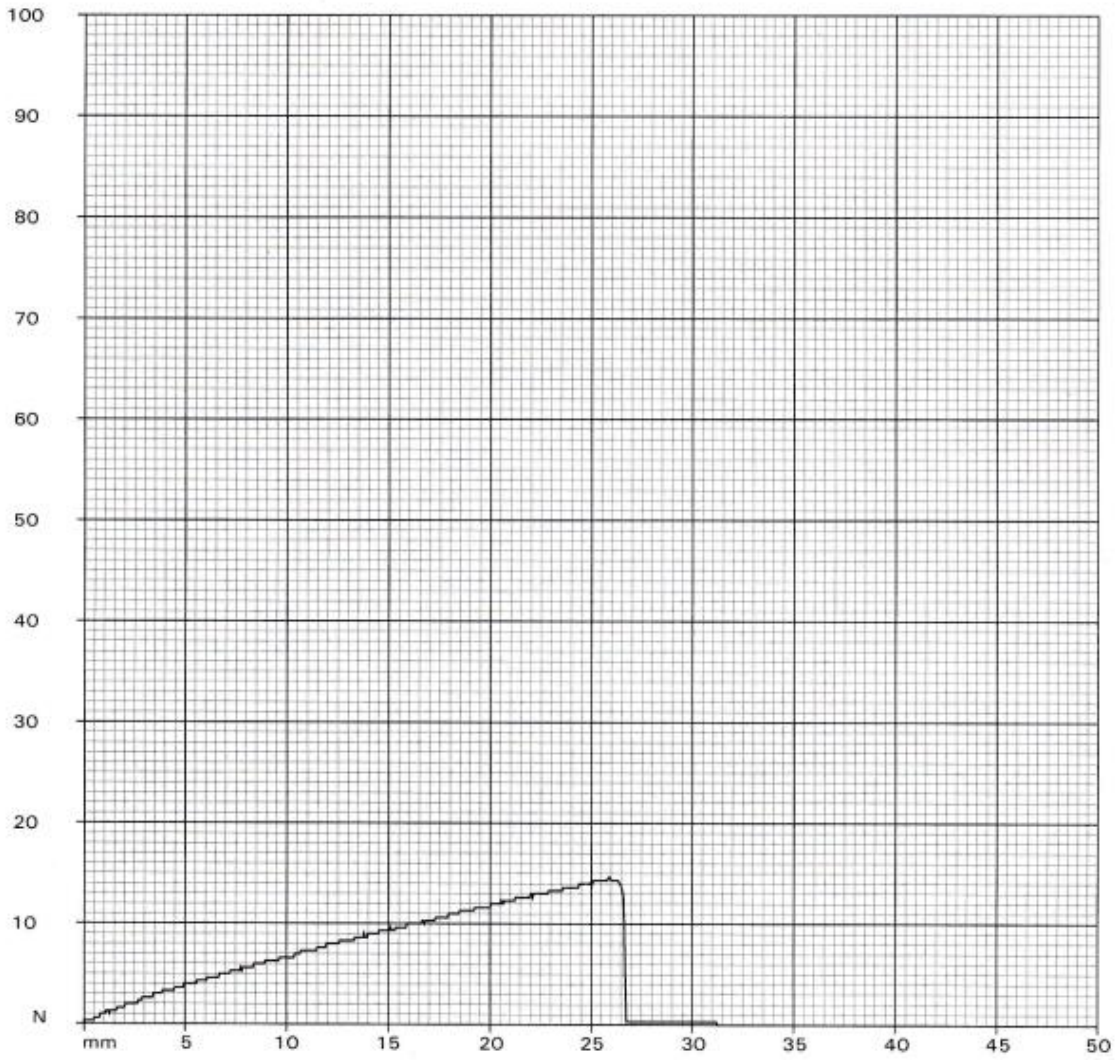
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	14.666	0.333	31.216	6.666	0.000	0.000	0.000	0.000



90%, 1

6.2 × 3.8

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Hounsfield
Test Report
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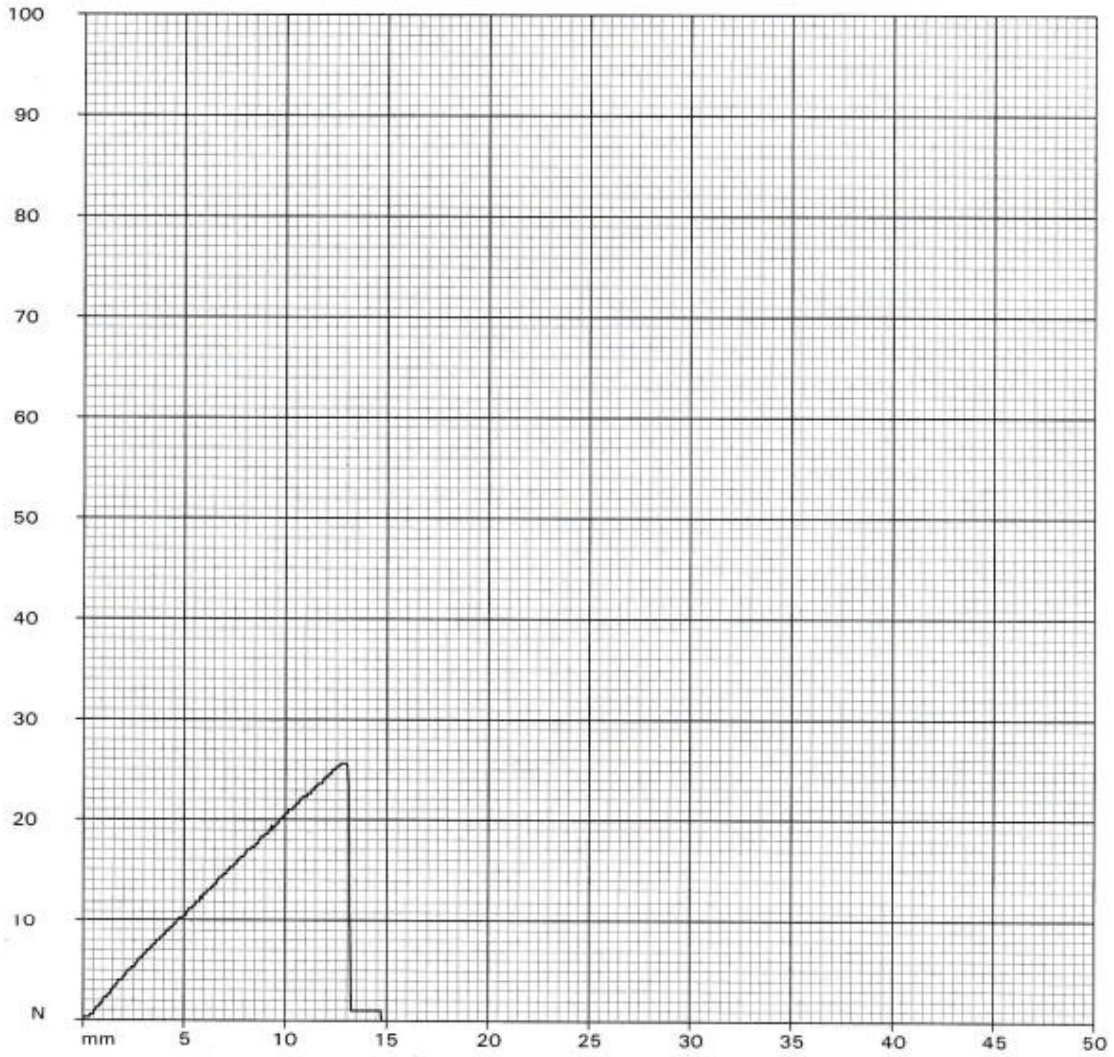
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	25.666	1.000	14.729	20.333	0.000	0.000	0.000	0.000



