DEVELOPMENT AND EVALUATION OF A VACUUM CASTING PROCESS

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DEVELOPMENT AND EVALUATION OF A VACUUM CASTING PROCESS

by

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A Dissertation

Submitted in fulfillment of the Requirements

for the Degree

Magister Technologiae

Engineering : Mechanical

In the

School for Mechanical Engineering and Applied Mathematics

Faculty of Engineering

At the

Central University of Technology, Free State

April 2004

Supervisor : Dr. D.J. De Beer

Central University of Technology, Free State

DECLARATION OF INDEPENDENT WORK

I, FREDERICK CHRISTIAAN AGGENBACHT, do hereby declare that this research project submitted for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: MECHANICAL, is my own independent work and that it has not previously been submitted to any institution by me, or anyone else, as part of any qualification.

10/8/2009

F.C. Aggenbacht **Date**

I want to thank the Lord for giving me the perseverance and the ability to complete this work.

I want to thank all the people who assisted and endured me with this project during the many years of study, especially Deon De Beer, Johan Strauss, Sarel Pelser and Chrisna Aggenbacht.

I also want to thank the Central University of Technology, Free State and the NRF for their financial support.

SUMMARY

The vacuum casting process plays an important role in Rapid Prototyping. It provides the designer/manufacturer with the ability to reproduce plastic components from various types of prototypes.

Casting under vacuum delivers components with a high degree of dimensional accuracy, free from unfilled cavities, in a wide spectrum of thermoset plastics, especially developed for this process. Components are cast in silicone moulds and cured at elevated temperatures to ensure specific characteristics of the cast component. The silicone moulds that are used in the process, are also produced under vacuum, cured and tempered at elevated temperatures to obtain reasonable mould life and to ensure specific characteristics of the cast components.

The aim of this research project was to investigate the equipment required for the process and to evaluate the results that can be obtained by utilizing the process under local conditions. Various factors, such as the mould temperature, curing temperature, ambient temperature etc., play a role in the dimensional accuracy that can be obtained. The outcome of the research project would be to provide manufacturers with a framework that can be used in the vacuum casting process to reproduce components of the desired quality and dimensions.

UITTREKSEL

Die vakuumgietproses speel 'n belangrike rol in snelprototipering. Dit maak dit vir die ontwerper/vervaardiger moontlik om plastiek komponente van prototipes te maak.

Deur komponente onder vakuum te giet, word onderdele met 'n hoë vlak van akkuraatheid, vry van defeksies en in 'n wye spektrum van plastieke, verkry. 'n Reeks termoset plastieke is spesifiek vir die vakuumgietproses ontwikkel. Plastieke word in silikoon gietvorms gegiet en teen verhoogde temperature gestol om komponente met spesifieke karakteristieke te lewer. Die silikoon gietvorms word ook onder vakuum gemaak en by verhoogde temperature gelaat om te stol om sodoende 'n aanvaarbare gietvormleeftyd te verseker en spesifieke karakteristieke aan die gegote komponente te lewer.

Die doel van die navorsingsprojek was om 'n ondersoek te loods na die tipe toerusting wat nodig is om die proses suksesvol uit te voer, asook om die karakteristieke van gegote komponente te bestudeer, wat onder plaaslike toestande gegiet is. Baie faktore, soos die gietvormtemperatuur, die stollingstemperatuur, omgewingstoestande ens., speel 'n belangrike rol in die dimensionele akkuraatheid van die gegote komponente. Die resultate wat verkry is uit die navorsingsprojek kan dien as 'n raamwerk vir vervaardigers, om komponente met spesifieke dimensionele karakteristieke en verlangde kwaliteit te lewer.

Central University of Technology, Free State

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INTRODUCTION

1.1 PROBLEM STATEMENT

As a result of increased competition between manufacturers worldwide, different processes and techniques are investigated to make the manufacturing process more time- and cost efficient. The vacuum casting process is used world wide as a relative low cost rapid prototyping or rapid tooling and manufacturing option with a high degree of dimensional accuracy as far as the reproduced components are concerned.

1.2 THE PURPOSE OF THE RESEARCH PROJECT

The purpose of the project was to design and construct a vacuum casting facility locally in order to evaluate the vacuum casting process in terms of:

1. The cost efficiency of vacuum casting as a rapid manufacturing option with reference to the cost of casting materials and equipment.

2. The type of components that can be reproduced as far as degree of complexity and size is concerned.

3. The effect of the available different types of thermoset plastics and silicones on the dimensional accuracy, strength and surface finish (in the vacuum casting process).

4. The accuracy that can be obtained in the reproduction process and the factors that influence the accuracy of the casting process.

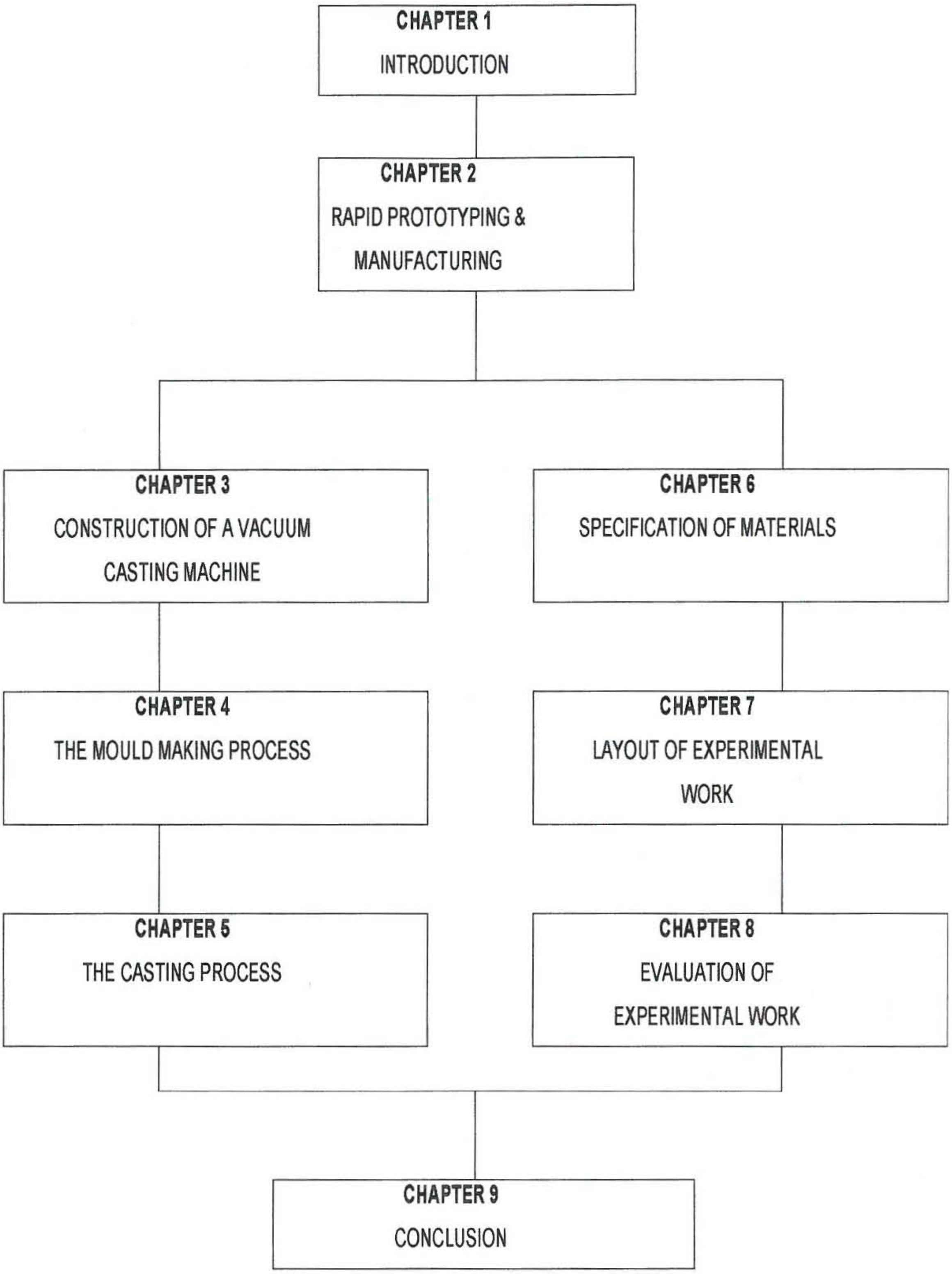
1.3 HYPOTHESIS

The vacuum casting process can be used as a low cost, low production run option in rapid prototyping and manufacturing, locally.

1.4 THE RESEARCH LIMITATIONS

A vacuum casting facility, as simple and inexpensive as possible will have to be developed. The casting chamber will be limited to 600 mm * 600 mm * 900 mm and the amount of raw material that can be handled will be limited to 4000 cc. Due to the high cost of vacuum pumps a pump with a maximum capacity of 10 m^3/h and ultimate pressure of $6 * 10^{-2}$ mbar will be used.

1.5 COMPOSITION OF THESIS



CHAPTER 2

RAPID PROTOTYPING & MANUFACTURING

2.1 IN GENERAL

Rapid prototyping defines a process whereby a computerised model is converted into a prototype (physical part). Several rapid prototyping processes are applied in industry these days. The most common are the stereolithography process (SLA), the selective laser sintering process (SLS) and the layer object manufacturing process (LOM), to name just a few. Rapid manufacturing defines a process whereby several physical parts can be produced from a computerized model, or reproduced from a prototype. Different processes are available for rapid manufacturing, like the different prototyping processes, gravity casting, spin casting (Centrifugal Rubber Mould Casting or CRMC), vacuum casting and RIM casting (Reaction Injection Moulding) [5],[9],[11].

2.2 WHY VACUUM CASTING?

Vacuum casting defines a process whereby a thermoset plastic (polyurethane) or melted wax is cast into a room temperature vulcanising (RTV) silicone mould, under vacuum. The only difference between vacuum casting and gravity casting is the vacuum that is applied, and the specially developed vacuum grade polyurethanes that are required for vacuum casting. RIM casting is a process whereby thermoset plastics is mixed and injected under pressure into a mould, while the mould is being kept at ambient conditions. Spincasting is a process whereby materials such as thermoset plastics, melted wax and low melting point alloys are cast into high temperature vulcanising silicone (HTV Silicone) moulds, that are being rotated at a certain required speed to force the material into the mould. With vacuum- and gravity casting, approximately 20 components can be reproduced from a single RTV mould, depending on the complexity of the component [11]. HTV moulds applied in the RIM casting process can go to approximately 50 reproductions from a single mould and up to 500 reproductions from a single mould if applied in the spin casting process [11].

Vacuum casting is most commonly used as a rapid manufacturing option alongside a rapid prototyping machine. Vacuum casting can reproduce parts much more cost effectively than rapid prototyping machines. The parts can be reproduced very accurately in resins with reasonable strength. The vacuum allows for easier filling of complex moulds if compared to gravity casting with about the same lead time as gravity casting, RIM casting and spin casting (approximately 2 - 14 days) [11],[5]. Parts reproduced with vacuum casting are more accurate if compared with parts reproduced with the other processes. The biggest disadvantage of vacuum casting is the high cost of equipment and the special vacuum grade resins.

CHAPTER 3

CONSTRUCTION OF VACUUM CASTING MACHINE

3.1 SPACEFRAME AND SHEETING

The frame of the vacuum casting machine was designed taking into account the available funds, equipment and skills in the workshop of the Technikon. There are a lot of possibilities for designing a cabin. It can be made with/without a supporting frame, from a range of materials. The cabin, as shown in figure 3.1, was

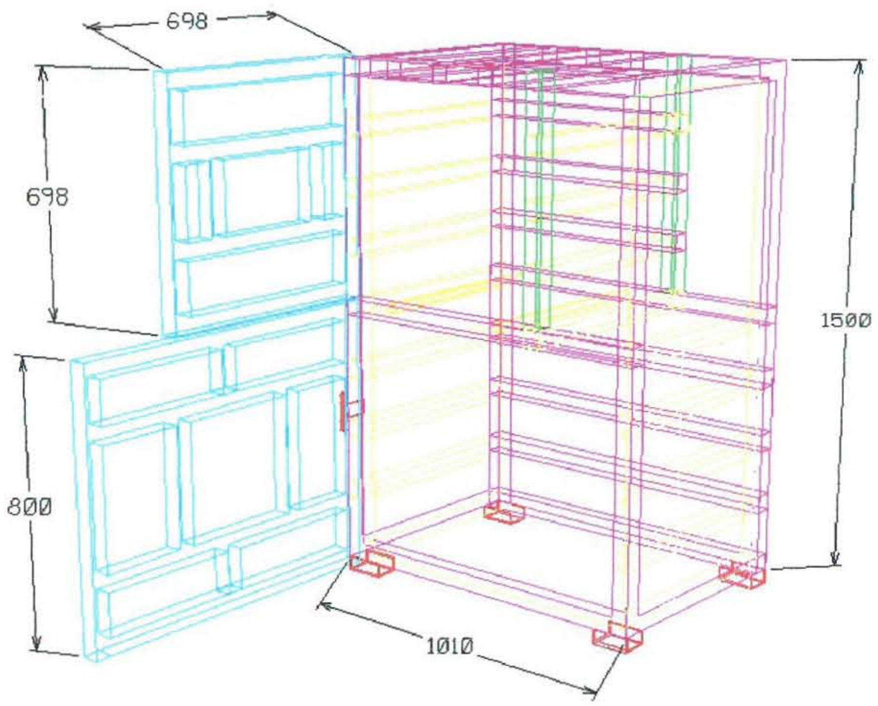


Fig. 3.1 : Frame of the Vacuum Caster

constructed with a welded square tubing supporting frame, covered with plate, all materials being mild steel. The square tubing frame was designed to handle the whole load on the walls of the chamber, due to the vacuum inside. The assumption was made that the cabin is subjected to an external pressure of 100 kPa instead of an internal vacuum of minus 100 kPa. For the required strength of the square tubing frame, the largest wall area of 800 * 1000 mm was considered.

Force on wall = pressure x area

$= (100 \times 10^3 \text{ [Pa]}) \times (0,8 \times 1 \text{ [m}^2\text{]})$

$= 80\,000 \text{ N}$

This force must be taken up by the bracing's. Each bracing was considered as a beam subjected to a uniform distributed load [1], [2]. The rigidity of the bracing's end supports was considered to act as an additional support. The total load was then divided between the number of bracing's.

For determining the number of bracing's:

Uniform load per bracing: = 80 000N/number of bracing's

The maximum tensile stress per bracing was not allowed to exceed 300 MPa.

Tensile stress $= My/I$ (1)

Where M $= wx(l-x)/2$

$= (80\,000/n)(1-0,5)/2$

$= 20\,000/n$

From (1)

Tensile stress = 300 Mpa $= (20000/n)(0,025)/(200*10^{-9})$

$\Rightarrow n = 8$

The cover plate was designed to be able to withstand the assumed external pressure between the square tubing bracing's. The theory for flat plates was used to determine the required plate thickness that will withstand the external pressure. The frame was welded with the normal arc-welding process. The frame was then powder coated to protect the cabin and also to seal it from the outside. The picture below shows the finished product.

Fig. 3.2 : The powder coated Casting Frame

3.2 VACUUM SOURCE

The size of the vacuum chamber and the type of materials that are processed inside the chamber determine the required size of vacuum source. To process a silicone mould, one needs to do primary degassing of the mixed silicone. The size of the chamber determines the size of container that can be used to degas silicone. If the container does not allow for a 500% increase in volume of the silicone, the silicone needs to be degassed in steps as discussed in section 6.5. After primary degassing has been done, the silicone is poured into the casting frame and secondary degassing starts. Most silicones has a pot life of approximately 90 minutes. The vacuum source must therefore be able to lower the pressure inside the chamber to at least 20 - 30 mBar, within the above mentioned timeframe, to be able to process a silicone mould. The vacuum pump and control unit (PLC) was installed right next to the mixing chamber as can be seen from the picture below.

Fig. 3.3 : The Vacuum Pump and Control Unit.

The vacuum pump that is used on the vacuum casting machine, is an Edwards RV 12 rotary vane pump. The volume of the chamber is 0,54 m^3. With an ultimate vacuum of 20 mBar, it would theoretically imply that the specified pump would degas the chamber in 3,24 minutes. The actual degassing time is approximately 14 minutes, which is not ideal for industrial applications but still satisfactory for experimental work. Leaks occur through the welded joints, the door seals and possibly the edges of the windows. The Pump is controlled by a vacuum valve, which shuts down the pump as soon as the ultimate vacuum is reached. The ultimate vacuum is adjustable on the vacuum valve.

3.3 MIXING BEAKERS AND STIRRERS

The volume of the larger mixing beaker determines the volume of material that can be cast. As a design specification, the volume of the larger beaker was taken as 5000 ml, therefore the volume of the smaller beaker was taken as 2500 ml because the two component resins are mostly mixed in a one to one ratio. The two beakers with the supporting frame were positioned inside the mixing chamber as shown in the picture below.

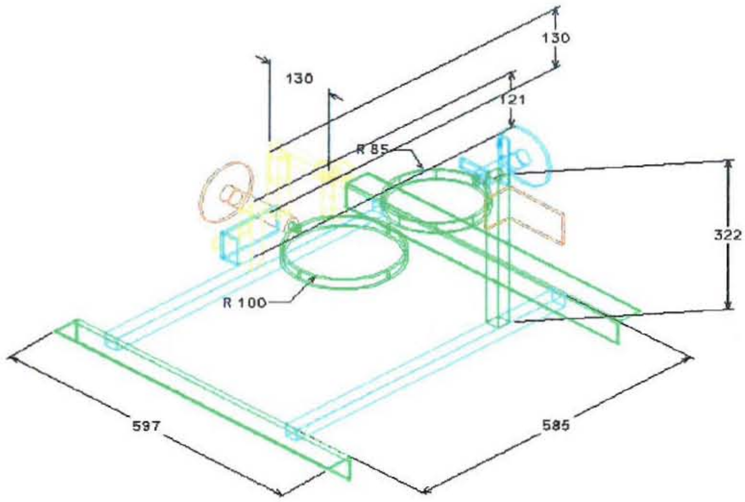


Fig. 3.4 : The Mixing Frame with Beaker Holders.

The tilting of the beakers, as well as the stirring inside the bottom beaker is done with geared DC motors. The timing of the mixing operation as well as the tilting speed of the beakers is controlled with a PLC, installed next to the vacuum pump, as shown in Figure 3.3.

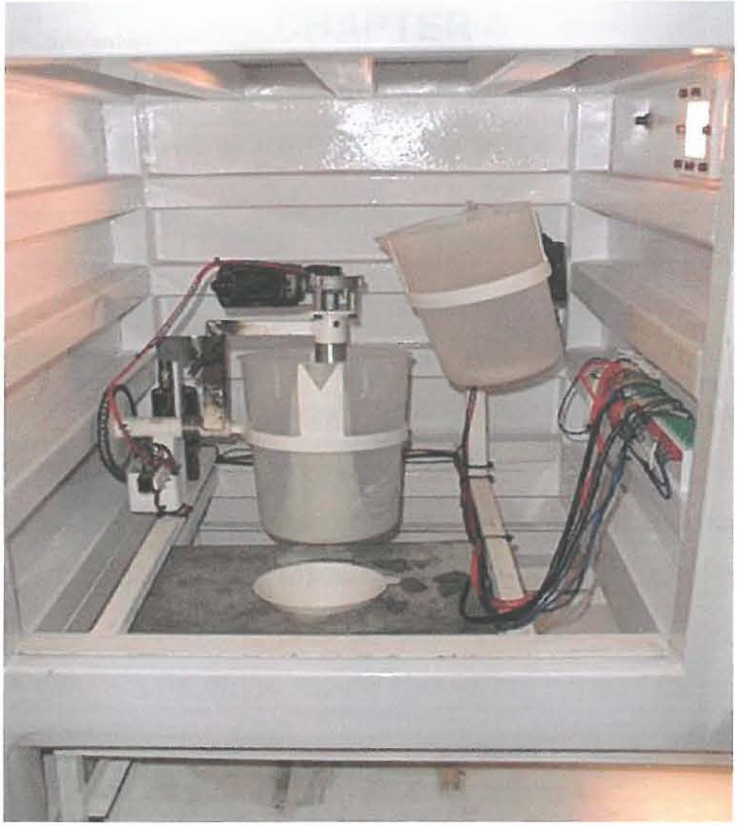


Fig. 3.5 : Mixing Beakers inside Mixing Chamber

Figure 3.5 presents a picture of how the actual mixing frame was installed inside the mixing chamber.

CHAPTER 4

THE MOULD MAKING PROCESS

4.1 The Master Model

A master model is used to produce a silicone mould in which plastic parts can be cast in vacuum casting. The master model can be either a hand made model, a model grown by the SLA, SLS or LOM process or a model that is CNC machined. Typical SLS master models are shown in figures 4.1 and 4.2. The following factors must be taken into account as far as the master model is concerned:

- The dimensions of the mould should not exceed those of the casting chamber.
- The volume of material required for the cast component, should not exceed the capacity of the larger beaker in the vacuum casting machine.
- The material of which the master model is made should be compatible to the silicone of which the mould is to be made.
- The part must be simple enough that adequate parting lines can be created in the silicone mould. Parts with deep undercuts may not release easily from the mould and will reduce the life expectancy of the mould.
- The maximum wall thickness of the master model should be compared to the specifications of the casting material. Thin walls may create problems if the viscosity of the casting material is too high to allow complete filling of the mould.

Deficiencies in the surface of the master model will be reproduced in the cast part. The surface of the master model should be as smooth as possible and sealed. Surfaces of master models such as those produced by the LOM process should be sealed and skillfully worked off by hand. If components are cast in a transparent plastic, the surface finish of the master model will influence the transparency of the cast component.

Fig. 4.1 & 4.2: A typical SLA part coated with a primer

4.2 Creating Parting Lines.

Three different techniques can be used to create a parting line in the mould, depending on the complexity of the component that are being reproduced.

4.2.1 Cutting the parting line after the mould was cast.

Uncomplicated and axially symmetrical parts can be suspended in the casting frame by a rod, used to create the in-gate/s, as well as by the rod/s, used to create the riser/s. All these rods should be parallel to allow for the release from the master model and the cast parts from the mould. The mould is then cast in one piece. After the silicone has vulcanised, the in-gate/s and riser/s are removed first. Compressed air is injected through the holes created by these in-gate/s and riser/s to separate the master model from the mould. The mould can then be cut into two or more sections to release the part. The parting line consists of two sections. The outer section of the parting line is cut with a wavelike movement of the blade, to ensure that the two or more halves can only be fitted together in one specific way. The second section of the parting line close to the master model, is cut in a straight line, to create the required parting line close to the cast part.