90%, 2

6.19 x 3.73

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Hounsfield
Test Report
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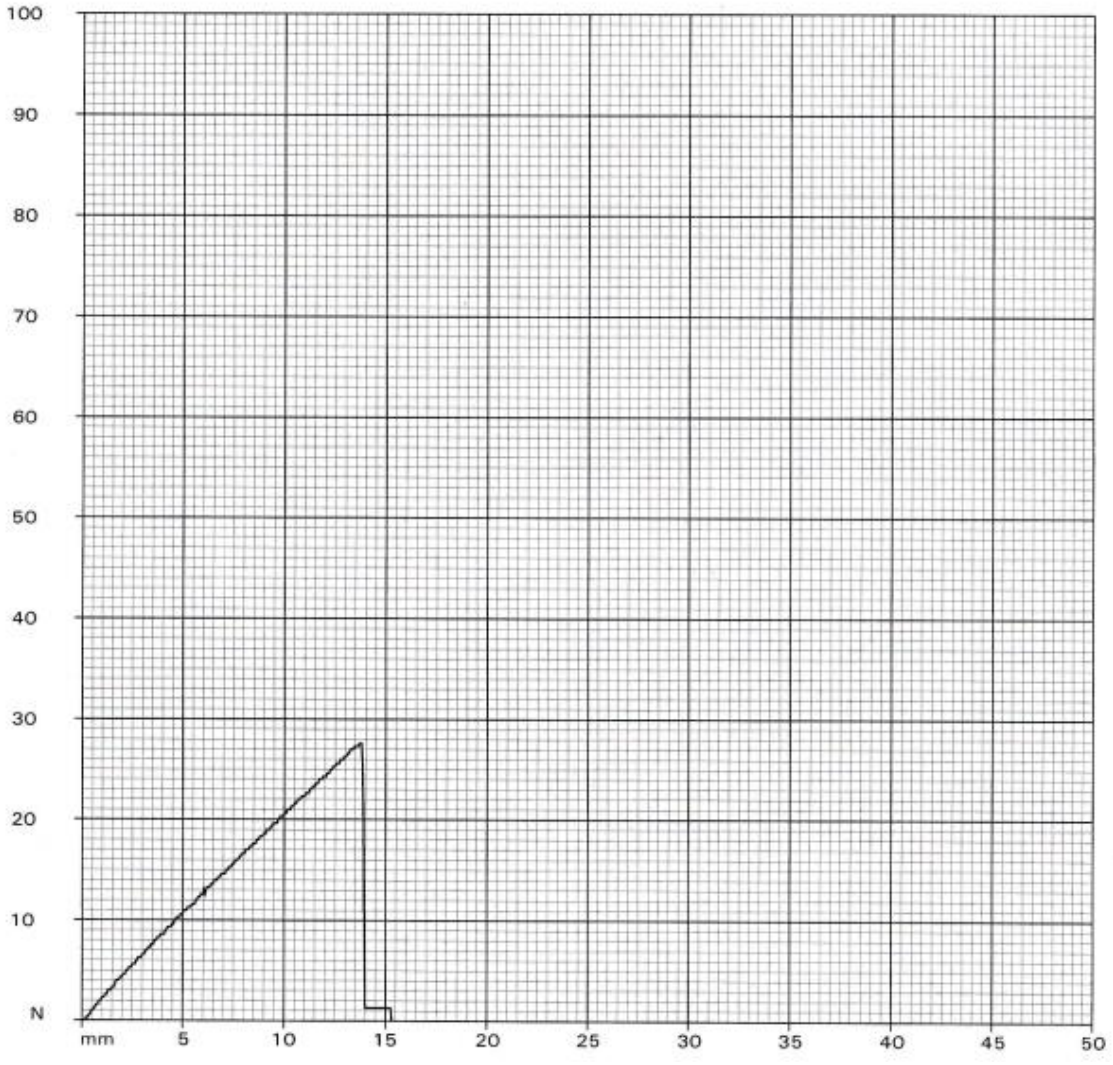
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	27.666	1.333	15.272	20.333	0.000	0.000	0.000	0.000



90%, 3

6.49 x 3.79

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Hounsfield
Test Report
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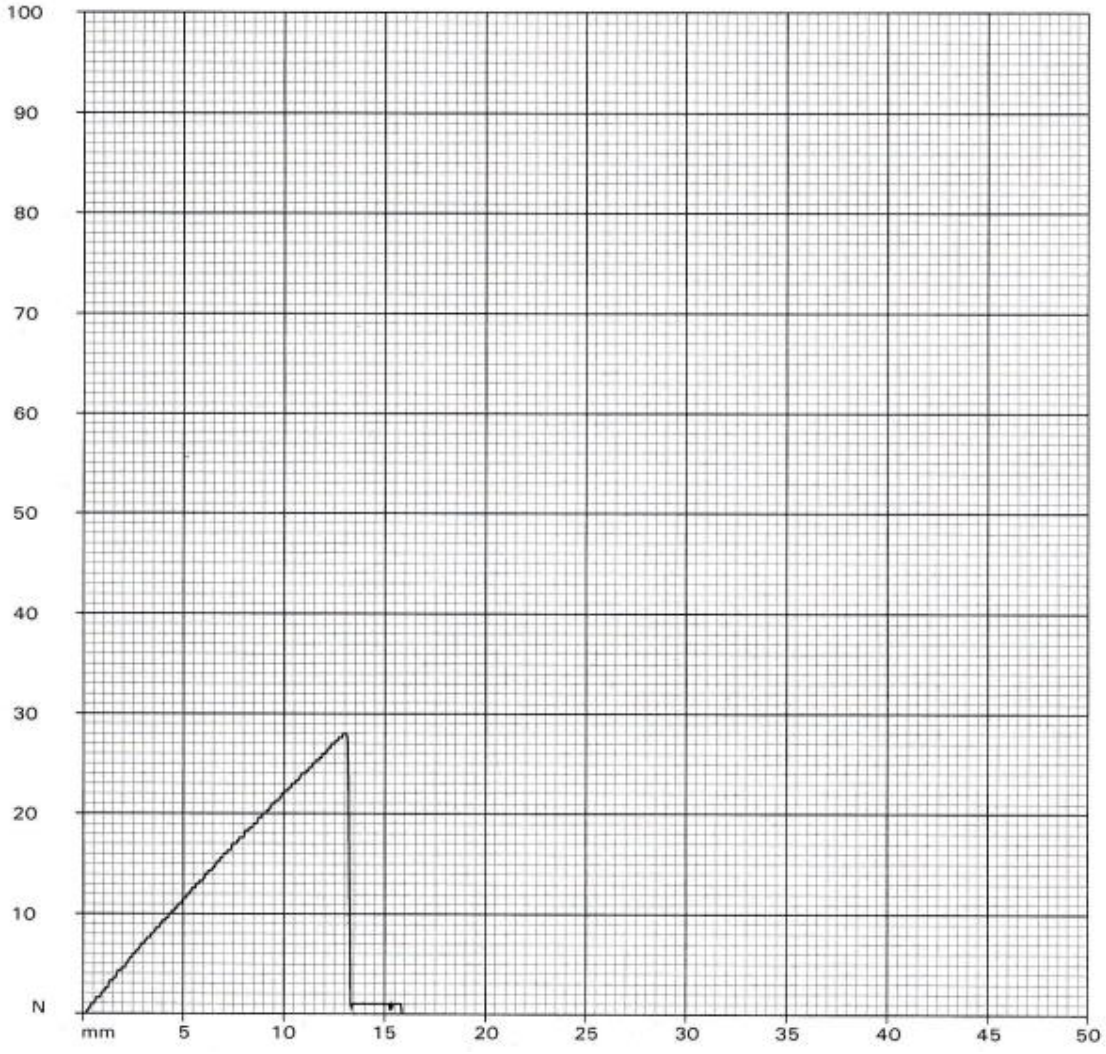
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	28.000	1.000	15.832	22.000	0.000	0.000	0.000	0.000