4.2.2 Creating parting lines with scotch tape.

For more complex parts, scotch tape, of approximately 150 μm, can be stuck to the master model to create the required parting line as shown in figure 4.3. Holes through the part can also be closed on this manner, to enable the separation of the two or more sections of the mould. The tape should preferably be of a dark color, so that it can be seen clearly through the silicone. The master model is suspended in the casting frame by the rod/s attached to it to create the in-gate/s and riser/s, if required. The mould is cast in one piece and only the outer wavelike section of the parting line is cut to the outer edge of the scotch tape. The scotch tape that was glued to the master model will create an error in the cast part directly related to the thickness of the tape.

Fig 4.3: Parting line created with scotch tape

4.2.3 Creating parting lines with modeling clay

If a part with deep undercuts needs to be cast, the mould can be made by embedding part of the master model in clay, and casting the mould in two or more pieces. This will ensure that the correct parting line is created exactly where it is needed. Care must be taken that the clay that is used is compatible with the silicone. The compatibility can be checked by casting a piece of silicone onto the clay, to check whether it releases clearly from the clay once it has vulcanised. The clay bed must also have a wavelike edge to ensure that when the two or more parts of the mould are fitted together, there is only one exact way to fit them. As soon as the required part of the master model has been embedded in clay, the clay must be degassed first before the first part of the silicone mould is cast over the master model. Once the first part of the mould has vulcanised, the casting frame can be opened and the clay removed. All the clay must be cleaned off the first part of the silicone to ensure a clear parting line. During this process the master model is left in the cast part of the silicone mould, and after the silicone has been cleaned, the second part of the mould can be cast. Release agent must be used on the first part of the mould to reserve the parting line.

4.3 Moulding Frame

A moulding frame is required to cast the silicone mould over the master model. The moulding frame must have the following characteristics:

- It must be possible to make the moulding frame to the exact size. The minimum wall thickness of the silicone must be at least 15 to 20 mm for small components and up to 100 mm for big components.
- The inner surface of the moulding frame, against which the silicone mould is cast, must be smooth. A smooth surface will create a

transparent mould. The transparency of the mould is important for cutting a clear parting line.

- The moulding frame must allow for a rise on the silicone during secondary degassing.
- The moulding frame must be stiff enough so that the mould do not deform during vulcanising.

Melamine board works exceptionally well for creating moulding frames of different sizes. A typical melamine moulding frame is shown in figure 4.4. The different sections of the moulding frame can be glued together using hot glue, which makes it quick to assemble and disassemble. The four walls of the moulding frame can be positioned in such a way that the required wall thickness is created in the mould. For smaller parts, beakers like the beakers of the vacuum caster can also be used as a moulding frame. The beaker must preferably be tapered to the top and have a smooth surface to ensure an easy release of the mould.

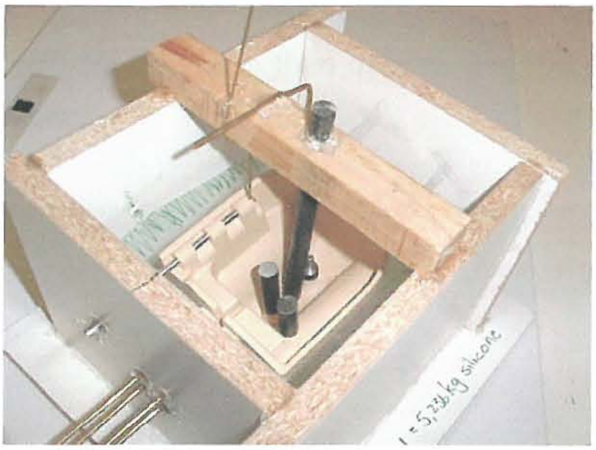


Fig 4.4 : A moulding frame made from melamine board

4.4 Gates and Risers

The gate in the mould is formed, by gluing a piece of rod to the master model, as shown in figure 4.5 and 4.6. The diameter of the gate will depend on the volume of resin that has to be cast through it, as well as by the time that is allowed to cast the resin into the mould. In other words, the pot life of the resin has to be taken into account as well. For small items, up to 50 g of resin, an 8mm gate should be sufficient. From 50 - 100g of resin one should preferably use a 10 mm gate, etc. To assist in the filling process of the mould, the master model is sometimes placed at an angle. The gate will then be connected to the lowest point of the cavity and the risers are created from the highest points of the cavity. A triangular shaped piece of flat material may be used to connect the rod, that creates the cavity for the gate to the master model in the mould making process. This will create a gate that can be broken off the cast part easily, and does not require too much extra finishing.

Certain parts and/or resins may require more than one gate. This can be done by creating more than one cavitiy inside the mould, with rods. A plastic tube, with a t-piece, is then used to connect the casting funnel and the extra gates.

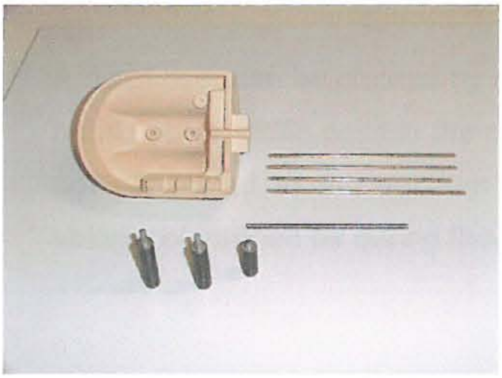


Fig 4.5 : Steel and brass rods are used to create cavities

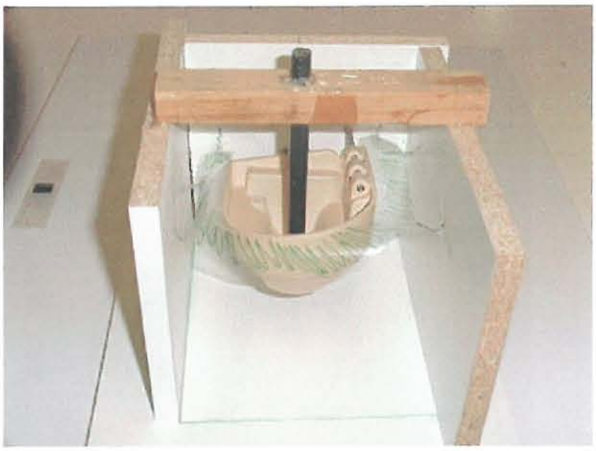


Fig 4.6 : A steel rod is used to create the in-gate

Risers are created by gluing 2 - 3 mm rods, normally brass, to the master model, as shown in figure 4.7. The purpose of the risers is to connect the highest points of the cavity to the vacuum chamber, so that trapped air can escape during the casting process. An ultimate vacuum is not achieved in the vacuum chamber, so there is still an amount of air left. One can see trapped air escaping through the in-gate when casting the resin into the mould. The number of risers required will be determined by the geometry of the specific part being cast. Risers can also be added afterwards to the mould, by drilling 3 mm holes at high speed through the mould.

A dead riser can be created by cutting a triangular shaped cavity into the mould at a specific point in the mould that tends to trap air. This cavity is not connected to the vacuum chamber, but can facilitate a required volume of trapped air during the casting process.

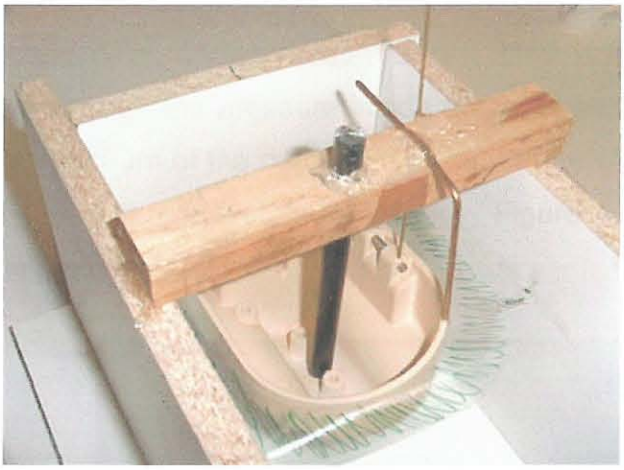


Fig 4.7 : Brass rods are used to create required risers

4.5 Casting the Mould

The amount of silicone required is calculated by using the inside volume of the moulding frame minus the volume of the part to be cast. During mixing and degassing of the silicone a certain amount of the silicone remains in the mixing bowl. This must be allowed for when determining the required amount of silicone. Silicone and hardener are added in a ratio of 10 : 1 and mixed well with a drilling machine and a mixer as shown in the picture below. Care must be taken that the pot life of the silicone is not exceeded during the mould making process. After the silicone and hardener are mixed the primary degassing process follows. Primary degassing of the silicone is done inside the vacuum chamber at a pressure of less than 15 hPa. The bowl in which the silicone is degassed must have a volume of at least 5 times the silicone inside, or the operator must apply a vacuum until the silicone reaches the rim of the bowl and then increase the pressure inside by 50 hPa. Once the silicone has dropped, the pressure is reduced again to ultimate vacuum until the silicone reaches the rim of the bowl again. The process of decreasing and increasing the pressure inside is repeated until the silicone stops rising under vacuum and is then fully degassed. If the bowl is big enough the pressure inside the chamber can be reduced to the ultimate vacuum of the machine and kept there. The silicone will rise and fall when it is completely degassed. Figure 4.8 shows a bowl of silicone being degassed.

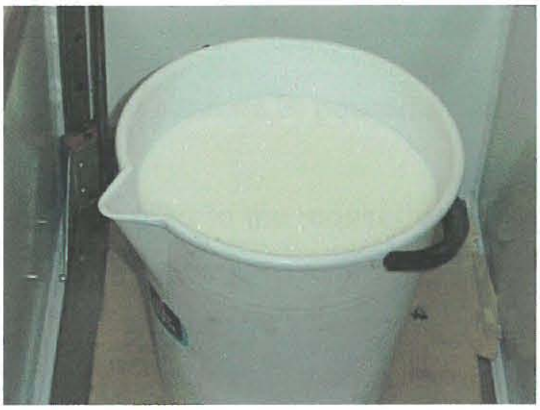


Fig 4.8 : Primary degassing of silicone in the casting chamber

The degassed silicone is then taken out of the vacuum chamber and poured slowly over the master model in the moulding frame, as shown in figure 4.9. The master model must be supported firmly inside the moulding frame.

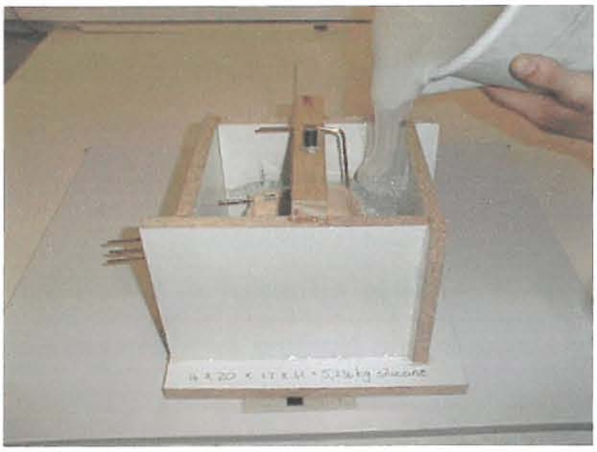


Fig 4.9 : Degassed silicone is poured in the casting frame

If the moulding frame is filled to the required level, it is put back into the vacuum chamber and degassed again, as shown in figure 4.10. This is called secondary degassing. The silicone will rise inside the moulding frame, but not as high as during primary degassing. Approximately 20% additional space on top of the mould must be allowed for, in the moulding frame, for secondary degassing. Once air bubbles stops appearing on the surface of the mould and **before the end of the pot life of the silicone,** the moulding frame with the mould must be taken out of the vacuum chamber and left to vulcanise.

Fig 4.10 : Secondary degassing of the silicone

If the mould is left inside the vacuum chamber after the pot life has expired bubbles will form underneath the top surface of the mould and will stay there after the silicone has vulcanised.

The mould must be left to vulcanise at **room temperature** for at least 15h. The figure below shows a mould after secondary degassing.

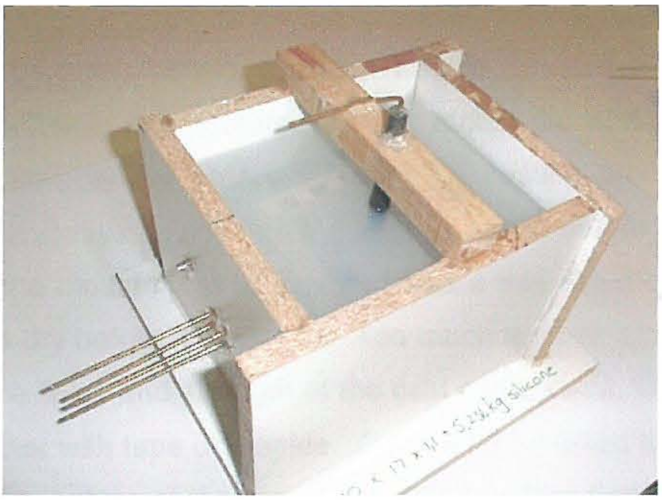


Fig 4.11 : The cast mould is left to vulcanise

4.6 OPENING THE MOULD

As soon as the mould has vulcanised completely, it can by opened, by cutting a wave-like parting line as discussed under section 3.2. The mould must not be opened too soon. If a part of the silicone has not hardened, it will deform and the mould will be destroyed. The master model can be separated from the mould by injecting pressurised air into the mould through the riser/s or the gate. This will facilitate the release of the master model from the mould later.

CHAPTER 5

THE CASTING PROCESS

5.1 PREPARING THE SILICONE MOULD

Some people prefer to store moulds at room temperature, while others prefer to store moulds at elevated temperature until they are used. One of the focus areas of this research was to determine the influence of elevated storage temperatures on the mould life and the dimensional accuracy that can be obtained during the casting process. A release agent must always be used on the silicone mould before it is closed. The inside of the mould must be covered with a thin cloud of release agent, and left to dry before it is closed. Too much release agent will influence the surface finish and strength of the cast component. The mould can be closed either with tape or staples. Care must be taken to ensure that the two or more halves of the mould are held together firmly. Large moulds may require supports to prevent distortion of the mould as a result of it's own weight.

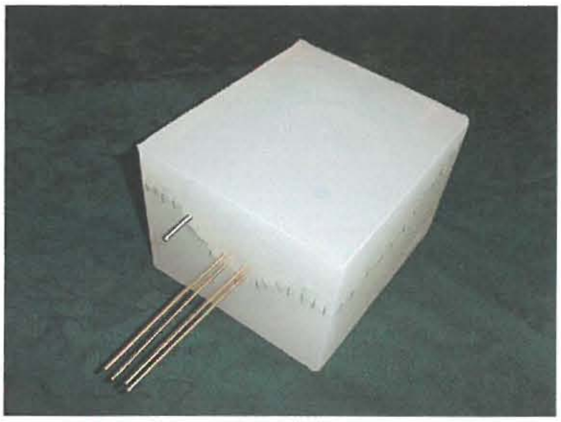


Fig 5.1 : A mould closed with staples, ready for casting

5.2 PREPARING THE RESIN

The two components of the casting resins are weighed off according to the required ratio of the specific plastic. The component with the lowest viscosity is poured into the smaller beaker on top, to limit the amount that remains in the cup after it has poured. An amount equal to that remaining in the cup, after the liquid is poured, must be added to this cup. Normally about 5 g is added to account for this. As a result of the amount remaining in the smaller cup, after it has been poured, there is a minimum amount of resin that can be processed (about 50 g), otherwise the influence on the ratio between the two components will be so significant that it influences the characteristics of the resin. If the same resin is processed, the smaller cup can be used continuously, without adding the additional amount to it.

The required amount of resin to be used must be estimated, according to the size of the master model. If the master model is made from plastic or a material with a known density, it can be weighed and the required amount of resin determined. If too much resin is used, the amount that stays in the funnel can be weighed and subtracted for the second cast. The resin is stored at 30^0C, to prevent crystallisation. Once the two containers are opened, the shelf life of the resin is reduced to approximately two weeks.

5.3 CASTING THE COMPONENT

Once the correct amount of resin is added to the two beakers, they are installed in their respective clamps. The chamber is now degassed to allow for primary degassing of the resins. The component in the lower beaker can be stirred while degassing. Primary degassing is done on the resins until all the air is removed from them. To save time, the primary degassing of the resin can be done while another component is being cast. The two cups with the resin is placed on the lifting table with the mould of the component that is cast, if there is available space.

After the resin is degassed the chamber is pressurised. The mould is now placed on the lifting table and lifted until the funnel reaches the gate. The chamber is degassed again to allow for secondary degassing of the resin. If the mould is required to be at room temperature, and time is not an issue, the primary and secondary degassing of the resin can be done in a single step.

Fig 5.2 : The mould on the lifting table ready for the cast

The chamber is degassed until the air is removed from the resin. The two components of the resin is now added together. Care must now be taken not to exceed the pot life if the resin. The mixed components can be stirred while degassing. If air is still coming off the mixed resin, a pressure shot of 50 mBar can be induced into the chamber to "calm" the resin. The bottom beaker is tilted and the resin flows into the mould. As soon as all the resin has flowed into the funnel the bottom beaker can be tilted back again.

When the resin starts flowing out of the risers, the chamber is pressurised and the mould taken out so that the resin can cure.

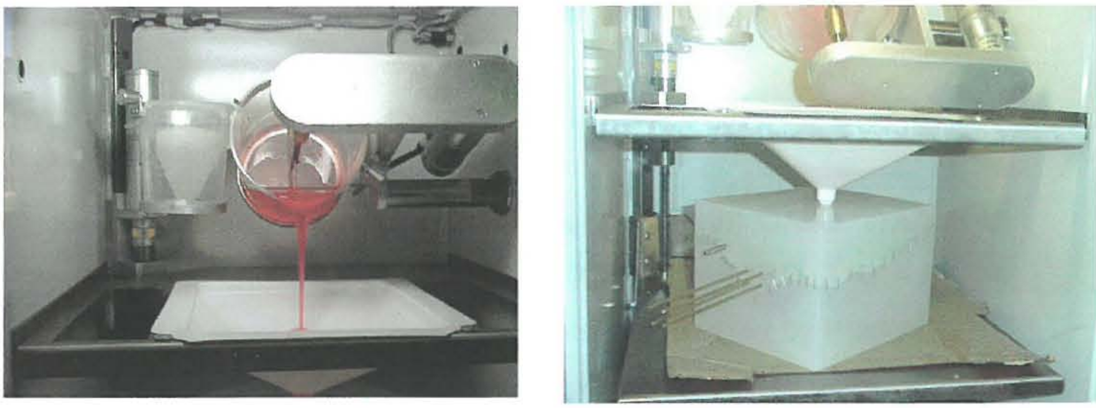


Fig 5.3 & 5.4 : Resin flows from the beaker into the mould

To assist in the curing of the resin the mould with resin can be stored at 40^0C, for approximately one hour. The mould with resin must not be left in the oven for too long as this might damage the mould. The required curing time for the resins are specified on their data sheets. During periods of high R.H. the curing time is prolonged. As soon as the resin has cured the mould can be opened and the casting removed.

Fig 5.5 : Casting removed from the mould

CHAPTER 6

SPECIFICATIONS OF MATERIALS

6.1 CASTING MATERIALS

The material manufacturer Huntsman, has 9 Vacuum Grade Thermoset Plastics that are available on the South African market. The sections below gives a summary from the data sheets, as provided by Huntsman, of these plastics. All these vacuum grade polyurethanes have been specially formulated for the vacuum casting process. Processing of the plastics can only be done with the necessary application equipment. The components are degassed, mixed and cast into silicone moulds that have been preheated at a temperature range of between 30 - 70 ^{0}C. The compatibility of the polyurethane with the silicone needs to be checked. The compatibility between the silicone mould and the plastic can be checked by casting a small amount of the plastic over a piece of silicone to verify whether the plastic releases clearly from the silicone after it has vulcanised.

6.1.1 UREOL 5231 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Black product
- Shore hardness A65
- Good tear resistance
- Simulates rubber
- Pot life : 5 - 6 min for 650 g at 25 ^{0}C.

- Demoulding time : 1 - 2 h for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 900 - 1500 mPas at 25 ^{0}C.
- Maximum wall thickness : 20 mm

6.1.2 UREOL 5232 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Pigmentable product
- Good temperature resistance
- Good flow characteristics
- Simulates Polyethilene/ Polypropelene (PE / PP)
- Pot life : 4 - 5 min for 500 g at 25 ^{0}C.
- Demoulding time : 1 - 1,5 h for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 470 mPas at 25 ^{0}C.
- Maximum wall thickness : 10 mm

6.1.3 UREOL 5233 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Pigmentable product
- High impact strength
- Good temperature resistance
- Simulates PP
- Pot life : 6 min for 500 g at 25 ^{0}C.

- Demoulding time : 45 mins for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 850 - 1150 mPas at 25 ^{0}C.
- Maximum wall thickness : 5 mm

6.1.4 UREOL 5234 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Pigmentable product
- High temperature resistance
- Good impact strength
- Simulates PP/ABS
- Pot life : 6 min for 500 g at 25 ^{0}C.
- Demoulding time : 45 mins for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 750 - 1050 mPas at 25 ^{0}C.
- Maximum wall thickness : 5 mm

6.1.5 UREOL 5235 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Black product
- High temperature resistance
- Good impact strength
- Simulates PP/ABS
- Pot life : 6 min for 500 g at 25 ^{0}C.

- Demoulding time : 45 mins for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 750 - 1050 mPas at 25 ^{0}C.
- Maximum wall thickness : 5 mm

6.1.6 UREOL 5236 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Pigmentable product
- High flexural modulus
- Longer working life
- Simulates ABS
- Pot life : 20 mins for 500 g at 25 ^{0}C.
- Demoulding time : 1,5 - 2 h for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 160 - 180 mPas at 25 ^{0}C.
- Maximum wall thickness : 12 mm

6.1.7 UREOL 5237 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Black glass filled product
- High flexural modulus
- High temperature resistance
- Simulates ABS
- Pot life : 9 mins for 850 g at 25 ^{0}C.

- Demoulding time : 30 - 50 mins for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 2500 - 3100 mPas at 25 ^{0}C.
- Maximum wall thickness : 10 mm

6.1.8 UREOL 5238 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Transparent product
- Good temperature resistance to 90 ^{0}C
- Excellent clarity and optical properties
- Simulates ABS
- Pot life : 10 mins for 850 g at 25 ^{0}C.
- Demoulding time : 1,5 - 2 h for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 700 - 900 mPas at 25 ^{0}C.
- Maximum wall thickness : 10 mm

6.1.9 UREOL 5239 - VG

Description

A two component , polyurethane vacuum casting plastic.