70%, 1

6.19 x 3.84

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Hounsfield
Test Report
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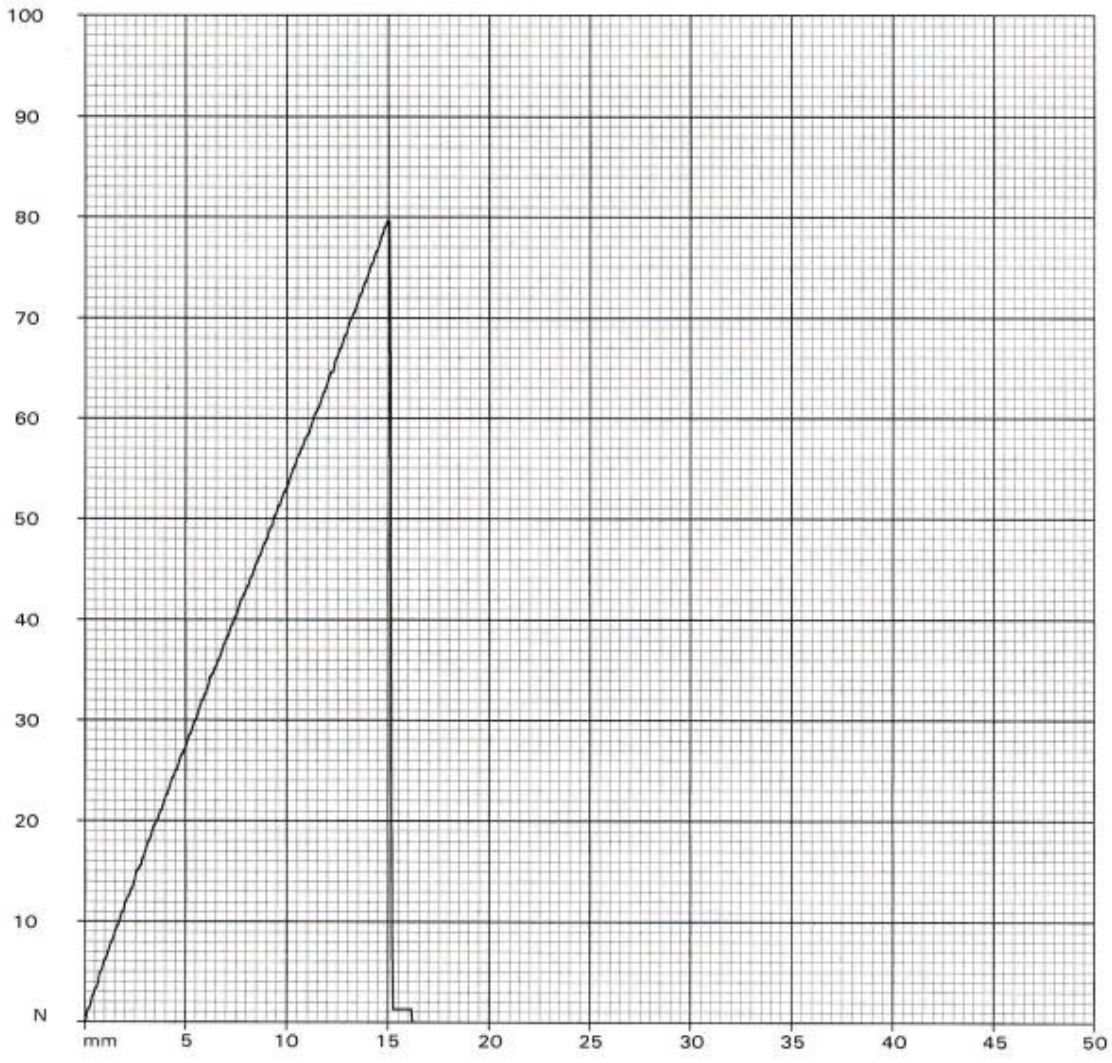
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	80.000	1.333	16.173	53.000	0.000	0.000	0.000	0.000



70%, 2

6.37 x 3.81

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Hounsfield
Test Report
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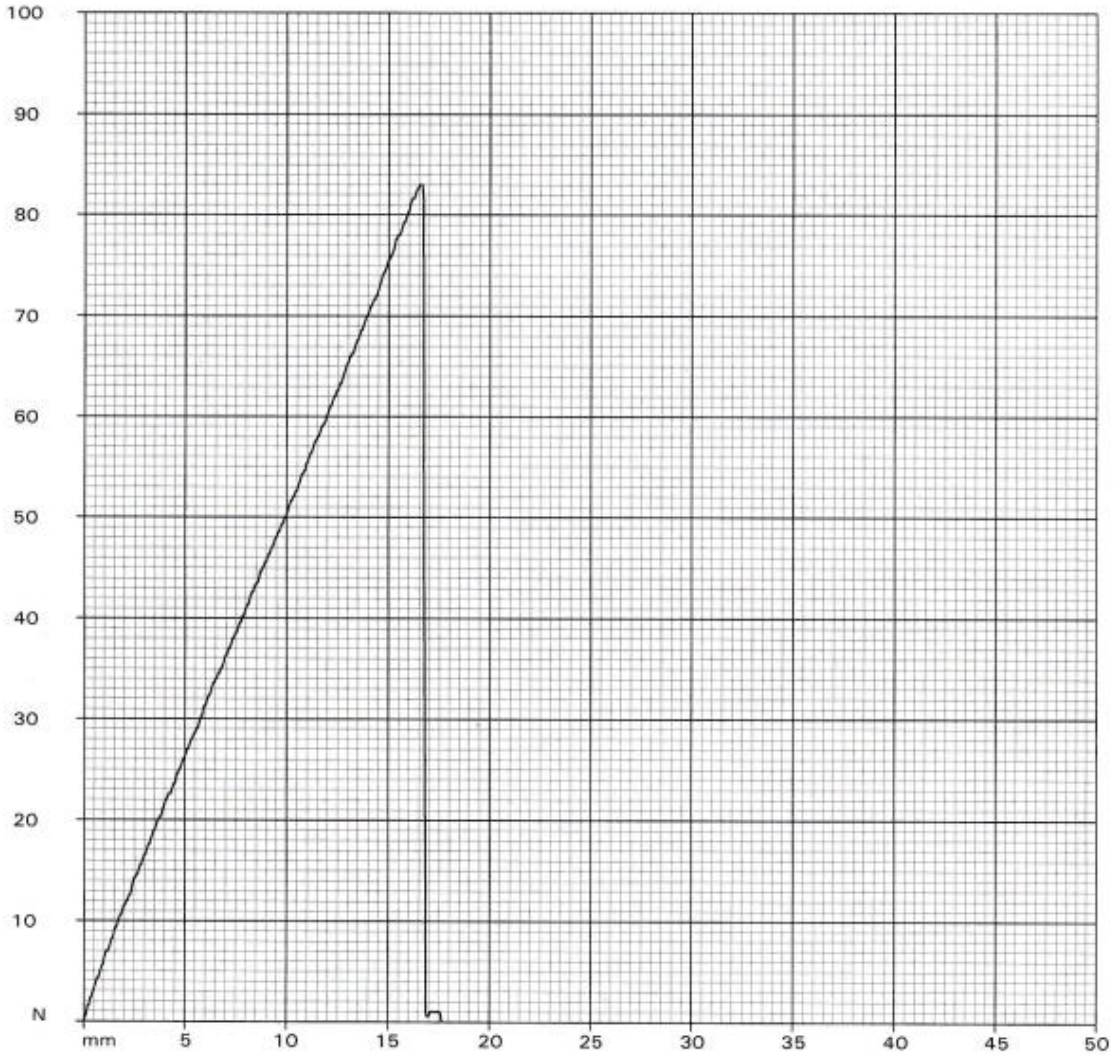
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	83.000	0.666	17.619	50.333	0.000	0.000	0.000	0.000