Key Properties

- Transparent system
- UV stable and temperature resistance to 90 ^{0}C
- Excellent clarity and optical properties
- Simulates ABS
- Pot life : 11 mins for 850 g at 25 ^{0}C.

- Demoulding time : 1,5 - 2 h for mould at 40 - 70 ^{0}C.
- Mixed Viscosity : 250 - 350 mPas at 25 ^{0}C.
- Maximum wall thickness : 10 mm

6.2 COLOURING AGENTS

Colouring agents are soluble or insoluble materials, that are used to obtain required colours within plastics.

Soluble coloring agents are known as dyes and the insoluble ones as pigments.Normally pigments have a particle size of 0,01 to 1 μm. Pigments are furthermore classified as either organic or inorganic. Usually inorganic pigments have a high light and heat stability, and high opacity, but do not have a high tinting strength.

Examples of inorganic pigments are:

White	:	Titanium dioxide, zinc oxide,
Yellow	:	Chrome yellow, nickel titanium yellow,
Red	:	Molybdenum red, red iron oxide,
Blue	:	Ultramarine blue, cobalt blue, manganese purple,
Green	:	Chrome green, cobalt green,
Brown	:	Brown iron oxide,
Black	:	Black iron oxide, carbon black.

Organic pigments have a high tinting strength and low opacity. For this reason an admixture of inorganic and organic pigments is quite often used for colouring [3],[4], [8], [10].

6.3 MOULD MATERIAL (4640 Silicone)

Description

A silicone rubber, that vulcanises at room temperature (RTV) after the addition of a pasty or liquid catalyst.

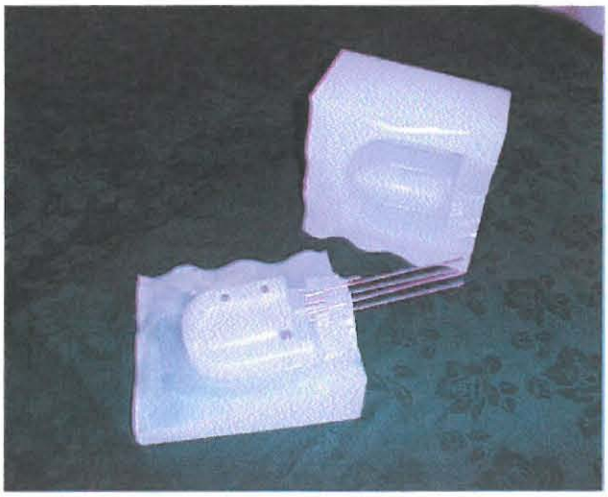


Fig 6.1 A typical silicone mould.

Key Properties

- A pourable transparent product
- Moderately hard
- High mechanical strength
- High resistance to polyurethanes and epoxy resins
- Linear shrinkage after 7 days : < 0,1 %
- Mixing ratio : 1 : 10 (by weight)
- Potlife at 23 ^{0}C & 50 % Relative Humidity (RH) : 90 min
- Demoulding time at 23 ^{0}C : 15h
- Demoulding time at 70 ^{0}C : 30h

6.4 MOULD MATERIAL (4642 Silicone)

Description

A silicone rubber, that vulcanises at room temperature (RTV) after the addition of a pasty or liquid catalyst.

Key Properties

- A pourable dark red product
- Moderately hard
- High extensibility
- Excellent mechanical strength
- General purpose grade
- Linear shrinkage after 7 days : < 0,1 %
- Mixing ratio : 1 : 10 (by weight)
- Potlife at 23 ^{0}C & 50 % RH : 90 min
- Demoulding time at 23 ^{0}C : 12h
- Demoulding time at 70 ^{0}C : 20 h

CHAPTER 7

DESCRIPTION OF EXPERIMENTAL WORK

7.1 PART CHOSEN FOR EVALUATION

To conduct the experiments on the material characteristics, a normal tensile test specimen, as shown in figure 7.1, was chosen because it can be used to determine the influence of the controllable factors on several dimensions of the specimen; the tensile strength can be measured accurately in the tensile test and the surface hardness can also be determined accurately. The figure below shows the critical dimensions on the specimen against which the cast components were compared.

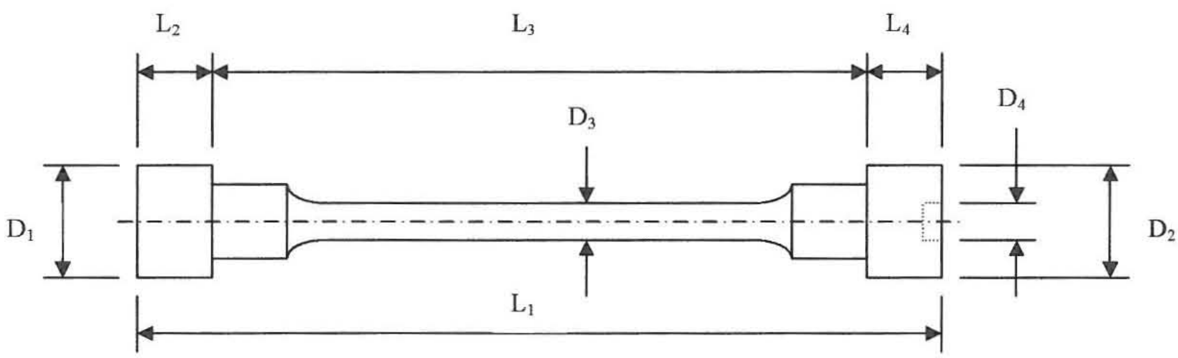


Fig 7.1 : Dimensions of specimen

A digital micrometer, able to measure to 10 μm, was used to measure the specimen. For each dimension, ten measurements were taken around the circumference of the specimen, as shown in the table below. The same method was used to measure the cast components. The average value were calculated and used as the correct value for the dimension. The standard deviation gives an indication of how accurate the measurements are.

Table 7.1 : Measurements of Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

7.2 CASTING OF PU SPECIMENS

Three similar silicone moulds were made from the steel specimen. During each casting, three PU specimen were cast. Ten measurements for each dimension were taken, and the average value for the three castings were taken as the correct value, to be compared to the dimensions of the steel specimen. The table below gives an example of how the measurements were taken, and the average value calculated.

Central University of Technology, Free State

Table 7.2 : Measurements on a typical PU specimen

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	**1**	170.00	15.85	139.23	15.46	28.60	28.89	9.43	3.36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3.31
	3	170.50	16.06	138.76	15.58	28.28	28.55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3.24
	5	170.55	16.00	138.79	15.68	28.65	28.88	9.55	3.23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3.36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3.34
	8	170.10	15.97	139.02	15.48	28.36	28.57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3.23
	10	170.50	15.93	139.34	15.57	28.42	28.89	9.43	3.25
Cast2	**1**	171.00	16.26	139.97	15.57	28.70	28.58	9.50	3.35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3.36
	3	171.00	16.26	139.75	15.71	28.56	28.84	9.61	3.32
	4	171.10	16.04	139.67	15.56	28.62	28.97	9.60	3.28
	5	171.40	15.97	139.72	15.65	28.70	28.99	9.56	3.35
	6	171.20	16.10	139.99	15.63	28.67	28.84	9.53	3.37
	7	171.00	16.09	139.96	15.72	28.59	28.56	9.60	3.36
	8	171.10	16.13	139.92	15.56	28.49	28.84	9.58	3.37
	9	171.00	16.09	139.85	15.61	28.59	28.92	9.52	3.37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	**1**	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3.39
	3	170.50	15.70	139.82	15.53	28.37	28.94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3.37
	5	170.60	15.75	139.70	15.44	28.70	28.88	9.59	3.37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3.38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3.39
	9	170.50	15.76	139.72	15.54	28.68	28.93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3.38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0.08

7.3 LAYOUT OF EXPERIMENTAL WORK

During the casting process three temperatures can be varied to obtain different results in the cast component. That is the mould temperature (the temperature to which the silicone mould is preheated before the cast is made), the curing temperature (the temperature at which the cast component is cured inside the mould) and the resin temperature (the temperature at which the resin is stored). One of the purposes of this research project was to determine what influence each of these temperatures would have on the physical characteristics of the cast component. Silicone moulds are normally preheated at temperatures ranging from 30 to 70 ^{o}C. A decision was made to to preheat the silicone mould to 30, 50 and 70 ^{o}C for the evaluation. The preheating temperatures were limited to three to limit the amount of castings necessary to make any significant conclusions. The curing temperatures were taken the same as the preheating temperatures. The resin temperature was kept at 30 ^{0}C, because the resin is normally stored at 30 ^{o}C to avoid crystallization. During the degassing of the resin in the vacuum chamber, the surrounding temperature drops considerably inside because there is a constant volume of which the pressure is reduced from 1 Atm to 5 mBar. It would therefore be difficult to keep the resin at an elevated temperature during degassing. The normal processing temperature for resin is 30 ^{o}C and it was therefore decided to keep the resin at that temperature and determine the influence of the mould temperature on the cast components. The castings were made in a matrix as shown in the table below. During each experiment one specific temperature was varied to determine the influence of that temperature on the cast component.

Table 7.3 : Layout of experimental work.

Experiment	Mould Temperature ^0C	Curing Temperature ^0C	Resin Temperature ^0C
1.1	30	30	30
	30	50	30
	30	70	30
1.2	50	30	30
	50	50	30
	50	70	30
1.3	70	30	30
	70	50	30
	70	70	30
2.1	30	30	30
	50	30	30
	70	30	30
2.2	30	50	30
	50	50	30
	70	50	30
2.3	30	70	30
	50	70	30
	70	70	30

CHAPTER 8

EVALUATION OF EXPERIMENTAL WORK

8.1 SUMMARY

Each subsection of this chapter gives a short description of the conditions under which each casting was made as well a summary of the conclusion that can be made from the results obtained.

8.2 EXPERIMENT 1.1: ALTERED CURING TEMPERATURE, MOULD TEMPERATURE AT 30 °C.

During this experiment, the mould was preheated to 30 °C, the resin kept at 30 °C and the curing temperature varied from 30 to 50 to 70 °C. At least two hours were allowed for curing the part inside the mould. The complete experimental data as obtained are presented in Appendix A. The graph, as presented figure 8.1, gives an indication of how the dimension L_1 has changed with a change in curing temperature. The dimension has changed from 171,25 to 171,50 mm, with an increase in the curing temperature, while the shrinkage has decreased from 0,8 % to 0,4 %.

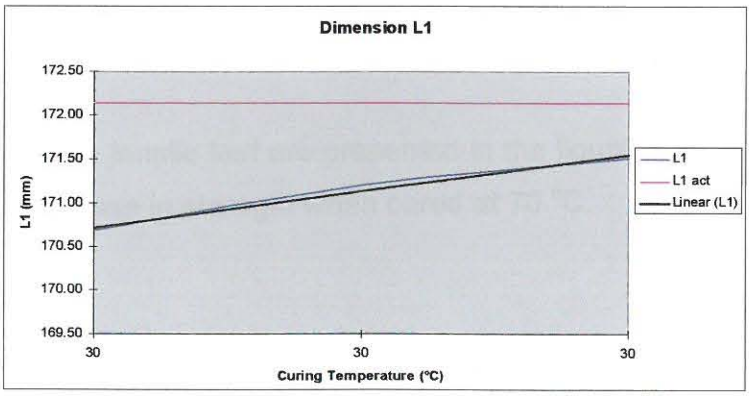


Fig. 8.1 : Change in dimension L_1.

Most dimensions showed a change in shrinkage ranging from 0,2 to 0,6%, with some increases and some decreases. It is interesting to note that all the length's showed an increase in shrinkage and all the diameters showed a decrease in shrinkage. The biggest change in dimension was in dimensions L_3 and L_1. One would expect the change in L_3 to be reflected in L_1, because L_3 is part of L_1. Because L_3 is a long thin section, one would expect it to reflect the biggest change. The change in shrinkage of dimension L1 is presented in the figure below.

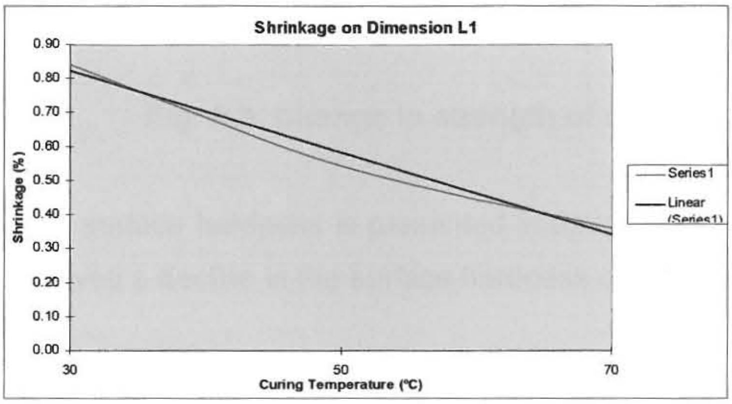


Fig. 8.2 : Change in the shrinkage of dimension L_1.

From the data obtained in this experiment it is clear that the change in curing temperature did not have a clear noticeable change in the dimensions of the cast component.

The results from the tensile test are presented in the figure below. The material showed some increase in strength when cured at 70 ^{0}C.

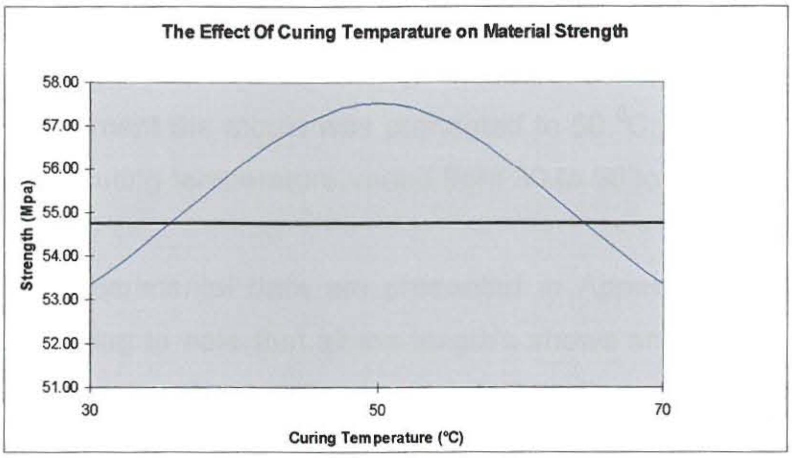


Fig. 8.3: Change in strength of component.

The change in the surface hardness is presented in the graph below. The last measurement showed a decline in the surface hardness of the component.

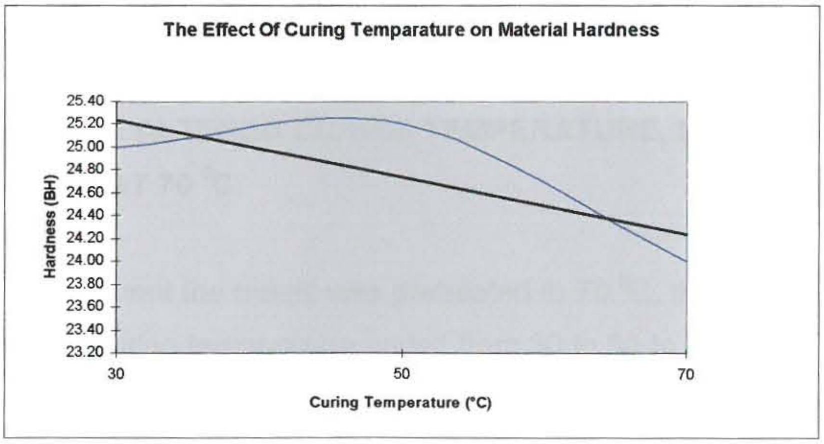


Fig. 8.4: Change in the surface hardness of the component.

8.3 EXPERIMENT 1.2: ALTERED CURING TEMPERATURE, MOULD TEMPERATURE AT 50 ^{0}C.

During this experiment the mould was preheated to 50 ^{0}C, the resin kept at 30 ^{0}C and the curing temperature varied from 30 to 50 to 70 ^{0}C.

The complete experimental data are presented in Appendix B. Once again it is interesting to note that all the length's shows an increase with an increase in curing temperature and all the diameters shows a decrease with an increase in curing temperature. All the length's moved closer to the required dimension (0 % shrinkage) and the diameters moved further away from the required dimensions. On the length's the shrinkage decreased in the order of 0,5% and on the diameters the shrinkage increased from 0,2 to 0,3%. The material strength decreased constantly with an increase in curing temperature while the surface hardness increased.

8.4 EXPERIMENT 1.3: ALTERED CURING TEMPERATURE, MOULD TEMPERATURE AT 70 ^{0}C.

During this experiment the mould was preheated to 70 ^{0}C, the resin kept at 30 ^{0}C and the curing temperature varied from 30 to 50 to 70 ^{0}C.

The complete data sheets for this experiment are presented in Appendix C. The shrinkage of dimensions L_1 to L_4 shows similar changes, with a slight increase at a curing temperature of 50 ^{0}C and a decrease again at a curing temperature of 70 ^{0}C. The shrinkage of the diameters shows a constant increase with an increase in the curing temperature.

The material strength shows an decrease from 66 Mpa to 62 Mpa with an increase in the curing temperature, while the surface hardness stays fairly constant at approximately 24 to 25 BH.

8.5 EXPERIMENT 2.1 :ALTERED MOULD TEMPERATURE, MOULD AND RESIN TEMPERATURE AT 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin and the curing temperature kept at 30 ^{0}C.

The detailed data sheets for this experiment are presented in Appendix D. All the length's showed a slight increase in value while some of the diameters showed an increase and some showed a decrease. The shrinkage in the length's decreased from 0,3 to 0,7 %, while that of the diameters varied with 0,2 %, some positive and some negative. It can clearly be seen from all the dimensions that the shrinkage stayed constant with a mould temperature increase from 30 to 50 ^{0}C, but started to vary when the mould temperature was increased above 50 ^{0}C. For most dimensions the variation was positive since the shrinkage decreased.

8.6 EXPERIMENT 2.2 :ALTERED MOULD TEMPERATURE, CURING AT 50 ^{0}C AND RESIN TEMPERATURE AT 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin temperature kept at 30 ^{0}C and the curing temperature kept at 50 ^{0}C. The detailed data sheets of this experiment are presented in Appendix E. Dimension L_1 decreased with an increase in the mould temperature, while dimensions L_2, L_3 and L_4 increased. This seems impossible because $L_1 = L_2 + L_3 + L_4$. The values used for these dimensions are the combined average for three specimen, where ten readings were taken per specimen. If one compares the dimensions taken from three specimen, as presented in table 6.1 and compare that with the measurements taken from the original specimen, as presented in table 6.2, it can be seen that the deviation in values are much bigger in the cast component than it is in the original machined steel specimen For such a deviation in the dimensions of the cast component, it is clear that the accuracy of the dimension on the cast component cannot be measured to two decimal places [5],[6],[7]. In general the shrinkage of the length's decrease with an increase in the mould temperature while the shrinkage of the diameters increased.

The material strength increased from 54 MPa to 60 MPa with the increase in mould temperature, while the surface hardness varied little from 24 to 25 BH.

8.7 EXPERIMENT 2.3 :ALTERED MOULD TEMPERATURE, CURING AT 70 ^{0}C AND RESIN TEMPERATURE AT 30 ^{0}C.

During this experiment the mould was preheated from 30 to 50 to 70 ^{0}C, the resin temperature kept at 30 ^{0}C and the curing temperature kept at 70 ^{0}C. No clear trend in the change of the dimensions can be seen from this experiment. The shrinkage of some of the dimensions increased while others decreased. The material strength decreased from 64 to 61 MPa, while the surface hardness stayed constant at 25 to 26 BH.

CHAPTER 9

CONCLUSION

9.1 INTRODUCTION

During this research project a vacuum casting machine was constructed in order to evaluate the vacuum casting process in terms of the conditions as set out in 1.2. The sections that follows presents a summarized conclusion on all those elements.

9.2 THE COST EFFICIENCY OF VACUUM CASTING

Vacuum casting is a relative expensive rapid manufacturing option if compared to gravity and RIM casting. The resins that are used for vacuum casting ranges from R 400 to R450 per kilogram at the time the experiments were conducted, while those for gravity and RIM casting were in the order of R 80 per kilogram.

At the time the experiments were conducted a small vacuum casting facility (able to handle 1000cc of plastic in a casting chamber of 450 * 450 *350 mm high) ranged from R 200k for a manually operated machine to R 300k for an automatically operated machine. A RIM casting machine cost approximately R 80k at that stage. It can thus be concluded that vacuum casting is one of the more expensive rapid manufacturing options however, less expensive than RP, and should only be applied if the specific characteristics that can be obtained with the process are required.

9.3 THE TYPE OF COMPONENTS THAT CAN BE REPRODUCED

Vacuum casting can reproduce components in a range of vacuum grade plastics as well as melted wax (an add-on to the machine). The size of components that can be reproduced is limited by the size of the casting chamber. The wall thickness is limited by specific material specifications. Shrinkage up to 0,1 % is obtainable by varying the factors that control the casting process, eg. the mould temperature, the curing temperature etc. To achieve complete mould filling with different types of plastics is an trial and error process by playing around with the controllable factors. Components with undercuts can be reproduced as long as they can be released from the flexible silicone mould, or by splitting the mould into more than two sections.

9.3 DIFFERENT TYPES OF PLASTICS AND SILICONES AVAILABLE

A very wide range of silicones and plastics are available from different manufacturers. New materials especially developed for vacuum casting as well as those not specifically developed for vacuum casting, appear on the market quite often. The availability of those materials on the South African market is a problem because of the limited shelf life of the products and the volumes that are being sold. At this stage all vacuum grade plastics are imported on request only. If the materials are urgently needed they are flown into the country which makes them more expensive.

9.4 THE ACCURACY THAT CAN BE OBTAINED

Vacuum casting is quite an accurate casting process but still a casting process. A lot of factors influence the casting process, like the controllable factors (the mould temperature, the curing temperature, the resin temperature, the hardness of the silicone mould, the ultimate vacuum and the mixing time allowed), as well as the uncontrollable factors (the ambient temperature, the relative humidity, and the viscosity of the mixed thermoset plastics). The silicone that was used in the experiments had a relative low shore hardness, resulting in clear parting lines being created on the cast component which in return influenced the average dimension that could be determined. At the stage at which the experiments were conducted that was the only silicone available. Silicones with a higher shore hardness appeared on the market later and would certainly have made a difference to the results that were obtained. The experiments that were conducted showed that no clear pattern in the dimensional accuracy could be observed. Certain dimensions increased while others decreased when a specific operating condition was altered. The material strength and surface hardness stayed fairly constant with a change in operating conditions.

It can be concluded that vacuum casting is a relative accurate rapid manufacturing option, which sometimes requires a lot of trial and error to create a part that can resemble the original part as close as possible in a range of plastics and wax. Shrinkage in the order of 0,1% is quite obtainable. If compared to other RP and RM technologies, vacuum casting is more expensive than RIM casting but less expensive than the SLS process [11].

1 DESIGN OF A MOUTH-PIECE

Introduction:

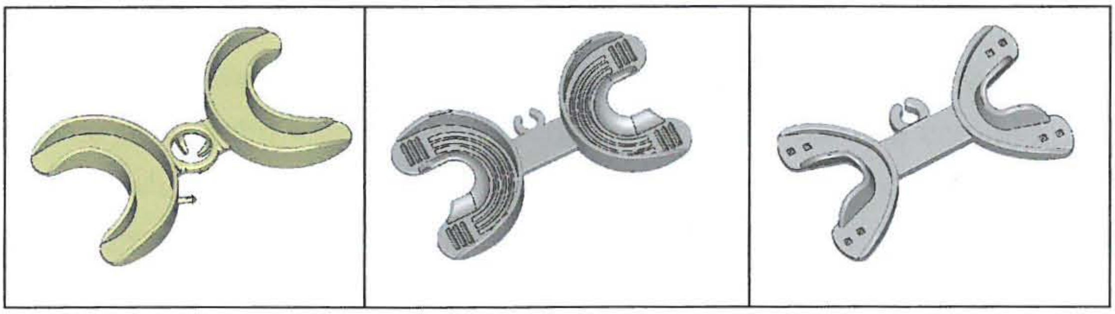
The purpose of the project was to develop a mouthpiece that can be used to keep a pipe in position, inside the mouth of a patient, being under the influence of anaesthetics.

Traditionally a development like this would consist of the following steps or phases:

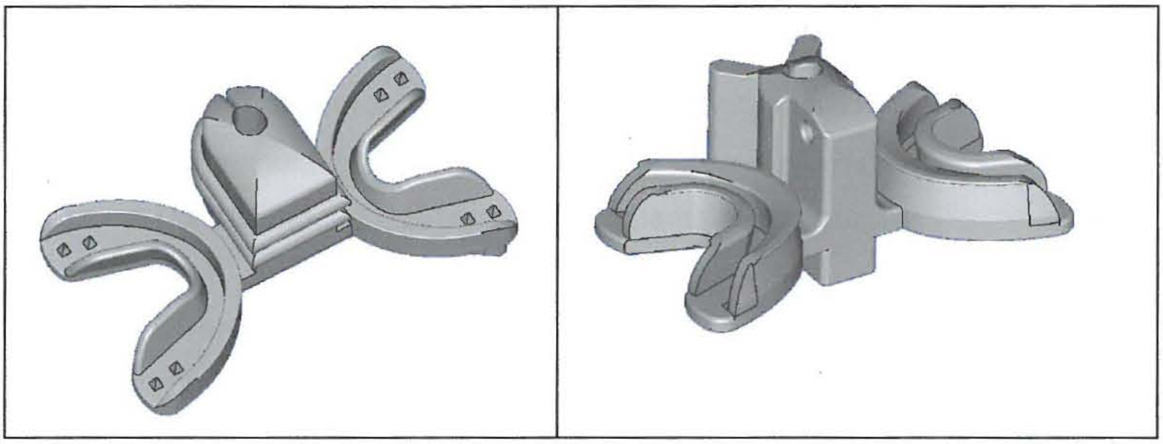
1. Design drawings or sketches of the concept;
2. Approval of the design by the client if satisfied with the outcomes;
3. Designing and manufacturing of a mould (also referred to as hard tooling) for the injection moulding process

Hard tooling allows for some small changes to be made, but if the changes are too radical a new tool will have to be designed and made. A different approach to hard tooling would be to make a prototype of the design by using various Rapid Prototyping options like SLA or SLS and then making a silicone mould (soft tooling) to cast limited quantities of the product. Various Rapid Manufacturing options like Vacuum Casting or the Reaction Injection Moulding process (RIM) can then be used to reproduce the prototype. When the customer is satisfied with the product or after the product has been proven, a hard tool can be made (if the required volumes require a hard tool), with the assurance that no alterations to the hard tool will be necessary.

For this specific product, the total development consisted of a series of iterations entailing 10 CAD designs, 6 prototypes being made (grown with the SLA process), and 6 different silicone moulds made to cast the different products, with the vacuum casting process. The figures below shows the different designs that were made in order to create the final product.



Figures 1,2 and 3 showing the first three designs of the mouthpiece



Figures 4 and 5 showing the last two designs of the mouth-piece

COST OF THE PROJECT

The total cost for this product to be developed amounted to R 46 220, consisting of 10 CAD designs at R 2500 per design with 2 alterations allowed, 6 SLA prototypes at R 2500 each, 6 silicone moulds at R 820 each and 26 cast components at R 50 each of the different designs. The pictures below show typical vacuum cast mouthpieces.

To manufacture an injection [obscured by logo] would amount to R 80 00 (8 weeks delivery) as per quotes obtained. The price to manufacture the product decreases dramatically from R 50 to R 3.61 (for a production of 30 000 per month) once a hard tool has been made, but one can only imagine what the cost and timeframe of development would have been if a decision was made to start directly with hard tooling.

1.2 REQUIRED TIMEFRAME

The following time frames were budgeted for in the project management and planning of the project:

- For the computer aided design of this specific product, 1 day:
- For manufacturing a mould, two days were allowed for;
- For casting, at least three components per day.

The timeframe in which such a product can be developed will however depend on the availability of personnel and machines as well as the time required for transport and the testing process. This specific product was developed in a time span of 5 months.

2 DEVELOPMENT OF A PRE-PAID METER

Actaris Manufacturing, an international company, contracted a local company, called Technimark, to design and deliver 10 fully functional prototypes of the pre-paid meter, as shown in figure 8, for final testing. The options was to either make injection moulding tools of all the parts, or to use rapid prototyping and manufacturing techniques to produce the 10 prototypes. A cost analyses showed that the latter option was more viable as will be discussed later. Technimark sub-contracted TFS to produce the SLA prototypes, and Freeplay Market Development, a company that specialises in low volume productions via silicone moulds, to produce 10 fully functional prototypes. In this case the client, Technimark, specifically require for this project, due to the following reasons:

- SLA models need less preparation time prior to moulding with silicone.
- The surface finish obtained from an SLA model is in most cases better of that of an SLS model.
- SLS models are much more porous and therefore need more filling, sanding and sealing than SLA models.

Figure 8: Front view of the pre-paid meter

The window and Light Guide parts needed to be cast in clear plastic, therefore it was decided that the masters were to be machined out of acrylic on a CNC machine. This ensured that the master could be polished to a mirror finish. Owing to time constraints, certain silicone molds were not produced, but rather 10 sets of SLS prototypes were grown that would fit into the cast parts.The superior strength and temperature specifications of the SLS prototypes were very suitable for actual tests and evaluations.

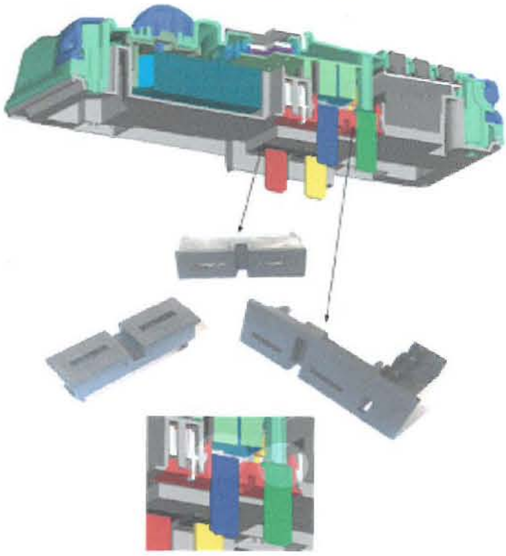


Figure 9 : A cross section of the meter with some internal parts

2.1 COST OF THE PROJECT

The entire cost for 10 sets of fully functional prototypes can be summarized as follows:

1.	SLA Masters	R 8 455.00
2.	Finishing masters	R 23 000.00
3.	Manufacturing moulds	R 34 500.00
4.	Casting of parts	R 38 000.00
5.	Finishing and spray-painting parts	R 5 500.00
6.	10 sets of certain SLS parts	R 3 500.00
		R 112 955.00

The total cost for a hard tool (injection molding tool) was in the region of R 1,3 million. The rapid prototyping and manufacturing techniques allowed the client to test the prototype while the injection molds were being manufactured. This particular prototype passed all the tests, so the client was sure that when the injection molds was finished, that the product to be manufactured was up to standard.

2.2 REQUIRED TIMEFRAME

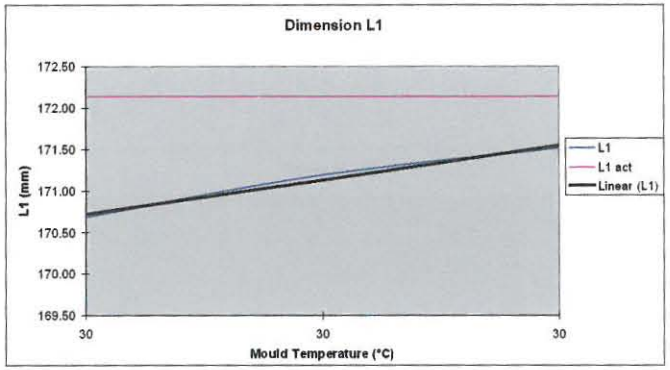
To grow the SLA masters of the product, TFS required 10 days. To finish and prepare the SLA masters for silicone moulding , Freeplay Market Development, required 7 days. The make the silicone molds took 5 days, and to vacuum cast all the relevant parts took 5 days. Finishing off of certain cosmetic parts required 3 days. Thus from the time the SLA master were delivered, 14 days were required to reproduce 10 sets of all the parts. A team of 6 model makers spent approximately 450 hours to finish and prepare the masters for master pattern in silicone moulds.

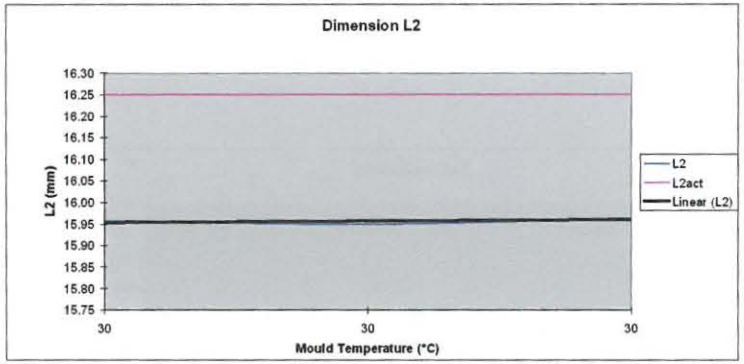
DATA OF EXPERIMENT 1.1

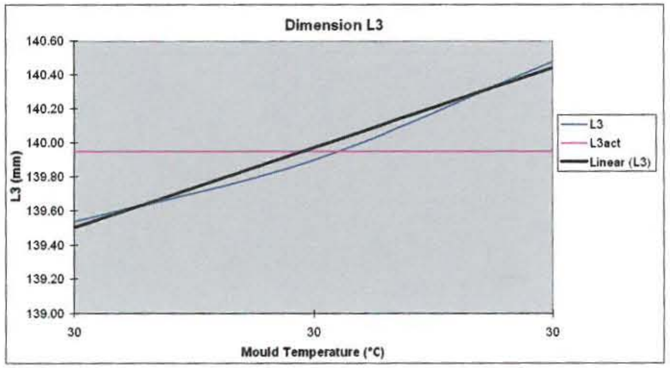
Central University of Technology, Free State

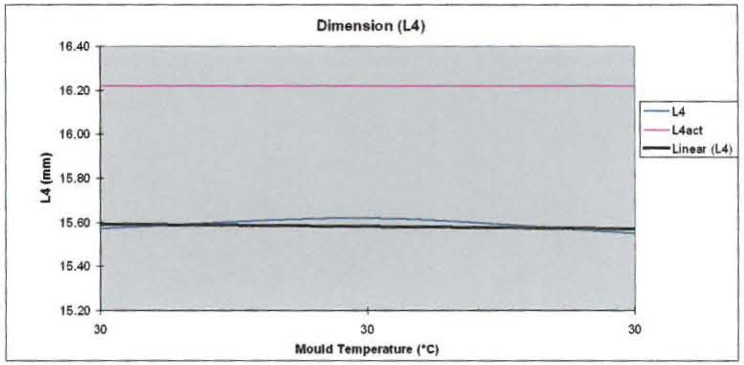
APPENDIX A : EXPERIMENT 1.1

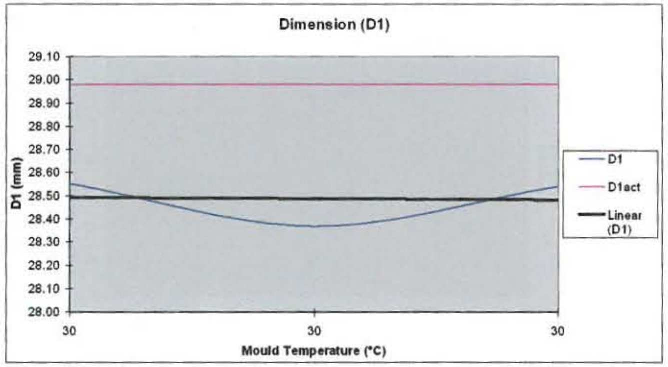
Mould Temp (°C)	Resin Temp (°C)	Curing Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
30	30	30	170.69	172.14	15.96	16.25	139.54	139.95	15.57	16.22	28.55	28.98	28.78	28.96	9.53
30	30	50	171.20	172.14	15.95	16.25	139.90	139.95	15.62	16.22	28.37	28.98	28.60	28.96	9.33
30	30	70	171.52	172.14	15.96	16.25	140.48	139.95	15.55	16.22	28.54	28.98	28.68	28.96	9.49

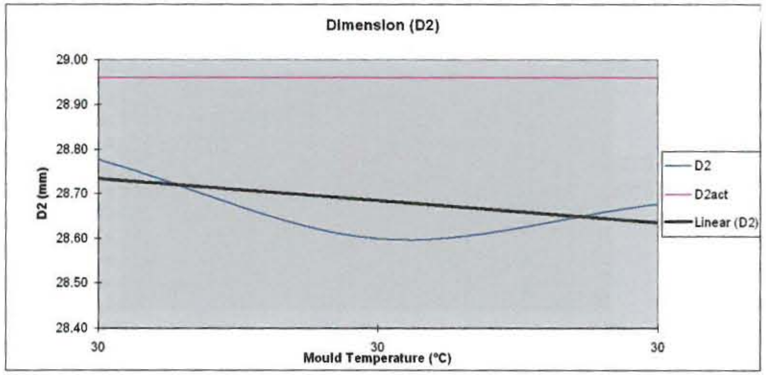


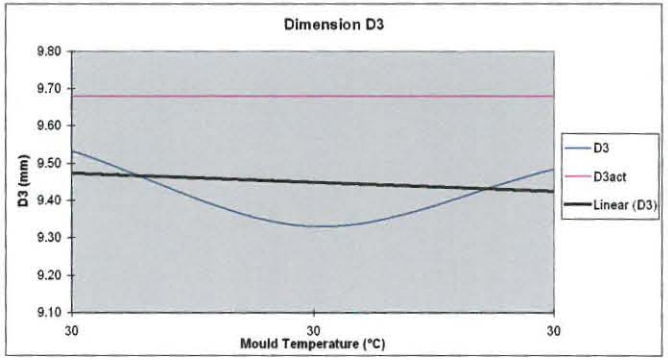


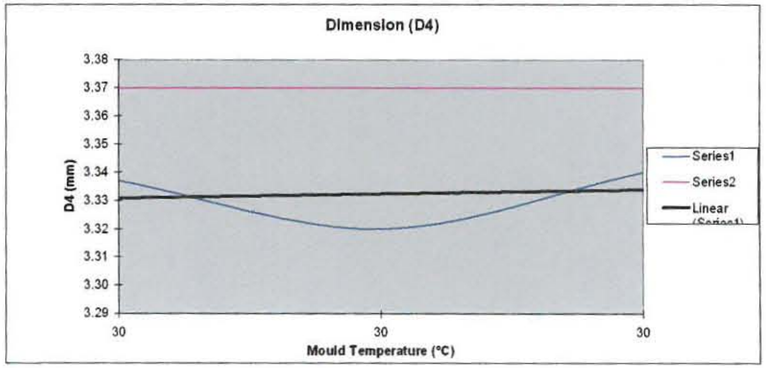


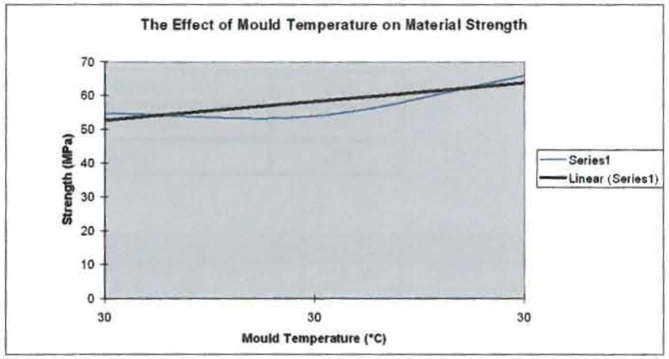


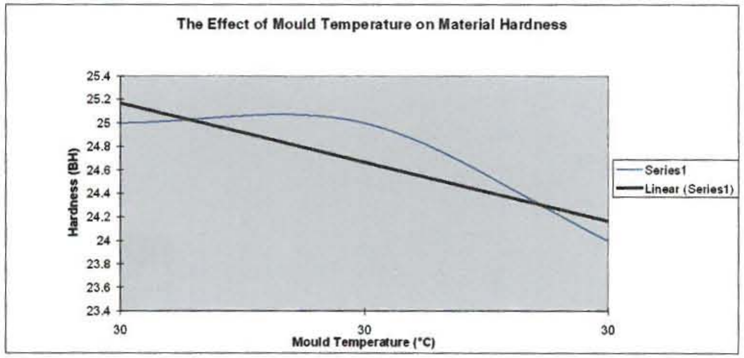

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
28.10
28.00
30
30
30
Mould Temperature (°C)
D1
D1act
Linear (D1)


Dimension (D2)
D2 (mm)
29.00
28.90
28.80
28.70
28.60
28.50
28.40
30
30
30
Mould Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.80
9.70
9.60
9.50
9.40
9.30
9.20
9.10
30
30
30
Mould Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.37
3.36
3.35
3.34
3.33
3.32
3.31
3.30
3.29
30
30
30
Mould Temperature (°C)
Series1
Series2
Linear


The Effect of Mould Temperature on Material Strength
Strength (MPa)
70
60
50
40
30
20
10
0
30
30
30
Mould Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
25.4
25.2
25
24.8
24.6
24.4
24.2
24
23.8
23.6
23.4
30
30
30
Mould Temperature (°C)
Series1
Linear (Series1)

Experiment 1.1

Mould Temp.	30
Curing Temp.	30
Resin Temp	30

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.00	15.85	139.23	15.46	28.60	28.89	9.43	3.36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3.31
	3	170.50	16.06	138.76	15.58	28.28	28.55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3.24
	5	170.55	16.00	138.79	15.68	28.65	28.88	9.55	3.23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3.36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3.34
	8	170.10	15.97	139.02	15.48	28.36	28.57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3.23
	10	170.50	15.93	139.34	15.57	28.42	28.89	9.43	3.25
Cast2	1	171.00	16.26	139.97	15.57	28.70	28.58	9.50	3.35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3.36
	3	171.00	16.26	139.75	15.71	28.56	28.84	9.61	3.32
	4	171.10	16.04	139.67	15.56	28.62	28.97	9.60	3.28
	5	171.40	15.97	139.72	15.65	28.70	28.99	9.56	3.35
	6	171.20	16.10	139.99	15.63	28.67	28.84	9.53	3.37
	7	171.00	16.09	139.96	15.72	28.59	28.56	9.60	3.36
	8	171.10	16.13	139.92	15.56	28.49	28.84	9.58	3.37
	9	171.00	16.09	139.85	15.61	28.59	28.92	9.52	3.37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	1	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3.39
	3	170.50	15.70	139.82	15.53	28.37	28.94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3.37
	5	170.60	15.75	139.70	15.44	28.70	28.88	9.59	3.37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3.38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3.39
	9	170.50	15.76	139.72	15.54	28.68	28.93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3.38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0.08

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.84	1.79	0.30	4.01	1.48	0.61	1.52	1.04
Experiment 2.1.1	171.20	15.95	139.90	15.62	28.37	28.60	9.33	3.32
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.54	1.83	0.04	3.72	2.11	1.23	3.62	1.54
Experiment 3.1.1	171.52	15.96	140.48	15.55	28.54	28.68	9.49	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.36	1.75	-0.37	4.15	1.52	0.96	2.01	0.95
Av Shrinkage (%)	0.58	1.79	-0.01	3.96	1.71	0.93	2.38	3.36

Central University of Technology, Free State

Experiment 1.1

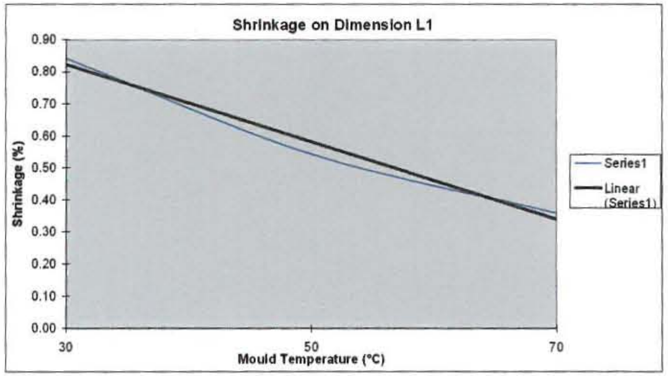
Mould Temp.	30
Curing Temp.	50
Resin Temp	30