70%, 3

6.34 x 3.89

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Hounsfield
Test Report
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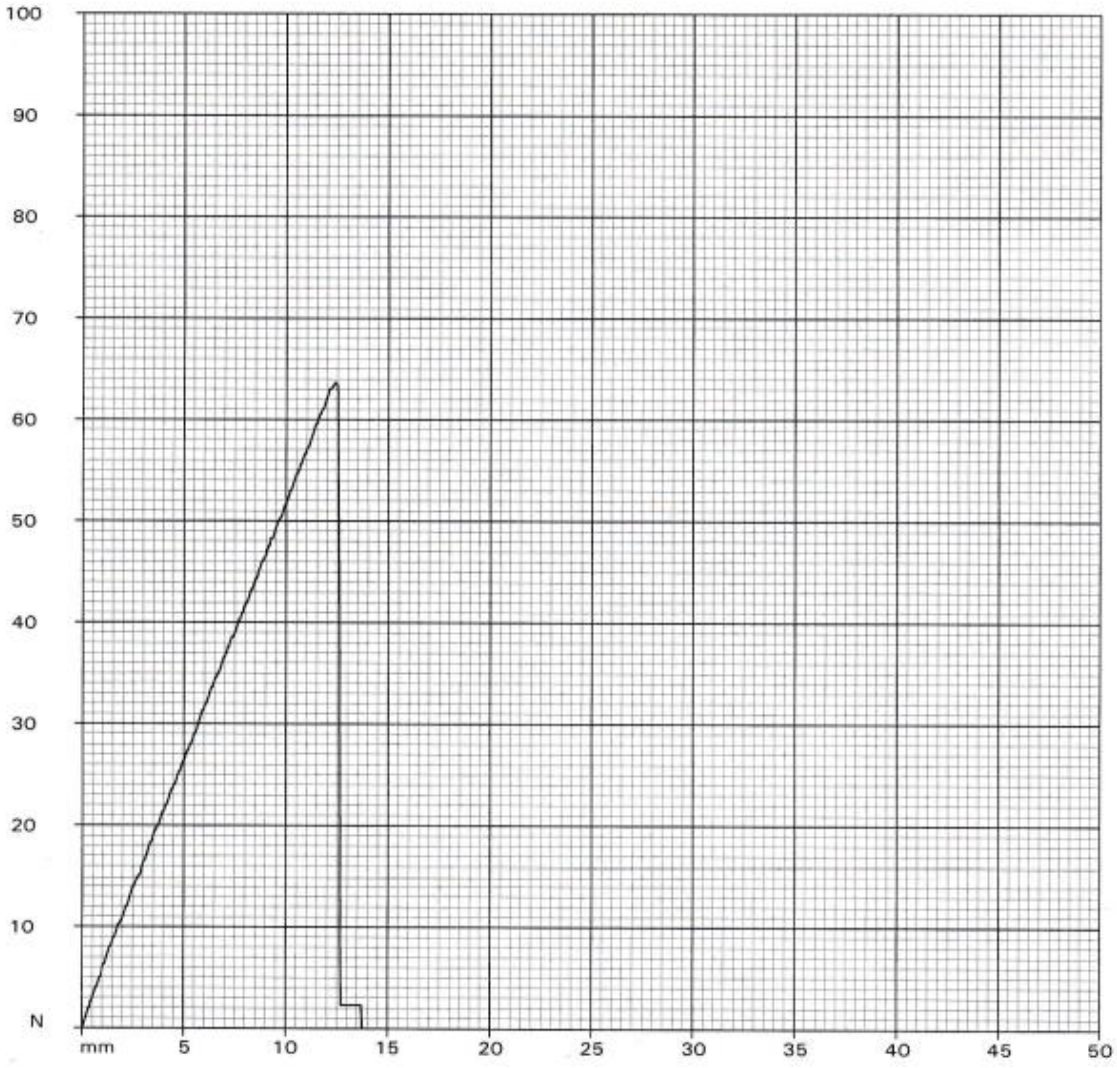
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	63.666	2.333	13.746	51.666	0.000	0.000	0.000	0.000



50%, 1

6.38×3.78

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Hounsfield
Test Report
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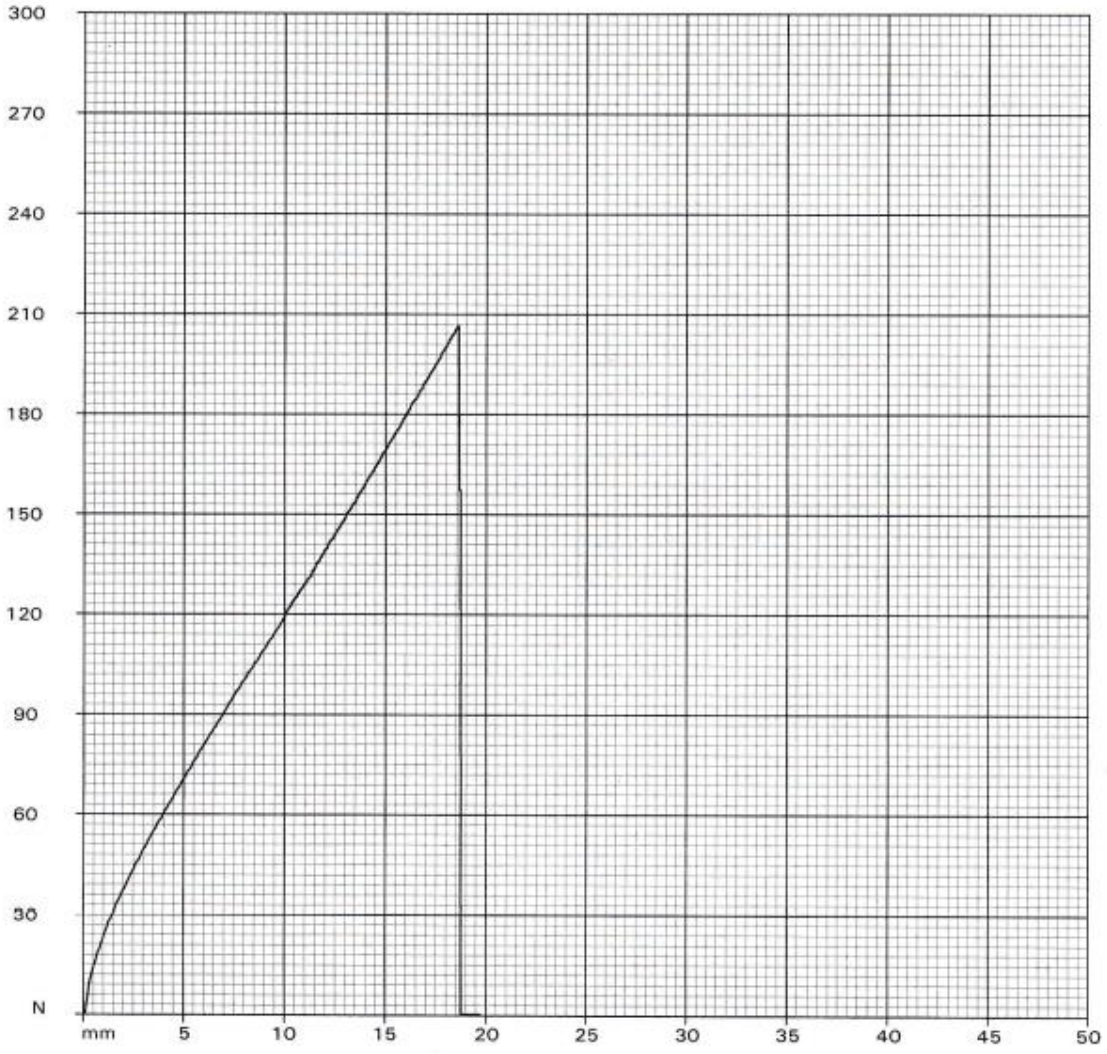
DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	207.000	0.333	19.707	120.000	0.000	0.000	0.000	0.000