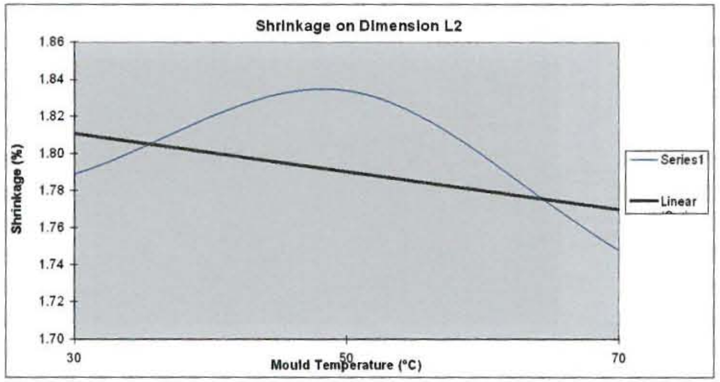
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.80	16.02	139.89	15.48	28.75	28.57	9.66	3.43
	2	170.90	16.12	139.90	15.45	28.58	28.63	9.39	3.32
	3	170.85	15.73	139.86	15.60	28.47	28.68	9.44	3.24
	4	171.20	15.77	139.82	15.47	28.46	28.78	9.52	3.35
	5	171.20	15.77	139.89	15.52	28.74	28.81	9.56	3.28
	6	171.20	15.81	139.89	15.71	28.55	28.78	9.65	3.42
	7	171.20	15.95	139.90	15.62	28.37	28.6	9.33	3.32
	8	171.00	16.11	139.92	15.60	28.43	28.63	9.39	3.38
	9	170.95	16.15	139.88	15.50	28.57	28.78	9.47	3.30
	10	171.85	15.75	139.81	15.50	28.72	28.62	9.57	3.31
Cast2	1	171.30	15.92	139.86	15.70	28.48	28.56	9.57	3.33
	2	171.20	15.89	139.79	15.61	28.51	28.72	9.75	3.37
	3	171.25	15.90	139.76	15.71	28.58	28.94	9.82	3.38
	4	171.30	15.89	139.65	15.83	28.64	29.1	9.73	3.32
	5	171.20	16.09	139.78	15.69	28.65	29.09	9.57	3.37
	6	171.20	16.03	139.80	15.69	28.58	28.9	9.75	3.31
	7	171.20	15.99	139.80	15.74	28.51	28.8	9.82	3.31
	8	171.10	15.97	139.79	15.89	28.55	28.84	9.60	3.26
	9	171.20	15.97	139.86	15.68	28.64	29.09	9.57	3.36
	10	171.20	16.02	139.85	15.63	28.53	28.86	9.71	3.31
Cast3	1	170.90	15.91	139.78	15.57	28.62	28.61	9.46	3.36
	2	170.90	15.99	139.75	15.54	28.55	28.6	9.49	3.41
	3	170.90	15.81	139.73	15.50	28.34	28.62	9.50	3.37
	4	170.95	15.87	139.75	15.53	28.48	28.73	9.52	3.42
	5	170.95	15.88	139.69	15.57	28.57	28.78	9.53	3.33
	6	170.95	15.85	139.69	15.50	28.59	28.72	9.47	3.38
	7	170.85	15.85	139.72	15.68	28.43	28.64	9.49	3.24
	8	170.75	16.02	139.75	15.76	28.42	28.59	9.52	3.38
	9	170.80	15.88	139.78	15.76	28.55	28.77	9.50	3.33
	10	170.85	15.86	139.77	15.66	28.60	28.68	9.45	3.39
Average Value		171.07	15.93	139.80	15.62	28.55	28.75	9.56	3.34
Std deviation		0.23	0.11	0.07	0.11	0.10	0.15	0.13	0.05

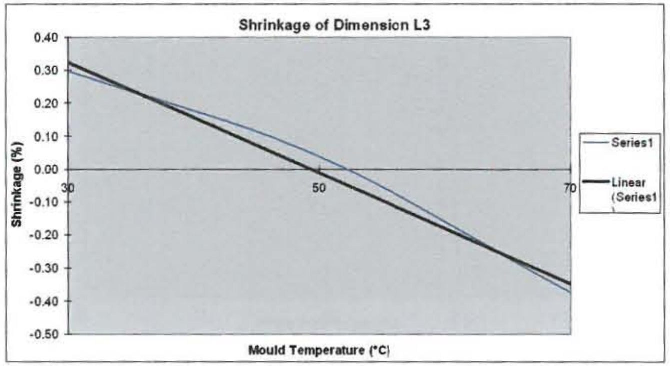
Experiment 1.1

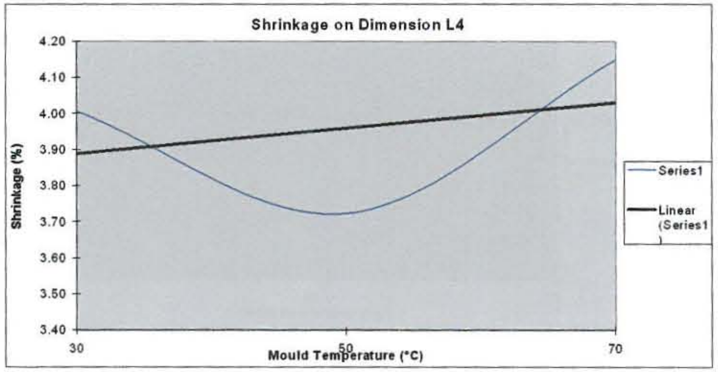
Mould Temp.	30
Curing Temp.	70
Resin Temp	30

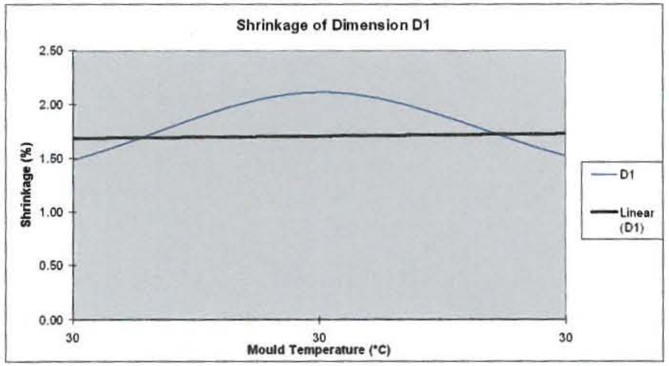
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.25	15.97	140.12	15.58	28.34	28.43	9.41	3.33
	2	171.30	15.96	140.14	15.53	28.51	28.53	9.46	3.38
	3	171.30	15.83	139.98	15.63	28.57	28.66	9.46	3.31
	4	171.25	15.88	140.02	15.68	28.39	28.75	9.46	3.27
	5	171.25	15.85	139.99	15.00	28.29	28.79	9.43	3.24
	6	171.45	16.10	139.99	15.54	28.32	28.73	9.41	3.18
	7	171.30	16.07	140.01	15.45	28.54	28.65	9.46	3.22
	8	171.25	16.03	140.08	15.50	28.57	28.44	9.46	3.18
	9	171.20	16.07	140.17	15.64	28.52	28.72	9.44	3.28
	10	171.25	16.18	140.18	15.49	28.28	28.66	9.42	3.26
Cast2	1	171.85	16.06	140.66	15.54	28.42	28.49	9.48	3.32
	2	171.90	16.10	140.68	15.68	28.36	28.82	9.59	3.31
	3	171.95	16.02	140.55	15.60	28.61	28.96	9.58	3.39
	4	171.95	16.06	140.53	15.57	28.77	28.96	9.57	3.34
	5	171.75	15.95	140.51	15.70	28.55	28.72	9.54	3.34
	6	171.70	15.97	140.52	15.59	28.36	28.55	9.50	3.35
	7	171.70	15.88	140.47	15.68	28.42	28.53	9.60	3.38
	8	171.80	16.18	140.58	15.80	28.70	28.97	9.57	3.40
	9	171.90	16.01	140.71	15.58	28.73	28.9	9.54	3.36
	10	171.95	15.93	140.63	15.63	28.49	28.63	9.49	3.38
Cast3	1	171.30	16.02	140.28	15.49	28.86	28.51	9.45	3.42
	2	171.35	15.94	140.28	15.53	28.59	28.56	9.47	3.39
	3	171.40	15.72	140.33	15.45	28.25	28.65	9.50	3.36
	4	171.45	15.78	140.37	15.48	28.77	28.74	9.48	3.42
	5	171.45	15.88	140.47	15.48	28.79	28.76	9.44	3.44
	6	171.60	16.00	140.54	15.49	28.55	28.72	9.50	3.43
	7	171.60	15.87	140.51	15.58	28.30	28.64	9.49	3.39
	8	171.40	16.00	140.39	15.53	28.73	28.51	9.44	3.39
	9	171.40	15.88	140.27	15.56	28.86	28.77	9.43	3.32
	10	171.30	15.73	140.25	15.53	28.78	28.6	9.48	3.42
Average Value		171.52	15.96	140.48	15.55	28.54	28.68	9.49	3.34
Std deviation		0.26	0.12	0.14	0.13	0.19	0.15	0.05	0.07

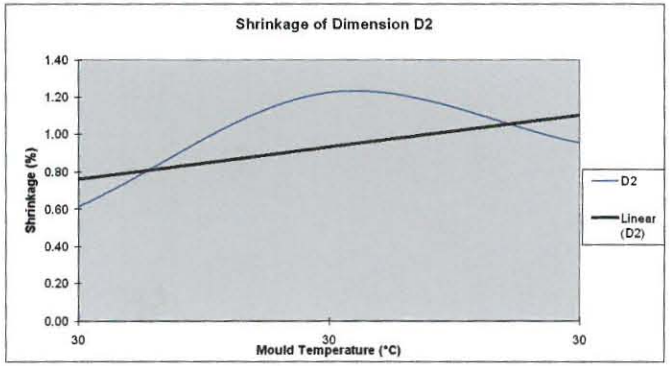

Shrinkage on Dimension L1
Shrinkage (%)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

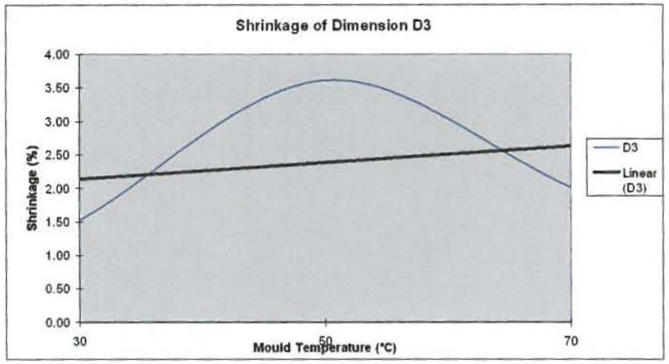

Shrinkage on Dimension L2
Shrinkage (%)
1.86
1.84
1.82
1.80
1.78
1.76
1.74
1.72
1.70
30
50
70
Mould Temperature (°C)
Series1
Linear

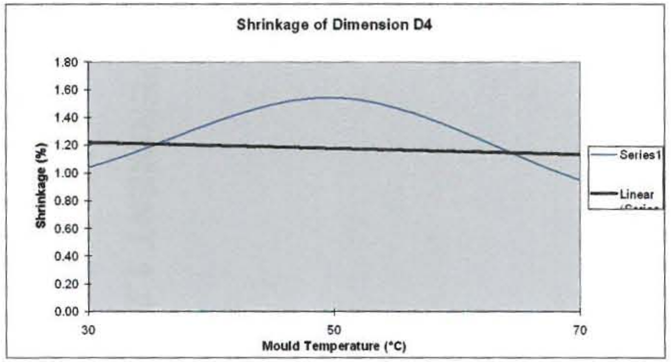

Shrinkage of Dimension L3
Shrinkage (%)
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage on Dimension L4
Shrinkage (%)
4.20
4.10
4.00
3.90
3.80
3.70
3.60
3.50
3.40
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage of Dimension D1
Shrinkage (%)
Mould Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
Mould Temperature (°C)
D2
Linear (D2)

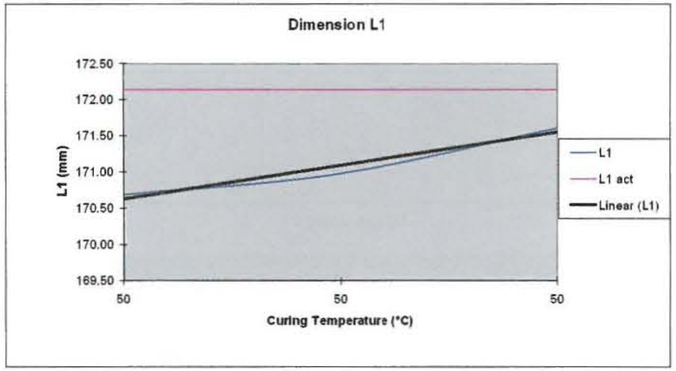

Shrinkage of Dimension D3
Shrinkage (%)
Mould Temperature (°C)
D3
Linear (D3)

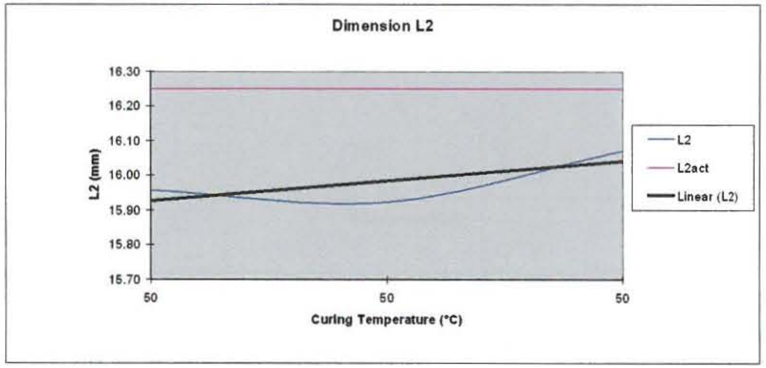

Shrinkage of Dimension D4
Shrinkage (%)
Mould Temperature (°C)
Series1
Linear

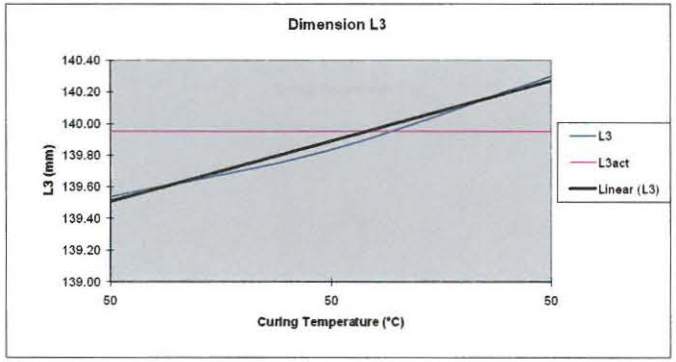
DATA OF EXPERIMENT 1.2

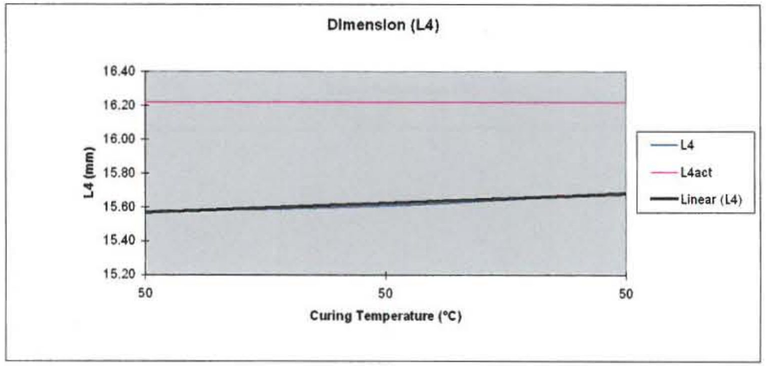
APPENDIX B : EXPERIMENT 1.2

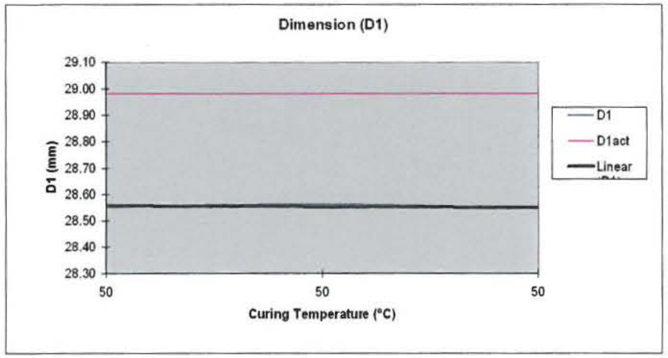
Mould Temp (°C)	Curing Temp (°C)	Resin Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
50	30	30	170.69	172.14	15.96	16.25	139.54	139.95	15.57	16.22	28.55	28.98	28.78	28.96	9.53
50	50	30	170.98	172.14	15.92	16.25	139.83	139.95	15.61	16.22	28.56	28.98	28.74	28.96	9.58
50	70	30	171.61	172.14	16.07	16.25	140.30	139.95	15.69	16.22	28.55	28.98	28.68	28.96	9.49

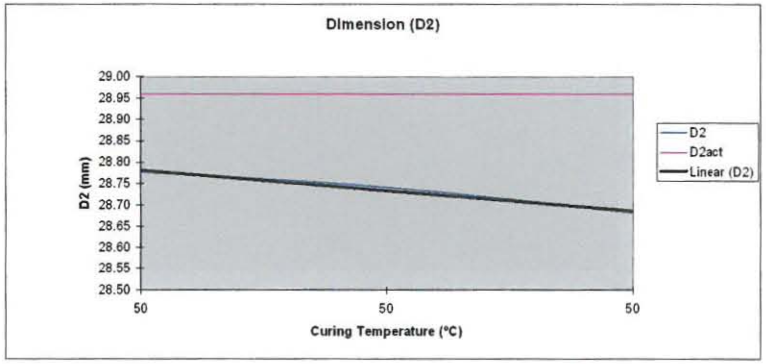


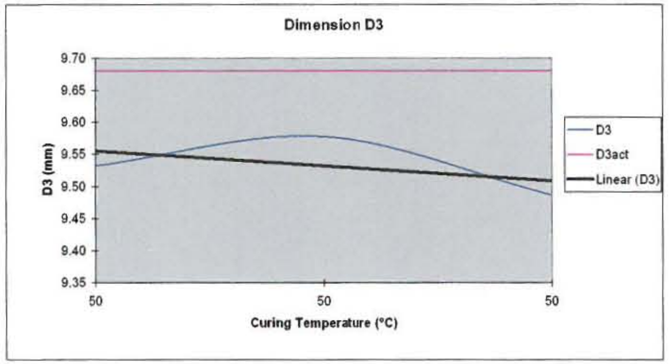


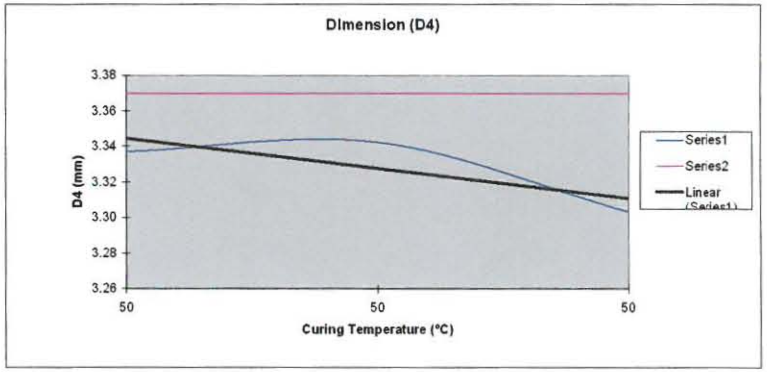


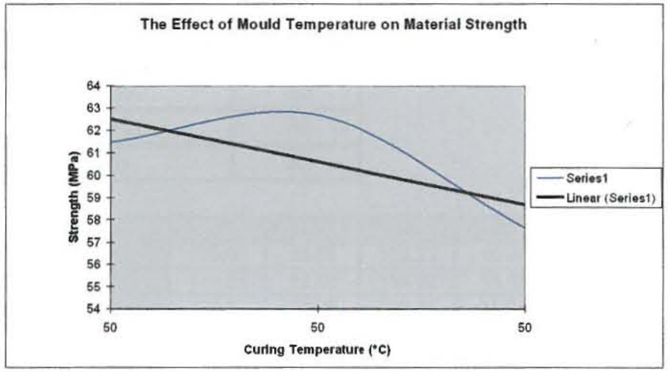


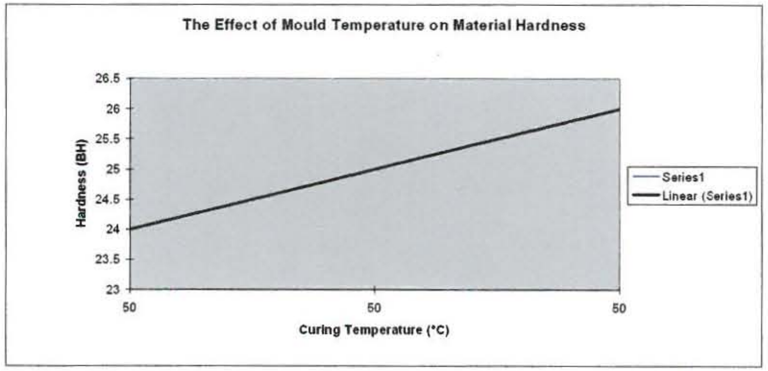

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
50
50
50
Curing Temperature (°C)
D1
D1act
Linear


Dimension (D2)
D2 (mm)
29.00
28.95
28.90
28.85
28.80
28.75
28.70
28.65
28.60
28.55
28.50
50
50
50
Curing Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.70
9.65
9.60
9.55
9.50
9.45
9.40
9.35
50
50
50
Curing Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.36
3.34
3.32
3.30
3.28
3.26
50
50
50
Curing Temperature (°C)
Series1
Series2
Linear


The Effect of Mould Temperature on Material Strength
Strength (MPa)
64
63
62
61
60
59
58
57
56
55
54
50
50
50
Curing Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
26.5
26
25.5
25
24.5
24
23.5
23
50
50
50
Curing Temperature (°C)
Series1
Linear (Series1)