50%, 3

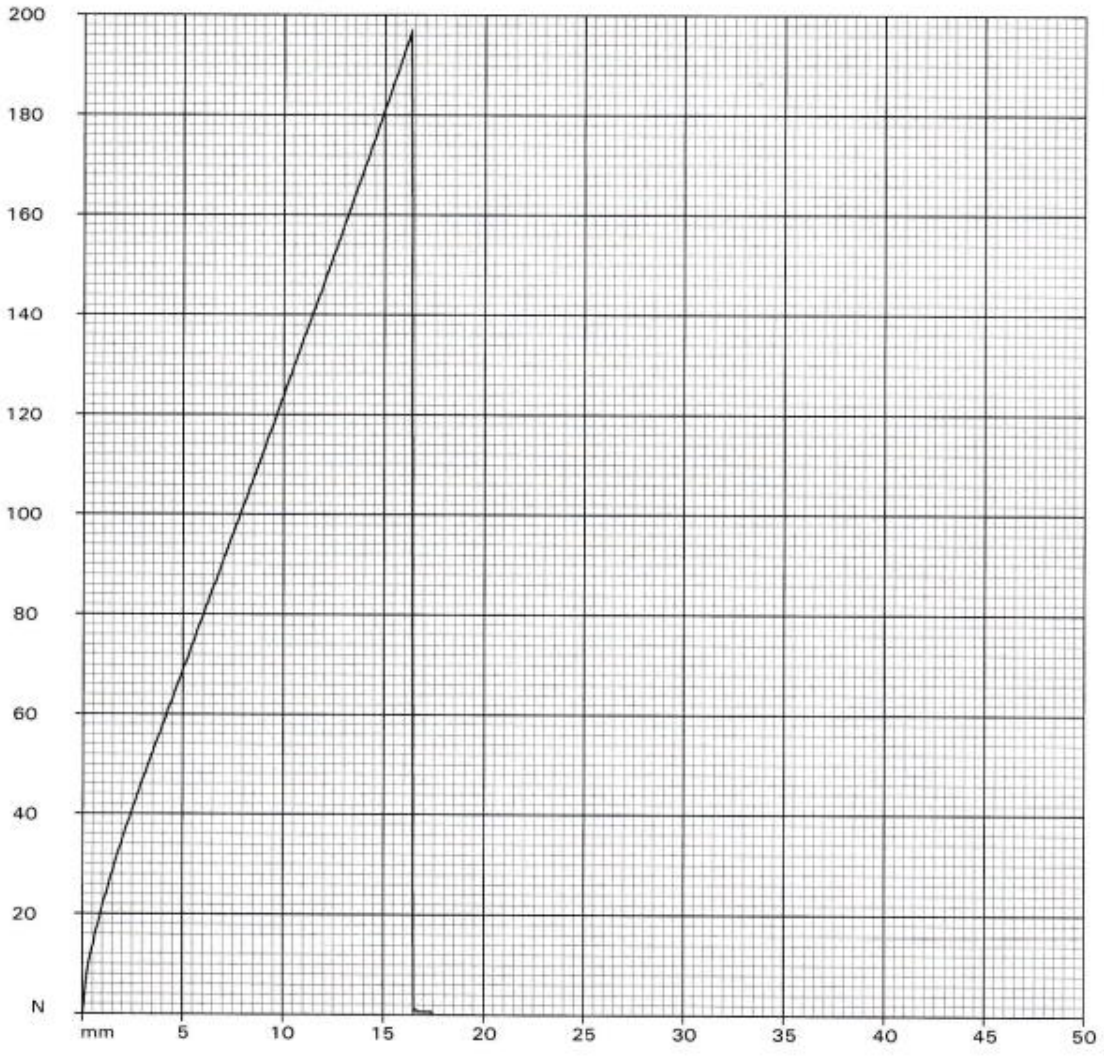
6.36 x 3.82

****
Hounsfield
Test Report
****

DEST TEST 2021 | EXT TEST 2021

Batch Number ..:----
Operator ......:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	196.666	0.666	17.435	123.666	0.000	0.000	0.000	0.000