Central University of Technology, Free State

Experiment 1.2

Mould Temp.	**50**
Curing Temp.	**30**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.00	15.85	139.23	15.46	28.60	28.89	9.43	3.36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3.31
	3	170.50	16.06	138.76	15.58	28.28	28.55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3.24
	5	170.55	16.00	138.79	15.68	28.65	28.88	9.55	3.23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3.36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3.34
	8	170.10	15.97	139.02	15.48	28.36	28.57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3.23
	10	170.50	15.93	139.34	15.57	28.42	28.89	9.43	3.25
Cast2	1	171.00	16.26	139.97	15.57	28.70	28.58	9.50	3.35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3.36
	3	171.00	16.26	139.75	15.71	28.56	28.84	9.61	3.32
	4	171.10	16.04	139.67	15.56	28.62	28.97	9.60	3.28
	5	171.40	15.97	139.72	15.65	28.70	28.99	9.56	3.35
	6	171.20	16.10	139.99	15.63	28.67	28.84	9.53	3.37
	7	171.00	16.09	139.96	15.72	28.59	28.56	9.60	3.36
	8	171.10	16.13	139.92	15.56	28.49	28.84	9.58	3.37
	9	171.00	16.09	139.85	15.61	28.59	28.92	9.52	3.37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	1	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3.39
	3	170.50	15.70	139.82	15.53	28.37	28.94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3.37
	5	170.60	15.75	139.70	15.44	28.70	28.88	9.59	3.37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3.38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3.39
	9	170.50	15.76	139.72	15.54	28.68	28.93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3.38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0.08

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.84	1.79	0.30	4.01	1.48	0.61	1.52	1.04
Experiment 2.1.1	170.98	15.92	139.83	15.61	28.56	28.74	9.58	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.67	2.00	0.09	3.80	1.45	0.74	1.06	0.88
Experiment 3.1.1	171.61	16.07	140.30	15.69	28.55	28.68	9.49	3.30
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.31	1.09	-0.25	3.31	1.51	0.95	2.00	2.04
Av Shrinkage (%)	0.61	1.62	0.05	3.70	1.48	0.77	1.53	3.36

Experiment 1.2

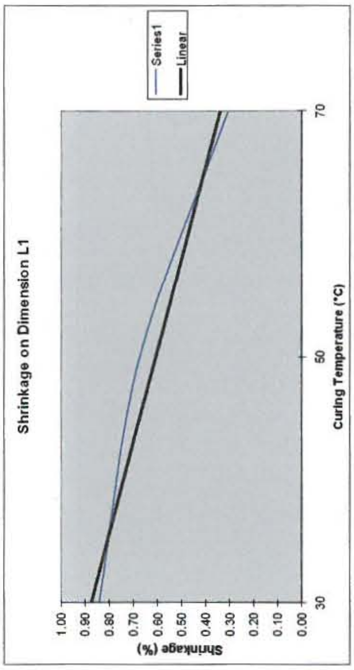
Mould Temp.	**50**
Curing Temp.	**50**
Resin Temp	**30**

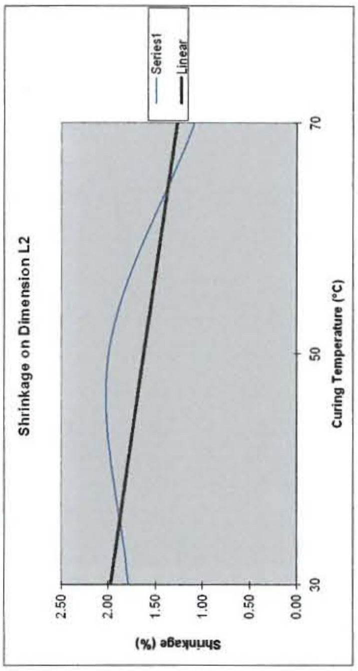
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.90	16.00	139.92	15.46	28.74	28.59	9.32	3.34
	2	170.90	15.75	139.95	15.52	28.59	28.64	9.40	3.36
	3	171.00	15.77	139.89	15.49	28.38	28.82	9.48	3.31
	4	171.00	15.77	139.94	15.49	28.44	28.77	9.65	3.31
	5	171.00	15.98	140.06	15.54	28.72	28.62	9.66	3.41
	6	171.20	16.13	140.00	15.66	28.67	28.62	9.51	3.40
	7	170.80	15.76	139.91	15.49	28.51	28.74	9.51	3.40
	8	170.80	15.85	139.91	15.52	28.29	28.83	9.63	3.33
	9	170.75	15.86	139.93	15.46	28.55	28.75	9.66	3.32
	10	170.80	15.94	139.93	15.56	28.71	28.56	9.32	3.38
Cast2	1	171.20	15.99	139.92	15.61	28.63	28.53	9.56	3.34
	2	171.20	15.95	139.87	15.77	28.50	28.8	9.70	3.29
	3	171.10	15.96	139.62	15.83	28.54	29.04	9.83	3.35
	4	171.25	16.03	139.79	15.68	28.63	29.09	9.85	3.29
	5	171.20	16.01	139.84	15.71	28.63	29.02	9.78	3.41
	6	171.20	16.15	139.82	16.28	28.52	28.84	9.56	3.29
	7	171.00	15.98	139.74	15.85	28.58	28.53	9.75	3.29
	8	171.20	15.99	139.83	15.59	28.60	28.79	9.85	3.27
	9	171.20	15.99	139.83	15.58	28.64	28.74	9.83	3.37
	10	171.20	15.96	139.63	15.70	28.64	29.08	9.56	3.35
Cast3	1	170.80	15.91	139.79	15.57	28.61	28.63	9.46	3.41
	2	170.80	15.89	139.74	15.52	28.48	28.61	9.49	3.36
	3	170.90	15.77	139.77	15.58	28.43	28.76	9.51	3.34
	4	170.95	15.93	139.77	15.46	28.59	28.78	9.51	3.35
	5	171.00	16.00	139.76	15.52	28.59	28.7	9.48	3.34
	6	170.80	15.94	139.74	15.54	28.41	28.58	9.50	3.37
	7	170.80	15.74	139.77	15.57	28.49	28.64	9.52	3.38
	8	170.80	15.89	139.77	15.57	28.57	28.75	9.46	3.27
	9	170.80	16.04	139.78	15.57	28.62	28.73	9.49	3.37
	10	170.80	15.77	139.78	15.54	28.57	28.66	9.50	3.27
Average Value		170.98	15.92	139.83	15.61	28.56	28.74	9.58	3.34
Std deviation		0.17	0.11	0.10	0.16	0.10	0.15	0.15	0.04

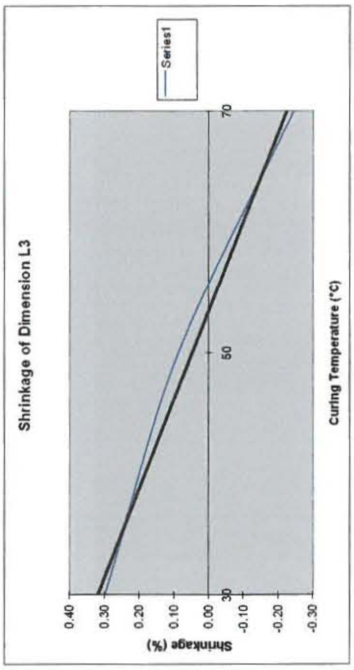
Experiment 1.2

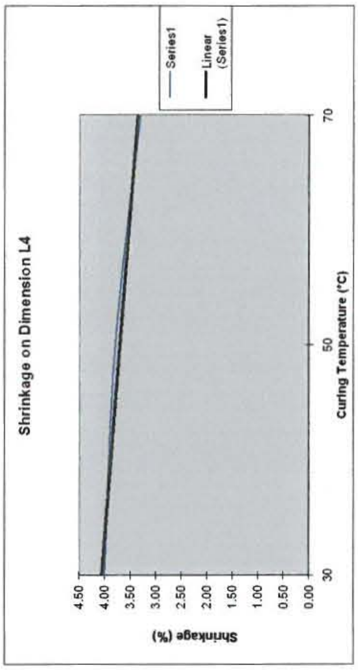
Mould Temp.	50
Curing Temp.	70
Resin Temp	30

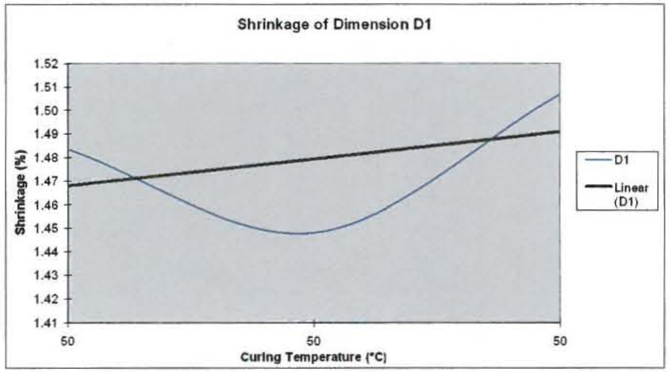
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.40	16.10	140.18	15.60	28.57	28.45	9.44	3.28
	2	171.35	16.11	140.19	15.69	28.43	28.61	9.51	3.32
	3	171.30	16.20	140.17	15.76	28.32	28.79	9.53	3.30
	4	171.30	16.16	139.93	15.85	28.35	28.7	9.50	3.23
	5	171.40	16.07	139.96	15.73	28.49	28.58	9.48	3.17
	6	171.45	15.94	139.95	15.58	28.57	28.57	9.43	3.18
	7	171.45	17.01	139.83	15.76	28.50	28.61	9.52	3.16
	8	171.50	16.14	140.21	15.84	28.34	28.78	9.52	3.32
	9	171.35	16.12	140.21	15.57	28.32	28.7	9.49	3.20
	10	171.30	16.16	140.13	15.72	28.55	28.59	9.45	3.22
Cast2	1	172.00	15.91	140.75	15.66	28.69	28.51	9.48	3.33
	2	172.10	16.09	140.71	15.74	28.40	28.78	9.47	3.27
	3	172.10	16.08	140.71	15.81	28.39	28.92	9.58	3.38
	4	172.10	16.07	140.69	15.93	28.78	28.99	9.57	3.34
	5	172.20	16.11	140.68	15.69	28.57	28.86	9.55	3.36
	6	172.10	16.11	140.68	15.70	28.38	28.49	9.51	3.38
	7	172.15	16.08	140.70	15.65	28.59	28.76	9.48	3.35
	8	172.05	15.98	140.75	15.72	28.77	28.98	9.57	3.41
	9	172.00	16.05	140.68	15.82	28.64	28.83	9.52	3.32
	10	172.10	16.16	140.73	15.87	28.53	28.53	9.48	3.38
Cast3	1	171.40	15.90	140.10	15.50	28.53	28.49	9.48	3.38
	2	171.50	15.88	140.08	15.59	28.67	28.68	9.39	3.30
	3	171.45	15.90	140.09	15.57	28.86	28.76	9.44	3.25
	4	171.40	16.00	140.09	15.61	28.76	28.73	9.46	3.22
	5	171.20	16.13	140.09	15.68	28.53	28.7	9.48	3.27
	6	171.25	15.90	140.15	15.63	28.27	28.5	9.48	3.33
	7	171.25	15.90	140.16	15.57	28.78	28.66	9.38	3.39
	8	171.35	15.97	140.12	15.53	28.84	28.77	9.44	3.41
	9	171.35	15.99	140.09	15.71	28.69	28.59	9.48	3.33
	10	171.40	15.92	140.11	15.54	28.25	28.53	9.48	3.32
Average Value		171.61	16.07	140.30	15.69	28.55	28.68	9.49	3.30
Std deviation		0.35	0.20	0.31	0.11	0.18	0.15	0.05	0.07

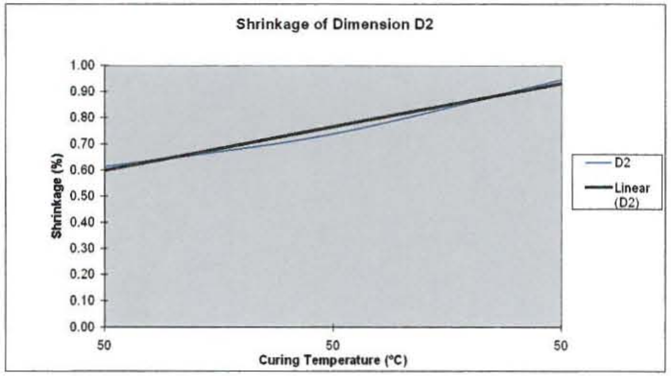

Shrinkage on Dimension L1
Shrinkage (%)
Curing Temperature (°C)
Series1
Linear
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
30
50
70

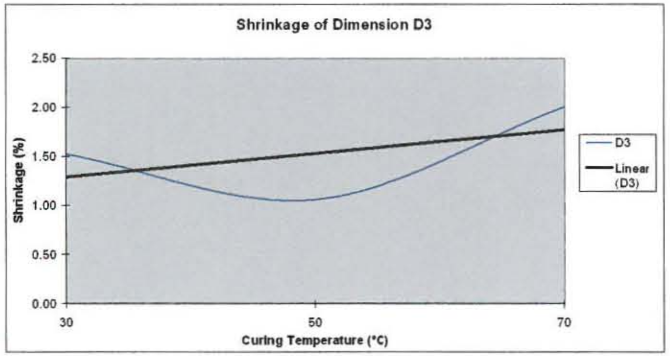

Shrinkage on Dimension L2
Shrinkage (%)
Curing Temperature (°C)
Series1
Linear
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70

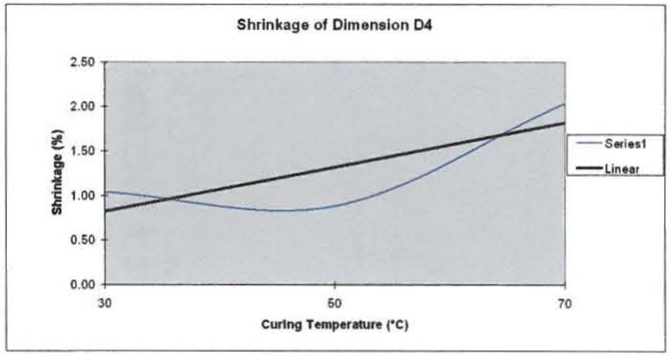

Shrinkage of Dimension L3
Shrinkage (%)
Curing Temperature (°C)
Series1
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
30
50
70


Shrinkage on Dimension L4
Shrinkage (%)
Curing Temperature (°C)
Series1
Linear (Series1)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70


Shrinkage of Dimension D1
Shrinkage (%)
1.52
1.51
1.50
1.49
1.48
1.47
1.46
1.45
1.44
1.43
1.42
1.41
50
50
50
Curing Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
50
50
50
Curing Temperature (°C)
D2
Linear (D2)

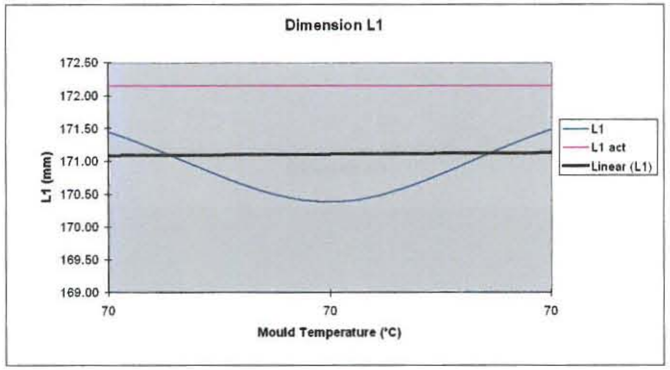

Shrinkage of Dimension D3
Shrinkage (%)
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Curing Temperature (°C)
D3
Linear (D3)

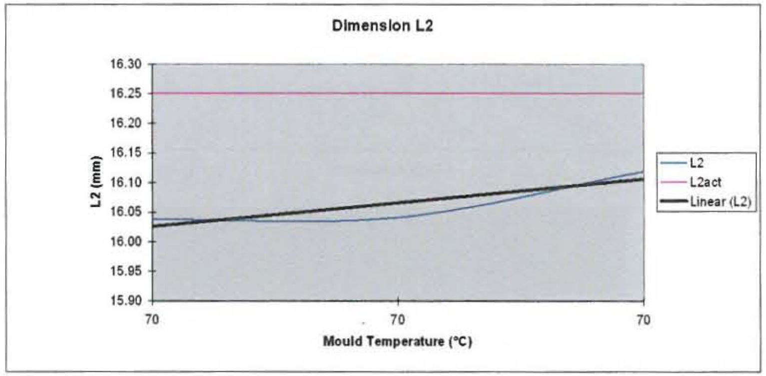

Shrinkage of Dimension D4
Shrinkage (%)
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Curing Temperature (°C)
Series1
Linear

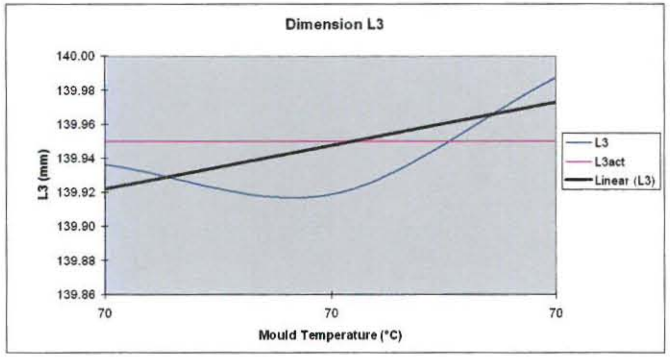
DATA OF EXPERIMENT 1.3

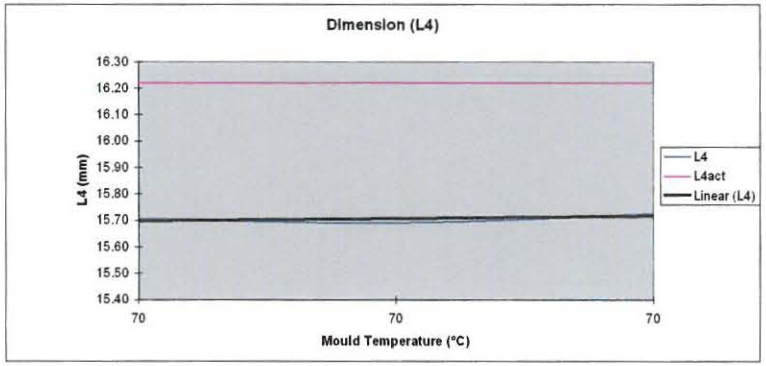
APPENDIX C : EXPERIMENT 1.3

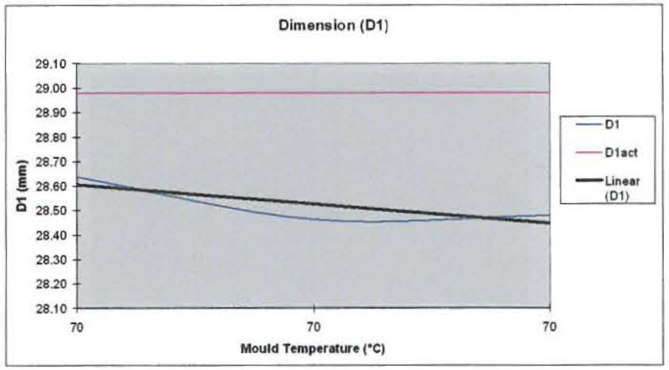
Mould Temp (°C)	Curing Temp (°C)	Resin Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
70	30	30	171.45	172.14	16.04	16.25	139.94	139.95	15.71	16.22	28.64	28.98	28.72	28.96	9.56
70	50	30	170.38	172.14	16.04	16.25	139.92	139.95	15.69	16.22	28.46	28.98	28.53	28.96	9.54
70	70	30	171.48	172.14	16.12	16.25	139.99	139.95	15.73	16.22	28.48	28.98	28.50	28.96	9.54

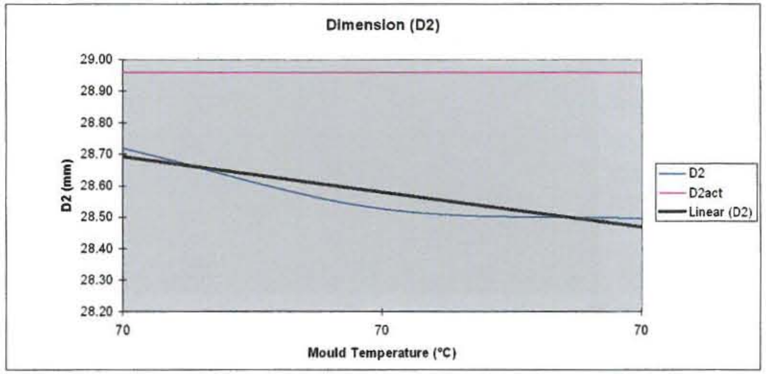


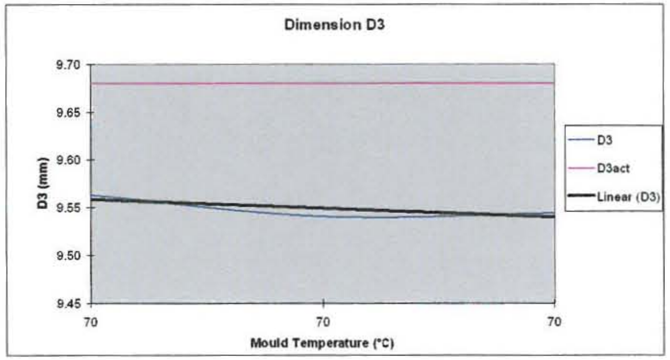


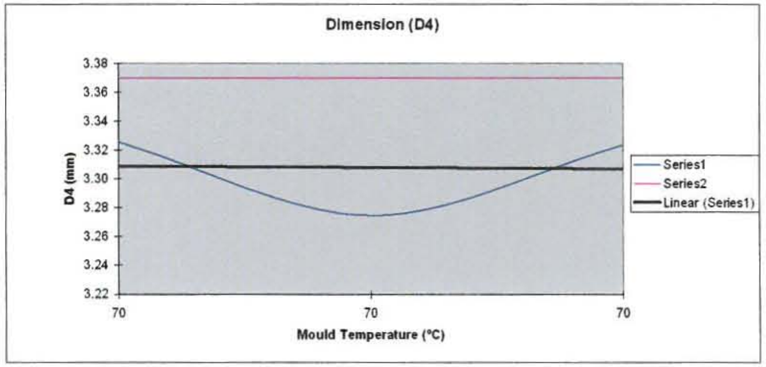


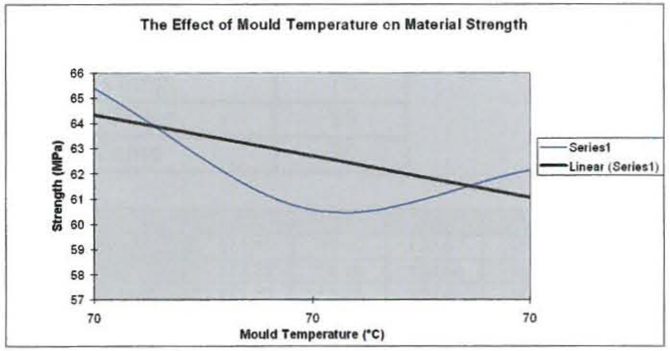


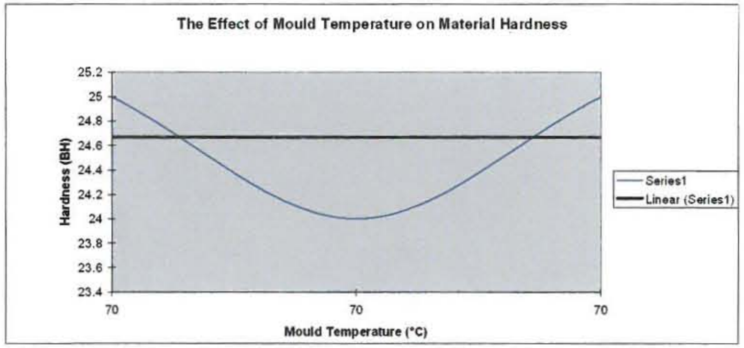

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
28.10
70
70
70
Mould Temperature (°C)
D1
D1act
Linear (D1)


Dimension (D2)
D2 (mm)
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
70
70
70
Mould Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.70
9.65
9.60
9.55
9.50
9.45
70
70
70
Mould Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.36
3.34
3.32
3.30
3.28
3.26
3.24
3.22
70
70
70
Mould Temperature (°C)
Series1
Series2
Linear (Series1)


The Effect of Mould Temperature on Material Strength
Strength (MPa)
66
65
64
63
62
61
60
59
58
57
70
70
70
Mould Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
25.2
25
24.8
24.6
24.4
24.2
24
23.8
23.6
23.4
70
70
70
Mould Temperature (°C)
Series1
Linear (Series1)

Experiment 3.1.1

Mould Temp.	**70**
Curing Temp.	**30**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.10	16.00	139.67	15.71	28.48	28.61	9.54	3.28
	2	171.20	15.99	139.66	15.74	28.58	28.5	9.54	3.23
	3	171.20	15.93	139.65	15.66	28.69	28.76	9.54	3.20
	4	171.10	15.91	139.67	15.63	28.68	28.81	9.54	3.19
	5	171.30	15.88	139.70	15.88	28.61	28.8	9.54	3.25
	6	171.20	15.88	139.66	15.86	28.48	28.57	9.55	3.24
	7	171.10	15.98	139.55	15.63	28.51	28.61	9.53	3.25
	8	171.20	16.03	139.66	15.00	28.58	28.8	9.55	3.33
	9	171.20	16.00	139.64	15.62	28.67	28.8	9.55	3.28
	10	171.30	15.92	139.69	15.72	28.49	28.43	9.53	3.19
Cast2	1	171.85	16.08	140.23	15.65	28.68	28.69	9.60	3.33
	2	171.80	16.08	140.19	15.73	28.69	28.78	9.57	3.37
	3	171.95	16.24	140.19	15.73	28.81	28.82	9.60	3.36
	4	171.90	16.24	140.23	15.74	28.74	28.74	9.58	3.37
	5	171.95	16.22	140.20	15.71	28.67	28.71	9.57	3.35
	6	171.70	16.31	140.22	15.74	28.74	28.82	9.55	3.36
	7	171.70	16.30	140.22	15.70	28.75	28.81	9.62	3.28
	8	171.80	16.12	140.18	15.76	28.62	28.74	9.57	3.39
	9	171.95	16.08	140.22	15.79	28.69	28.69	9.58	3.29
	10	171.90	16.19	140.21	15.75	28.80	28.74	9.57	3.40
Cast3	1	171.25	15.92	139.98	15.65	28.58	28.68	9.57	3.41
	2	171.30	15.98	139.95	15.81	28.49	28.75	9.56	3.38
	3	171.30	16.10	139.93	15.74	28.70	28.83	9.57	3.37
	4	171.20	16.04	139.96	15.71	28.59	28.78	9.56	3.39
	5	171.20	15.96	139.97	15.74	28.56	28.65	9.57	3.33
	6	171.25	15.95	139.93	15.80	28.67	28.75	9.56	3.37
	7	171.40	15.95	139.92	15.71	28.70	28.8	9.57	3.38
	8	171.45	15.90	139.98	15.82	28.56	28.71	9.57	3.37
	9	171.30	15.96	139.90	15.84	28.72	28.65	9.57	3.42
	10	171.30	16.00	139.93	15.59	28.61	28.73	9.57	3.41
Average Value		171.45	16.04	139.94	15.71	28.64	28.72	9.56	3.33
Std deviation		0.31	0.13	0.23	0.15	0.09	0.10	0.02	0.07

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	171.45	16.04	139.94	15.71	28.64	28.72	9.56	3.33
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.40	1.29	0.01	3.20	1.19	0.82	1.21	1.37
Experiment 2.1.1	170.38	16.04	139.92	15.69	28.46	28.53	9.54	3.27
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	1.02	1.27	0.03	3.29	1.79	1.48	1.44	2.89
Experiment 3.1.1	171.48	16.12	139.99	15.73	28.48	28.50	9.54	3.32
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.38	0.80	-0.02	3.08	1.74	1.59	1.40	1.43
Av Shrinkage (%)	0.60	1.12	0.00	3.19	1.57	1.29	1.35	3.36

Experiment 3.2.1

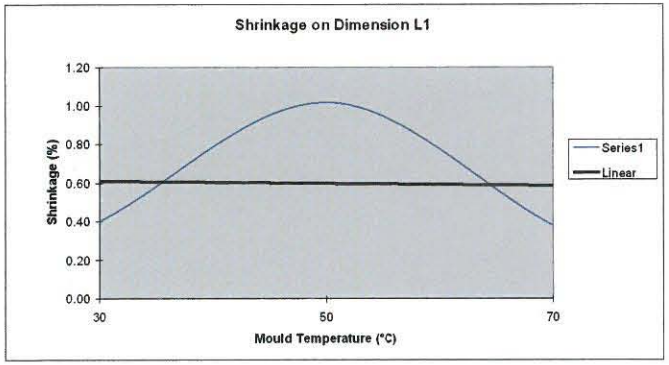
Mould Temp.	**70**
Curing Temp.	**50**
Resin Temp	**30**

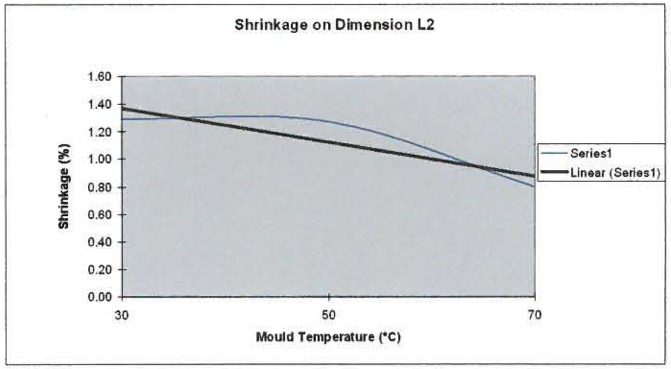
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.30	16.08	139.88	15.61	28.34	28.49	9.51	3.25
	2	170.30	16.07	139.88	15.62	28.26	28.28	9.46	3.28
	3	170.30	16.09	139.85	15.69	28.53	28.62	9.51	3.29
	4	170.30	16.02	139.79	15.67	28.51	28.64	9.49	3.30
	5	170.35	16.01	139.93	15.69	28.37	28.63	9.51	3.14
	6	170.30	16.08	139.89	15.64	28.20	28.25	9.58	3.18
	7	170.30	16.08	139.85	15.87	28.51	28.51	9.56	3.18
	8	170.30	16.07	139.74	15.65	28.49	28.64	9.51	3.22
	9	170.30	16.02	139.80	15.65	28.35	28.66	9.50	3.24
	10	170.35	16.05	139.90	15.74	28.30	28.35	9.51	3.13
Cast2	1	170.60	16.04	140.18	15.72	28.39	28.42	9.52	3.30
	2	170.70	16.07	140.16	15.78	28.47	28.58	9.56	3.29
	3	170.70	16.13	140.11	15.78	28.64	28.81	9.58	3.22
	4	170.70	15.97	140.05	15.71	28.71	28.62	9.58	3.27
	5	170.70	16.21	140.01	15.71	28.55	28.42	9.58	3.28
	6	170.50	16.13	140.06	15.73	28.41	28.52	9.52	3.33
	7	170.50	16.04	139.97	15.73	28.57	28.77	9.54	3.30
	8	170.50	16.00	140.08	15.68	28.70	28.76	9.58	3.31
	9	170.60	16.03	140.16	15.67	28.66	28.49	9.58	3.30
	10	170.60	16.07	140.17	15.76	28.43	28.39	9.60	3.34
Cast3	1	170.10	16.05	139.74	15.65	28.62	28.36	9.53	3.35
	2	170.10	16.12	139.72	15.63	28.58	28.52	9.54	3.31
	3	170.20	15.96	139.73	15.65	28.27	28.69	9.56	3.30
	4	170.30	15.88	139.82	15.65	28.31	28.61	9.57	3.33
	5	170.30	15.93	139.83	15.57	28.65	28.38	9.53	3.29
	6	170.30	15.94	139.94	15.74	28.43	28.36	9.53	3.35
	7	170.30	16.10	139.92	15.66	28.21	28.56	9.54	3.31
	8	170.35	16.08	139.81	15.74	28.31	28.71	9.57	3.26
	9	170.20	16.05	139.82	15.66	28.43	28.4	9.56	3.28
	10	170.10	15.87	139.77	15.68	28.67	28.37	9.51	3.31
Average Value		170.38	16.04	139.92	15.69	28.46	28.53	9.54	3.27
Std deviation		0.18	0.07	0.14	0.06	0.15	0.15	0.03	0.06

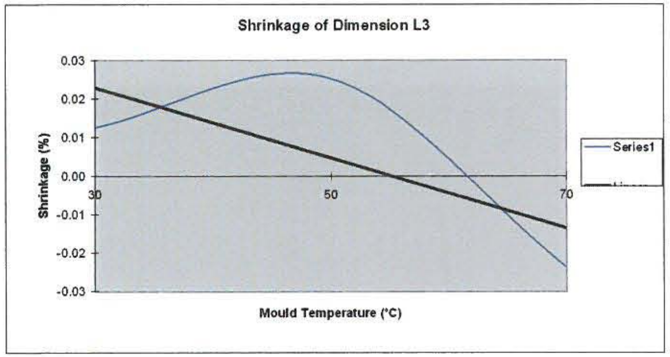
Experiment 3.3.1

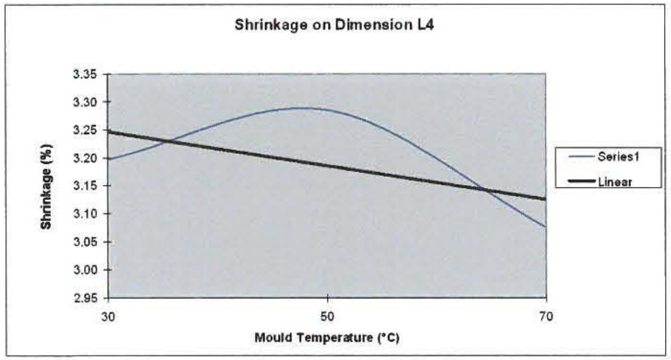
Mould Temp.	70
Curing Temp.	70
Resin Temp	30

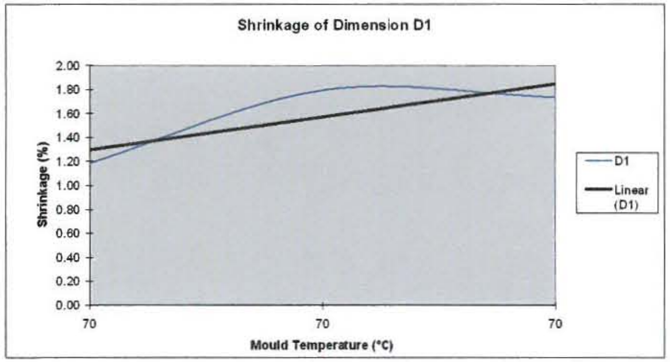
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.20	16.42	139.63	15.65	28.75	28.37	9.54	3.23
	2	171.00	16.21	139.65	15.73	28.70	28.47	9.55	3.33
	3	171.00	16.05	139.68	15.73	28.46	28.65	9.55	3.32
	4	171.20	16.04	139.58	15.71	28.36	28.68	9.52	3.28
	5	171.15	16.16	139.63	15.62	28.23	28.41	9.49	3.15
	6	171.10	16.28	139.75	15.62	28.32	28.23	9.54	3.19
	7	171.15	16.22	139.68	15.61	28.72	28.47	9.55	3.19
	8	171.25	16.25	139.38	15.76	28.55	28.72	9.54	3.19
	9	171.10	16.16	139.55	15.73	28.25	28.35	9.52	3.28
	10	171.25	16.36	139.64	15.68	28.65	28.23	9.49	3.20
Cast2	1	171.80	16.03	140.26	15.76	28.61	28.44	9.57	3.34
	2	171.80	16.24	140.31	15.72	28.69	28.54	9.52	3.32
	3	171.75	16.15	140.26	15.75	28.50	28.64	9.57	3.38
	4	171.80	16.19	140.18	15.78	28.46	28.70	9.58	3.37
	5	171.80	16.08	140.25	15.78	28.68	28.53	9.56	3.37
	6	171.70	15.96	140.24	15.71	28.62	28.48	9.51	3.33
	7	171.70	16.03	140.21	15.63	28.46	28.50	9.56	3.33
	8	171.70	16.11	140.23	15.83	28.45	28.70	9.58	3.38
	9	171.75	16.24	140.25	15.81	28.57	28.51	9.55	3.34
	10	171.75	16.27	140.27	15.93	28.61	28.44	9.49	3.39
Cast3	1	171.50	15.97	140.10	15.61	28.30	28.23	9.54	3.40
	2	171.50	15.89	140.11	15.64	28.14	28.53	9.59	3.33
	3	171.60	16.01	140.12	15.66	28.19	28.68	9.60	3.43
	4	171.50	16.03	140.02	15.68	28.55	28.63	9.56	3.26
	5	171.50	16.06	140.11	15.68	28.63	28.36	9.52	3.36
	6	171.50	16.09	140.10	15.77	28.35	28.27	9.59	3.41
	7	171.60	16.04	140.05	15.74	28.18	28.57	9.58	3.44
	8	171.60	15.96	140.07	15.93	28.39	28.72	9.55	3.38
	9	171.65	16.02	140.16	15.73	28.66	28.57	9.51	3.36
	10	171.60	16.02	140.15	15.77	28.33	28.24	9.51	3.43
Average Value		171.48	16.12	139.99	15.73	28.48	28.50	9.54	3.32
Std deviation		0.27	0.13	0.28	0.08	0.18	0.16	0.03	0.08

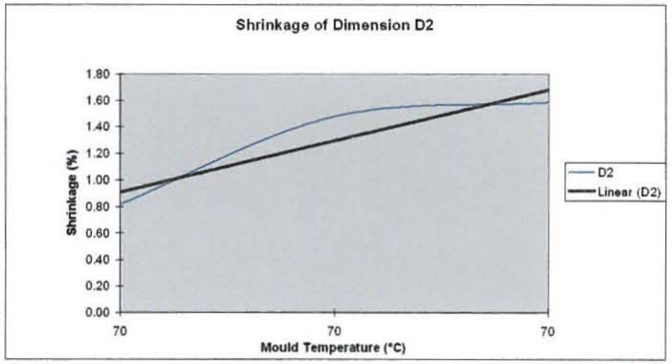

Shrinkage on Dimension L1
Shrinkage (%)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear

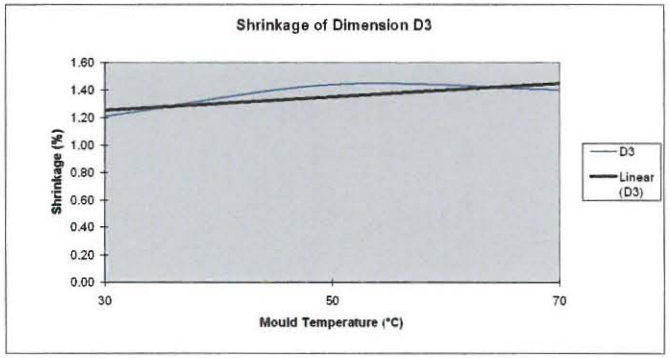

Shrinkage on Dimension L2
Shrinkage (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

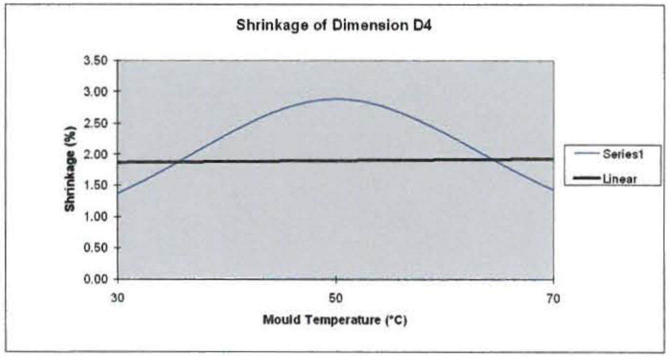

Shrinkage of Dimension L3
Shrinkage (%)
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
30
50
70
Mould Temperature (°C)
Series1


Shrinkage on Dimension L4
Shrinkage (%)
3.35
3.30
3.25
3.20
3.15
3.10
3.05
3.00
2.95
30
50
70
Mould Temperature (°C)
Series1
Linear


Shrinkage of Dimension D1
Shrinkage (%)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
70
70
70
Mould Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
70
70
70
Mould Temperature (°C)
D2
Linear (D2)

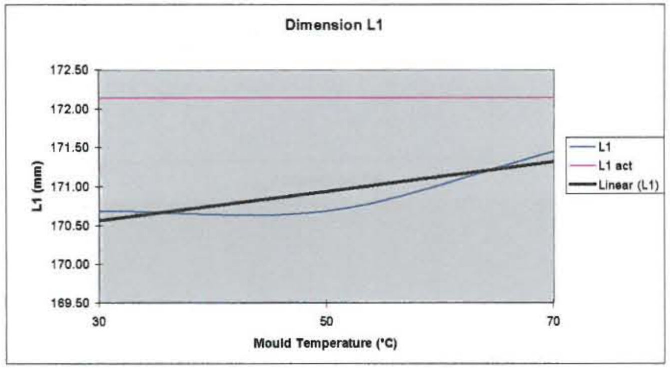

Shrinkage of Dimension D3
Shrinkage (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
D3
Linear (D3)

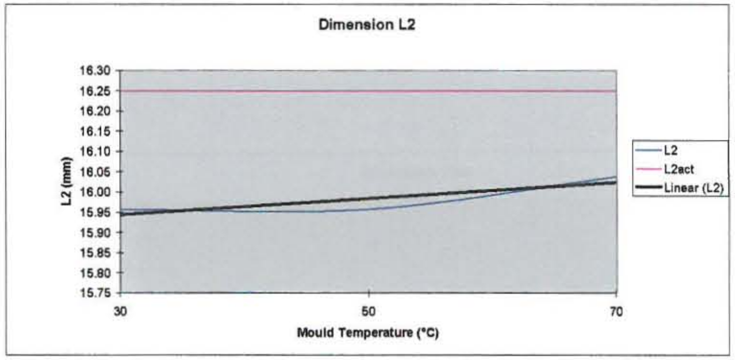

Shrinkage of Dimension D4
Shrinkage (%)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear

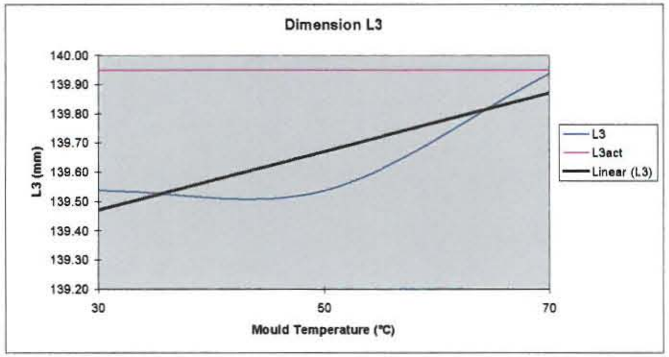
DATA OF EXPERIMENT 2.1

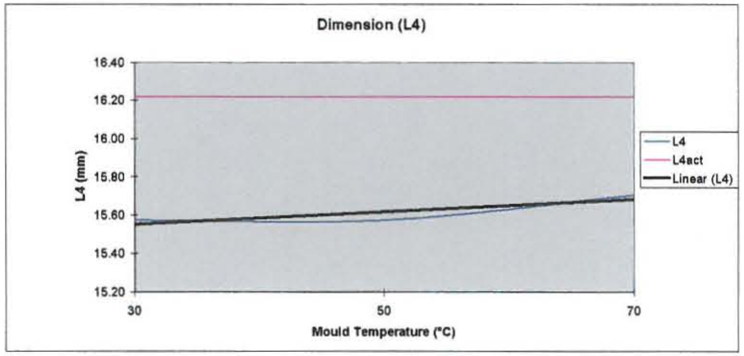
APPENDIX D : EXPERIMENT 2.1

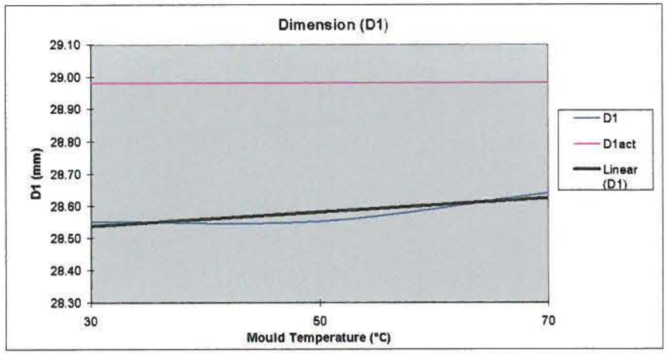
Mould Temp (°C)	Resin Temp (°C)	Curing Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
30	30	30	170.69	172.14	15.96	16.25	139.54	139.95	15.57	16.22	28.55	28.98	28.78	28.96	9.53
50	30	30	170.69	172.14	15.96	16.25	139.54	139.95	15.57	16.22	28.55	28.98	28.78	28.96	9.53
70	30	30	171.45	172.14	16.04	16.25	139.94	139.95	15.71	16.22	28.64	28.98	28.72	28.96	9.56