50%, 5 x

6.57 x 3.9

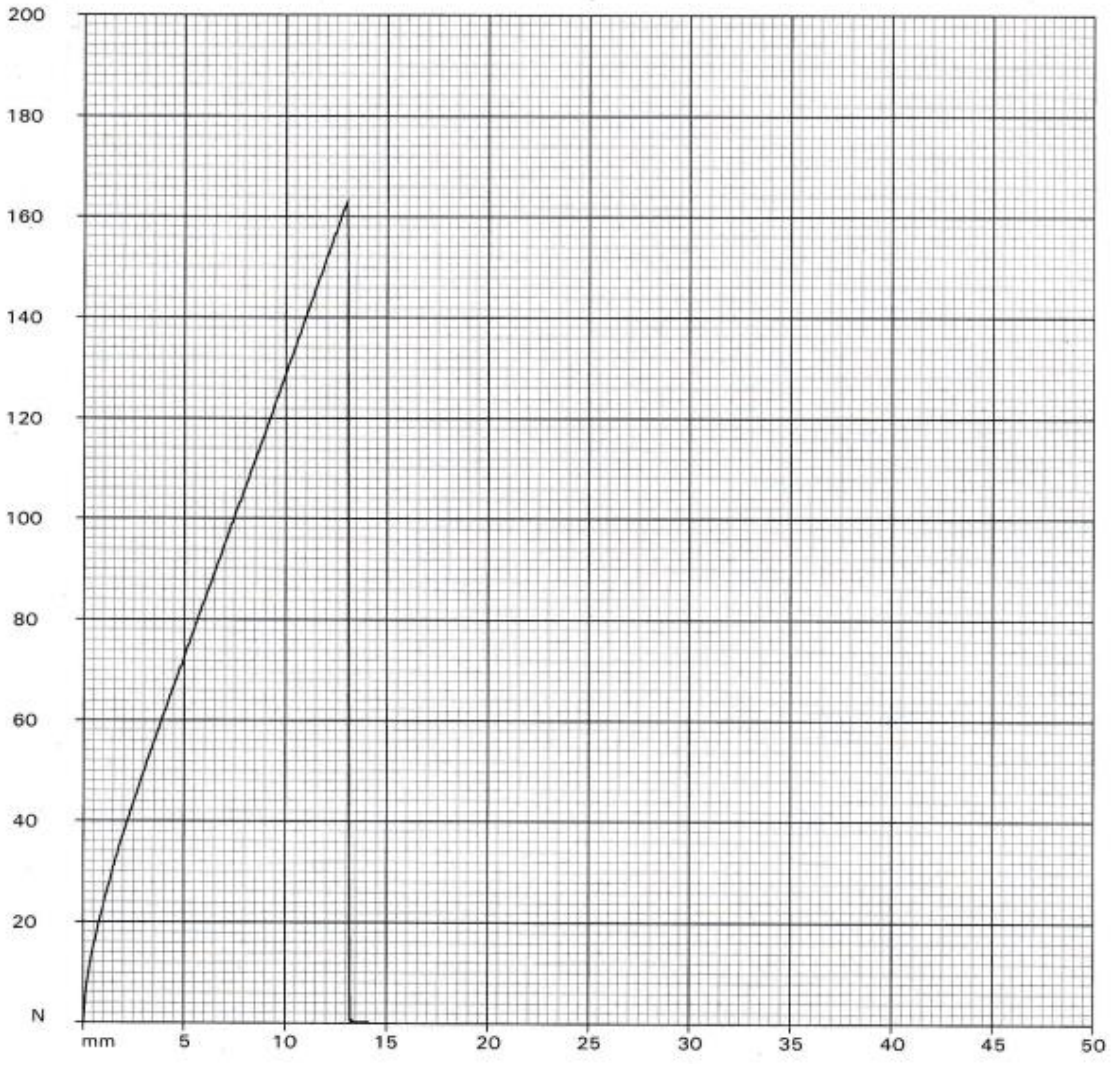
****
Hounsfield
Test Report
****

DEST TEST
2021

EXT TEST
2021

Batch Number ..:----
Operator ......:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	163.333	0.333	14.122	128.666	0.000	0.000	0.000	0.000



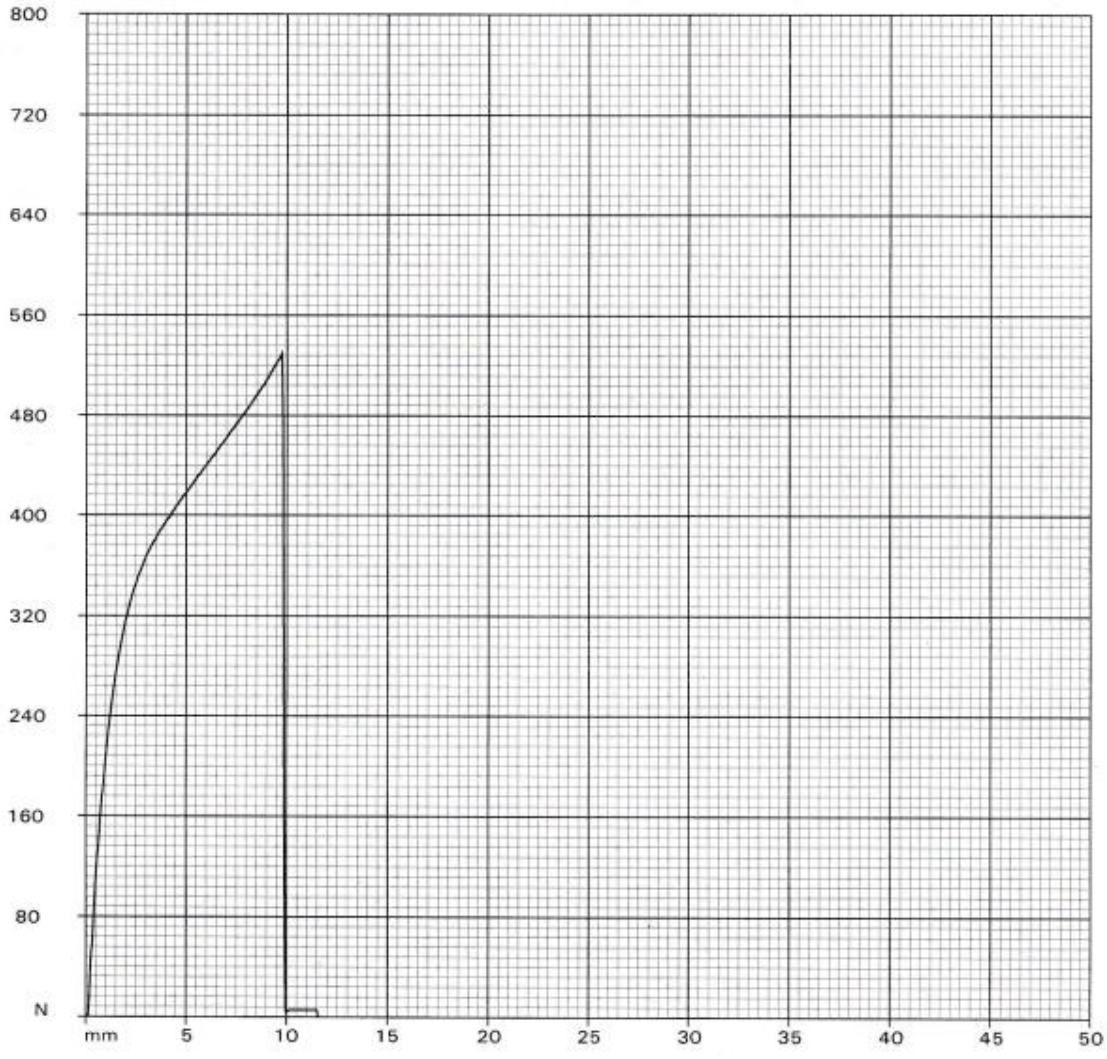
25%, 1

6.4 x 3.79

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	530.666	-5.666	11.470	-5.666	0.000	0.000	0.000	0.000



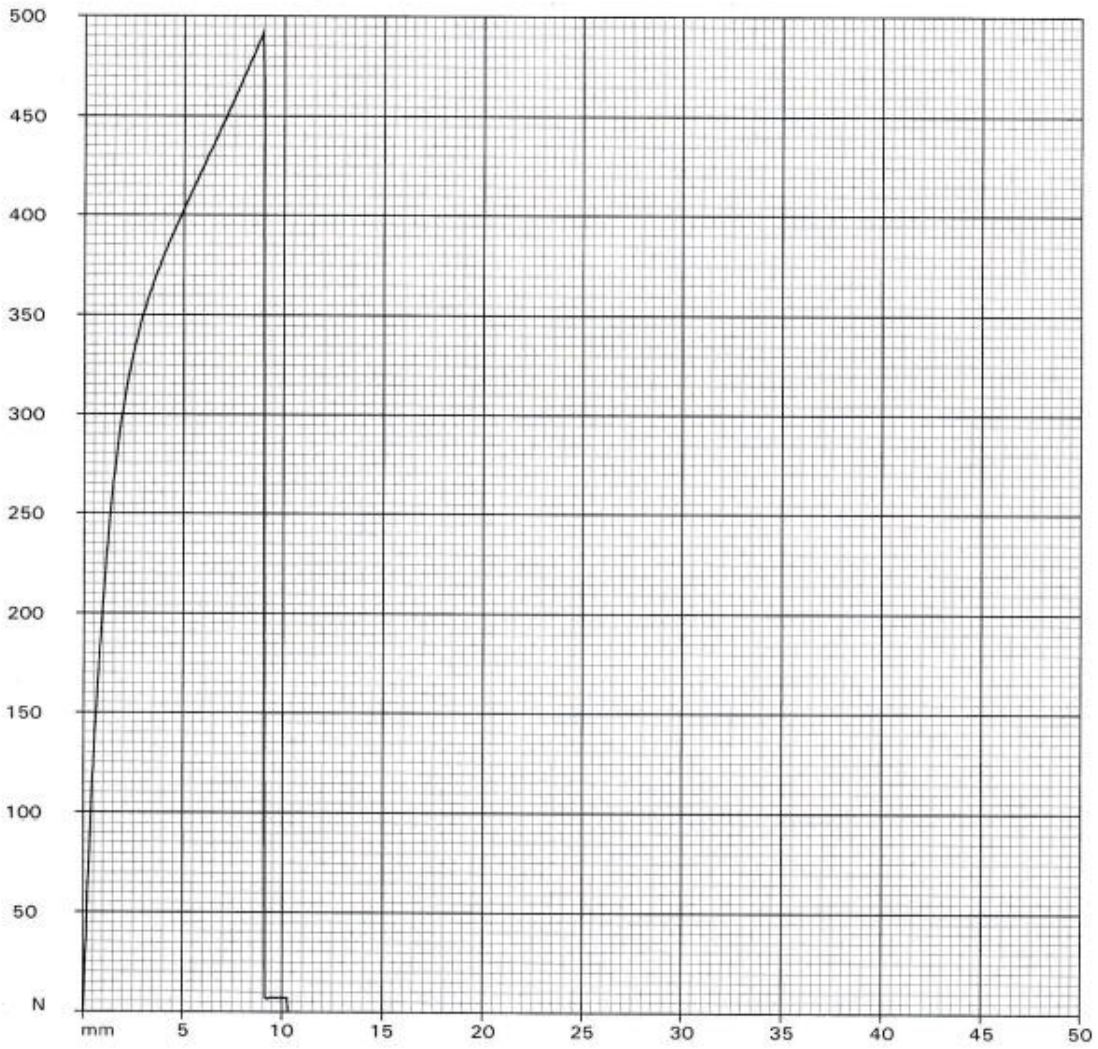
25%, 2

6.39 × 3.79

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	493.333	-7.000	10.264	-7.000	0.000	0.000	0.000	0.000



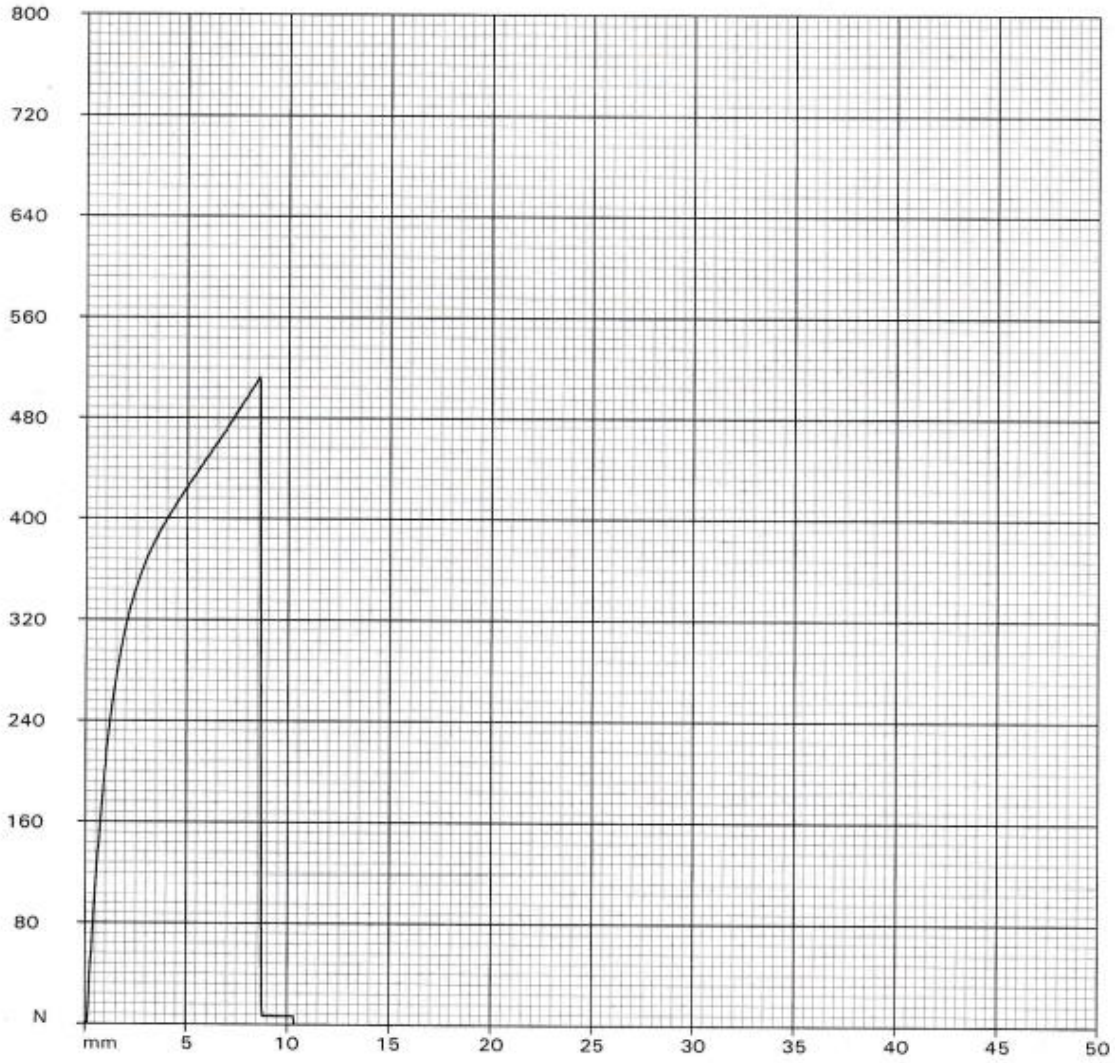
25%, 3

6.49 x 3.77

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator ......:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	513.333	-7.000	10.232	-7.000	0.000	0.000	0.000	0.000



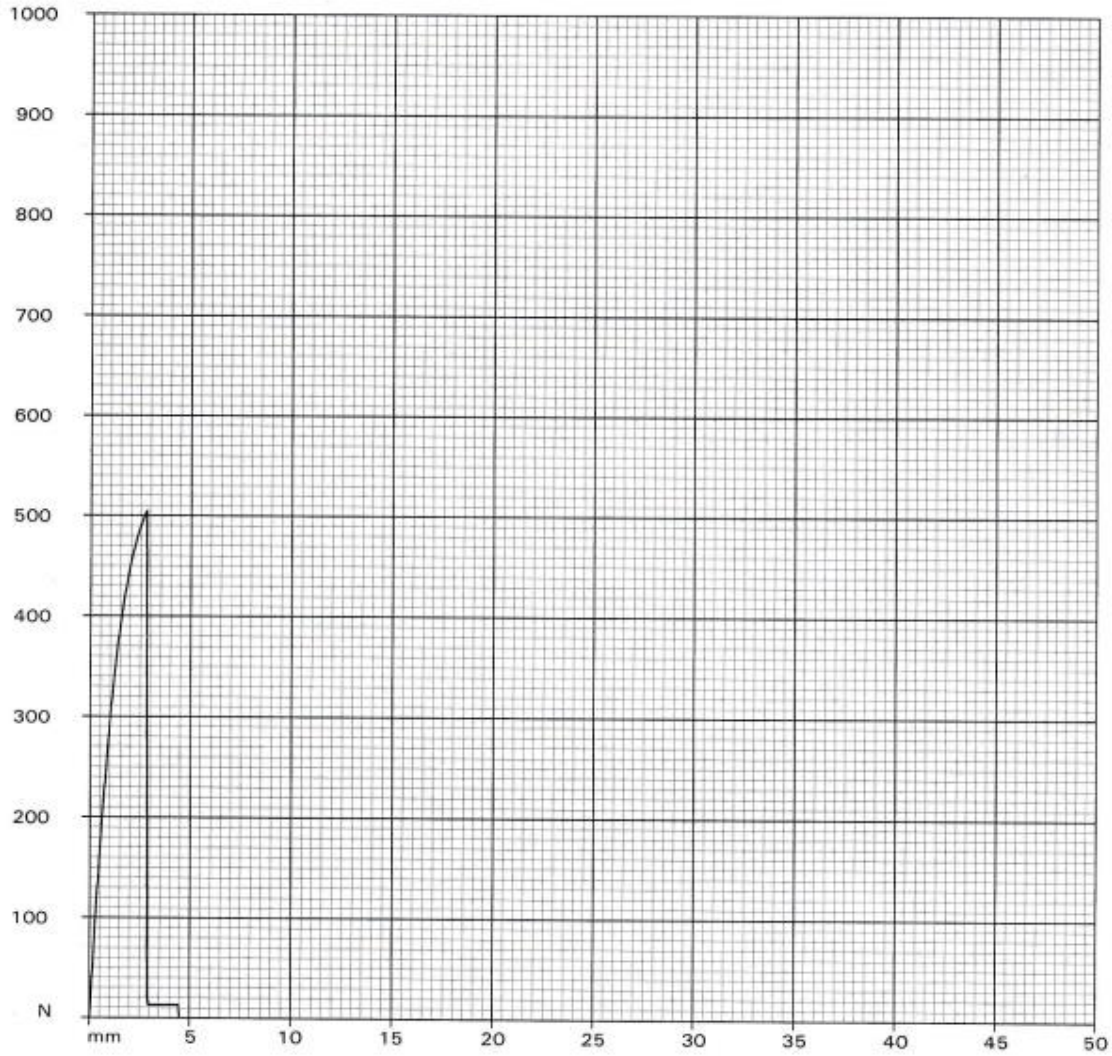
0%, 3

6.39 x 3.68

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	504.333	-13.666	4.497	0.000	0.000	0.000	0.000	0.000



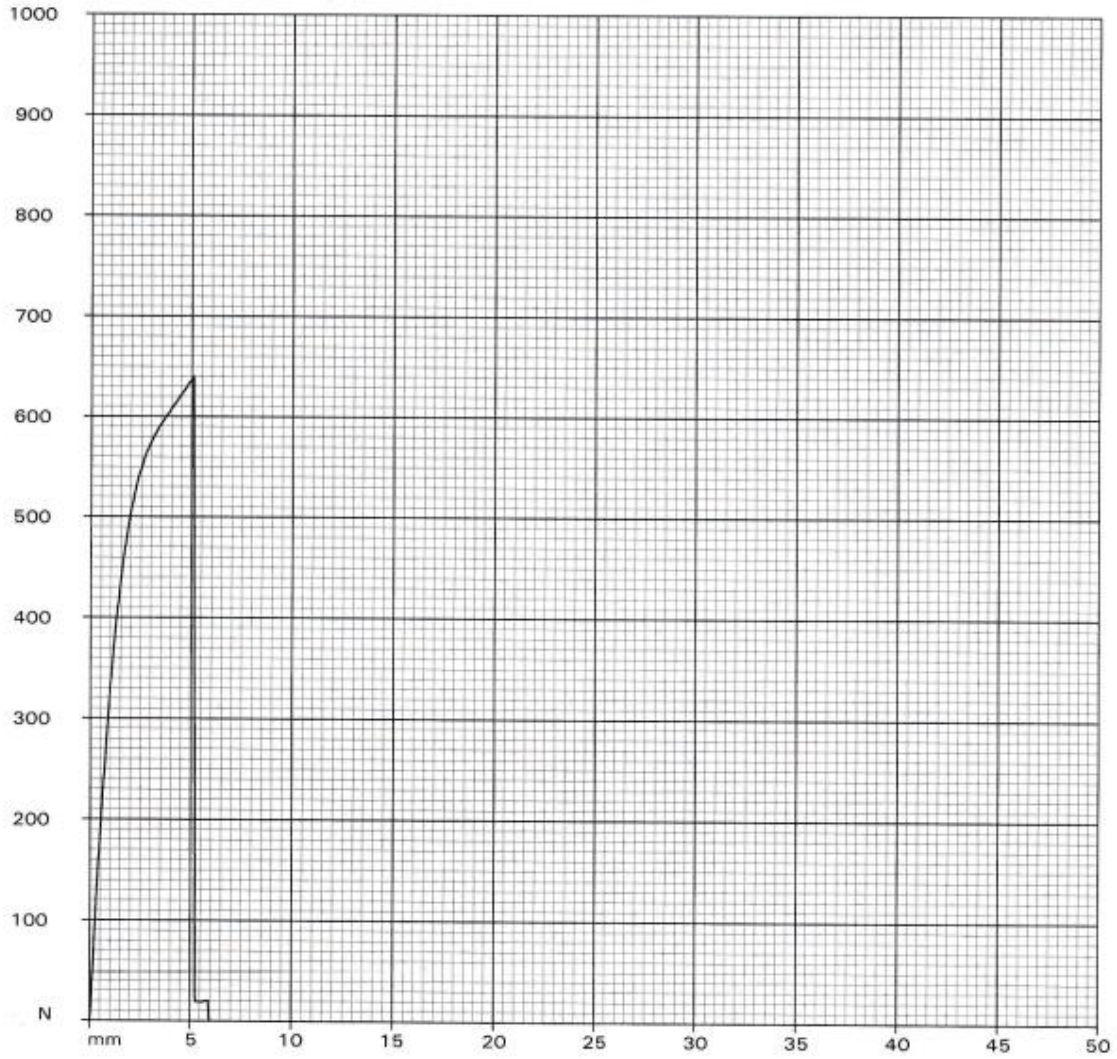
0%, 4

6.51 x 3.77

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator .....:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	640.000	-20.000	5.906	0.000	0.000	0.000	0.000	0.000



0%, S

6.37 x 3.76

****
Hounsfield
Test Report
****

DEST TEST 2021
EXT TEST 2021
Batch Number ..:----
Operator ......:----
Test Speed.....: 50.000{mm/min}

	Max N	Break N	Ext @ Brk mm	10.000 N	50.000 N	100.000 N	200.000 N	300.000 N
1	552.666	-19.000	5.188	0.000	0.000	0.000	0.000	0.000