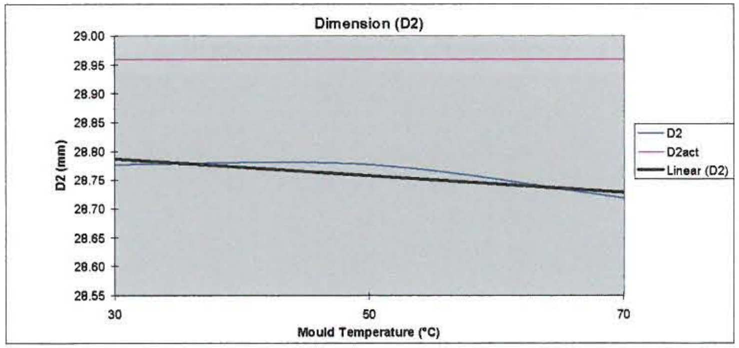


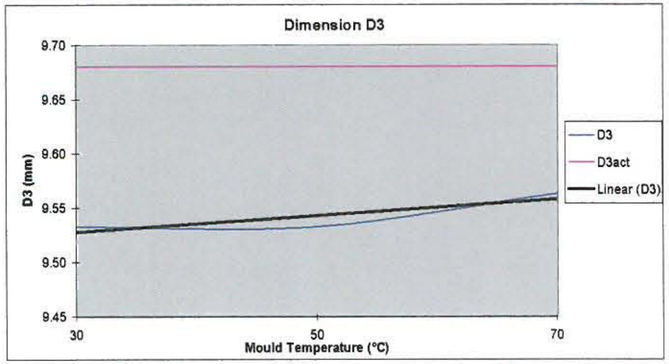


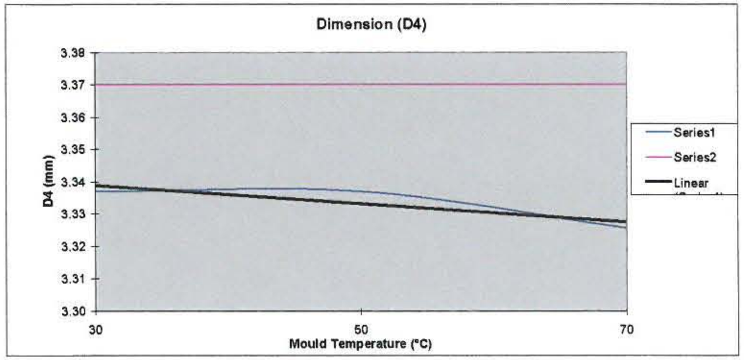


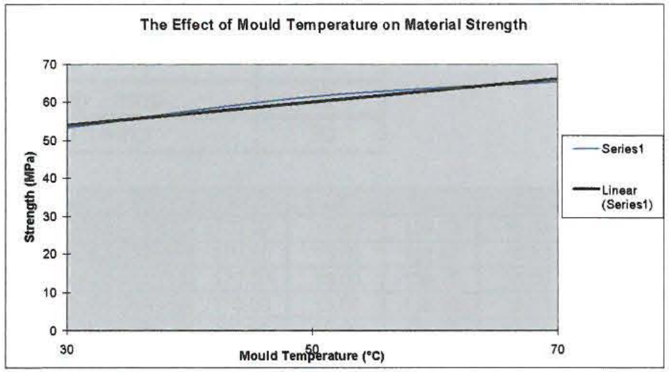


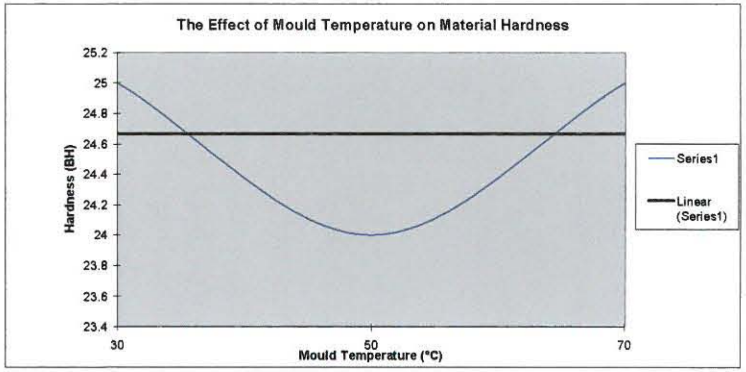

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
30
50
70
Mould Temperature (°C)
D1
D1act
Linear (D1)


Dimension (D2)
D2 (mm)
29.00
28.95
28.90
28.85
28.80
28.75
28.70
28.65
28.60
28.55
30
50
70
Mould Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.70
9.65
9.60
9.55
9.50
9.45
30
50
70
Mould Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.37
3.36
3.35
3.34
3.33
3.32
3.31
3.30
30
50
70
Mould Temperature (°C)
Series1
Series2
Linear


The Effect of Mould Temperature on Material Strength
Strength (MPa)
70
60
50
40
30
20
10
0
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
25.2
25
24.8
24.6
24.4
24.2
24
23.8
23.6
23.4
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

Experiment 2.1

Mould Temp.	**30**
Curing Temp.	**30**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.00	15.85	139.23	15.46	28.60	28.89	9.43	3.36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3.31
	3	170.50	16.06	138.76	15.58	28.28	28.55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3.24
	5	170.55	16.00	138.79	15.68	28.65	28.88	9.55	3.23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3.36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3.34
	8	170.10	15.97	139.02	15.48	28.36	28.57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3.23
	10	170.50	15.93	139.34	15.57	28.42	28.89	9.43	3.25
Cast2	1	171.00	16.26	139.97	15.57	28.70	28.58	9.50	3.35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3.36
	3	171.00	16.26	139.75	15.71	28.56	28.84	9.61	3.32
	4	171.10	16.04	139.67	15.56	28.62	28.97	9.60	3.28
	5	171.40	15.97	139.72	15.65	28.70	28.99	9.56	3.35
	6	171.20	16.10	139.99	15.63	28.67	28.84	9.53	3.37
	7	171.00	16.09	139.96	15.72	28.59	28.56	9.60	3.36
	8	171.10	16.13	139.92	15.56	28.49	28.84	9.58	3.37
	9	171.00	16.09	139.85	15.61	28.59	28.92	9.52	3.37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	1	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3.39
	3	170.50	15.70	139.82	15.53	28.37	28.94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3.37
	5	170.60	15.75	139.70	15.44	28.70	28.88	9.59	3.37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3.38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3.39
	9	170.50	15.76	139.72	15.54	28.68	28.93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3.38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0.08

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.84	1.79	0.30	4.01	1.48	0.61	1.52	1.04
Experiment 2.1.1	170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.84	1.79	0.30	4.01	1.48	0.61	1.52	1.04
Experiment 3.1.1	171.45	16.04	139.94	15.71	28.64	28.72	9.56	3.33
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.40	1.29	0.01	3.20	1.19	0.82	1.21	1.37
Av Shrinkage (%)	0.69	1.62	0.20	3.74	1.38	0.68	1.42	3.36

Experiment 2.1

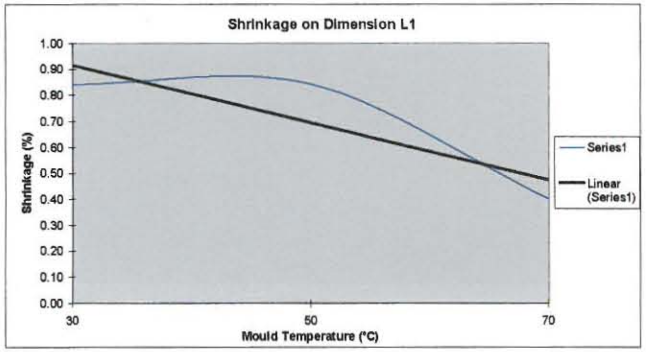
Mould Temp.	**50**
Curing Temp.	**30**
Resin Temp	**30**

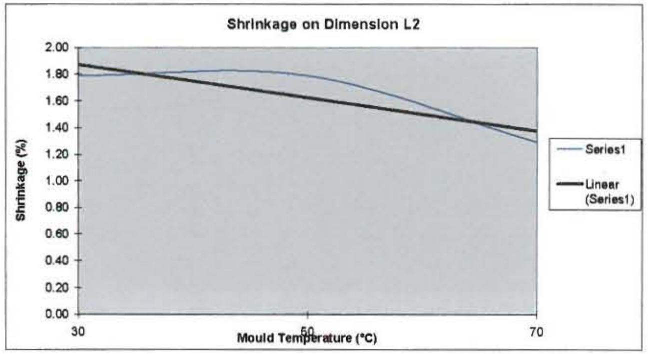
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.00	15.85	139.23	15.46	28.60	28.89	9.43	3.36
	2	170.25	15.86	138.92	15.53	28.59	28.75	9.48	3.31
	3	170.50	16.06	138.76	15.58	28.28	28.55	9.52	3.11
	4	170.60	15.88	138.92	15.53	28.25	28.75	9.55	3.24
	5	170.55	16.00	138.79	15.68	28.65	28.88	9.55	3.23
	6	170.35	15.97	139.51	15.61	28.46	28.9	9.43	3.36
	7	170.25	15.83	139.18	15.50	28.27	28.65	9.53	3.34
	8	170.10	15.97	139.02	15.48	28.36	28.57	9.54	3.18
	9	170.10	16.06	138.85	15.54	28.62	28.72	9.42	3.23
	10	170.50	15.93	139.34	15.57	28.42	28.89	9.43	3.25
Cast2	1	171.00	16.26	139.97	15.57	28.70	28.58	9.50	3.35
	2	171.10	16.19	139.98	15.66	28.60	28.75	9.62	3.36
	3	171.00	16.26	139.75	15.71	28.56	28.84	9.61	3.32
	4	171.10	16.04	139.67	15.56	28.62	28.97	9.60	3.28
	5	171.40	15.97	139.72	15.65	28.70	28.99	9.56	3.35
	6	171.20	16.10	139.99	15.63	28.67	28.84	9.53	3.37
	7	171.00	16.09	139.96	15.72	28.59	28.56	9.60	3.36
	8	171.10	16.13	139.92	15.56	28.49	28.84	9.58	3.37
	9	171.00	16.09	139.85	15.61	28.59	28.92	9.52	3.37
	10	171.10	16.20	139.67	15.83	28.63	28.8	9.52	3.41
Cast3	1	170.75	15.81	139.66	15.48	28.77	28.71	9.49	3.42
	2	170.70	15.85	139.71	15.56	28.69	28.69	9.50	3.39
	3	170.50	15.70	139.82	15.53	28.37	28.94	9.55	3.42
	4	170.50	15.73	139.76	15.55	28.43	28.63	9.59	3.37
	5	170.60	15.75	139.70	15.44	28.70	28.88	9.59	3.37
	6	170.80	15.86	139.75	15.57	28.70	28.8	9.60	3.43
	7	170.75	15.88	139.47	15.50	28.24	28.78	9.50	3.38
	8	170.80	15.88	139.59	15.49	28.64	28.63	9.57	3.39
	9	170.50	15.76	139.72	15.54	28.68	28.93	9.59	3.41
	10	170.50	15.76	139.92	15.58	28.69	28.69	9.48	3.38
Average Value		170.69	15.96	139.54	15.57	28.55	28.78	9.53	3.34
Std deviation		0.36	0.16	0.39	0.09	0.16	0.13	0.06	0.08

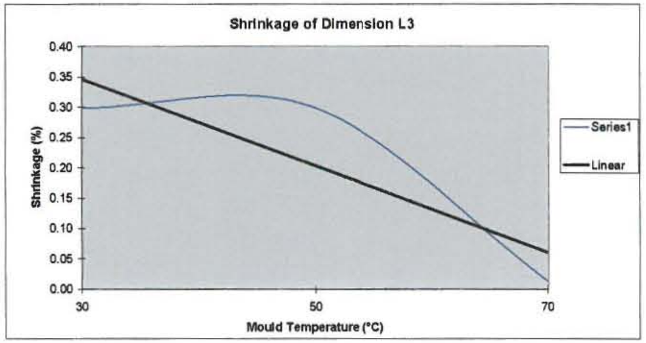
Experiment 2.1

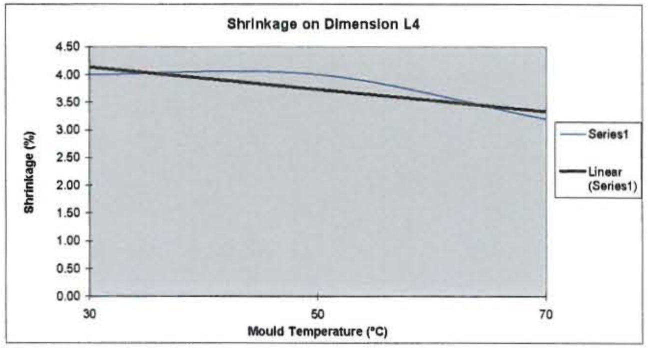
Mould Temp.	**70**
Curing Temp.	**30**
Resin Temp	**30**

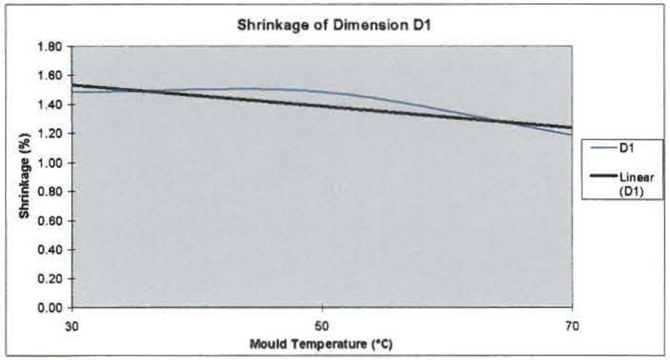
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.10	16.00	139.67	15.71	28.48	28.61	9.54	3.28
	2	171.20	15.99	139.66	15.74	28.58	28.5	9.54	3.23
	3	171.20	15.93	139.65	15.66	28.69	28.76	9.54	3.20
	4	171.10	15.91	139.67	15.63	28.68	28.81	9.54	3.19
	5	171.30	15.88	139.70	15.88	28.61	28.8	9.54	3.25
	6	171.20	15.88	139.66	15.86	28.48	28.57	9.55	3.24
	7	171.10	15.98	139.55	15.63	28.51	28.61	9.53	3.25
	8	171.20	16.03	139.66	15.00	28.58	28.8	9.55	3.33
	9	171.20	16.00	139.64	15.62	28.67	28.8	9.55	3.28
	10	171.30	15.92	139.69	15.72	28.49	28.43	9.53	3.19
Cast2	1	171.85	16.08	140.23	15.65	28.68	28.69	9.60	3.33
	2	171.80	16.08	140.19	15.73	28.69	28.78	9.57	3.37
	3	171.95	16.24	140.19	15.73	28.81	28.82	9.60	3.36
	4	171.90	16.24	140.23	15.74	28.74	28.74	9.58	3.37
	5	171.95	16.22	140.20	15.71	28.67	28.71	9.57	3.35
	6	171.70	16.31	140.22	15.74	28.74	28.82	9.55	3.36
	7	171.70	16.30	140.22	15.70	28.75	28.81	9.62	3.28
	8	171.80	16.12	140.18	15.76	28.62	28.74	9.57	3.39
	9	171.95	16.08	140.22	15.79	28.69	28.69	9.58	3.29
	10	171.90	16.19	140.21	15.75	28.80	28.74	9.57	3.40
Cast3	1	171.25	15.92	139.98	15.65	28.58	28.68	9.57	3.41
	2	171.30	15.98	139.95	15.81	28.49	28.75	9.56	3.38
	3	171.30	16.10	139.93	15.74	28.70	28.83	9.57	3.37
	4	171.20	16.04	139.96	15.71	28.59	28.78	9.56	3.39
	5	171.20	15.96	139.97	15.74	28.56	28.65	9.57	3.33
	6	171.25	15.95	139.93	15.80	28.67	28.75	9.56	3.37
	7	171.40	15.95	139.92	15.71	28.70	28.8	9.57	3.38
	8	171.45	15.90	139.98	15.82	28.56	28.71	9.57	3.37
	9	171.30	15.96	139.90	15.84	28.72	28.65	9.57	3.42
	10	171.30	16.00	139.93	15.59	28.61	28.73	9.57	3.41
Average Value		171.45	16.04	139.94	15.71	28.64	28.72	9.56	3.33
Std deviation		0.31	0.13	0.23	0.15	0.09	0.10	0.02	0.07

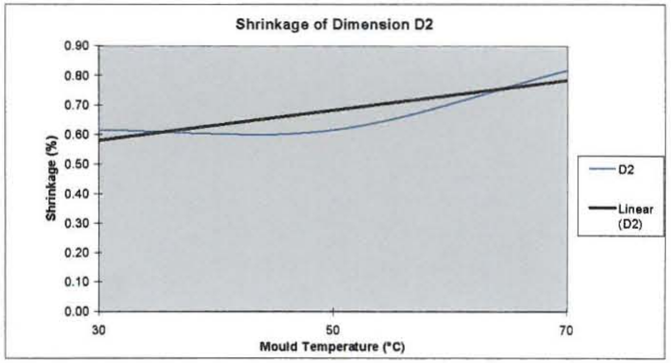

Shrinkage on Dimension L1
Shrinkage (%)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

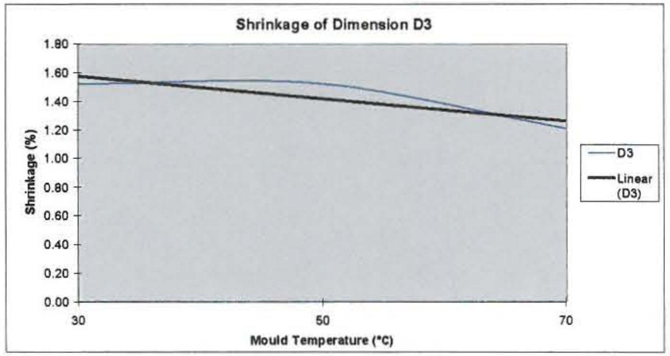

Shrinkage on Dimension L2
Shrinkage (%)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

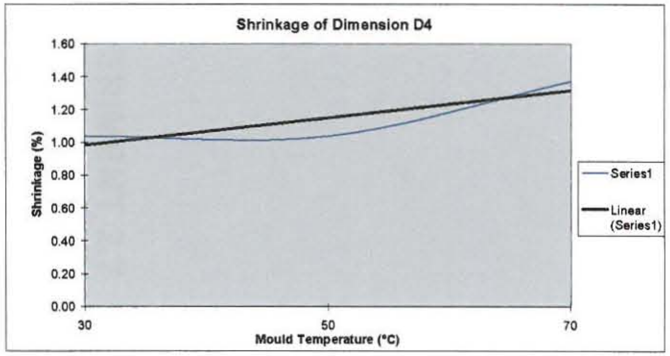

Shrinkage of Dimension L3
Shrinkage (%)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear


Shrinkage on Dimension L4
Shrinkage (%)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage of Dimension D1
Shrinkage (%)
Mould Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
Mould Temperature (°C)
D2
Linear (D2)

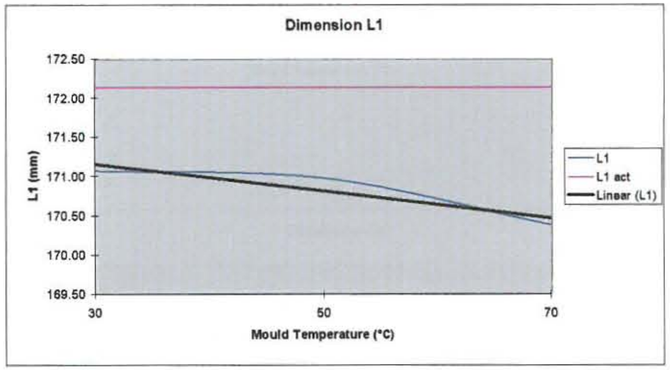

Shrinkage of Dimension D3
Shrinkage (%)
Mould Temperature (°C)
D3
Linear (D3)

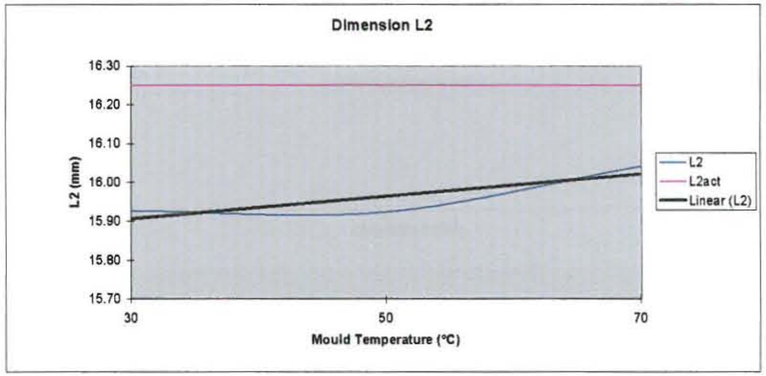

Shrinkage of Dimension D4
Shrinkage (%)
Mould Temperature (°C)
Series1
Linear (Series1)

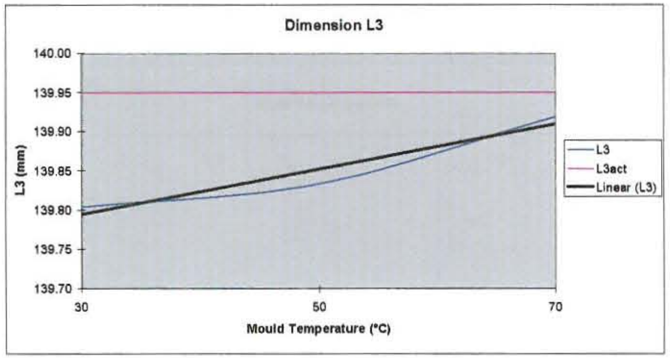
DATA OF EXPERIMENT 2.2

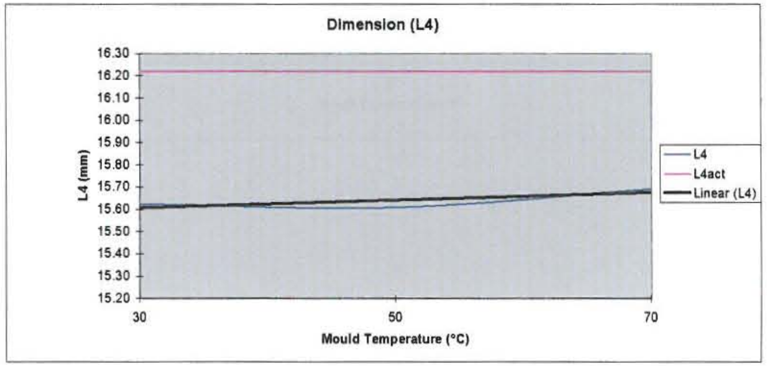
APPENDIX E : EXPERIMENT 2.2

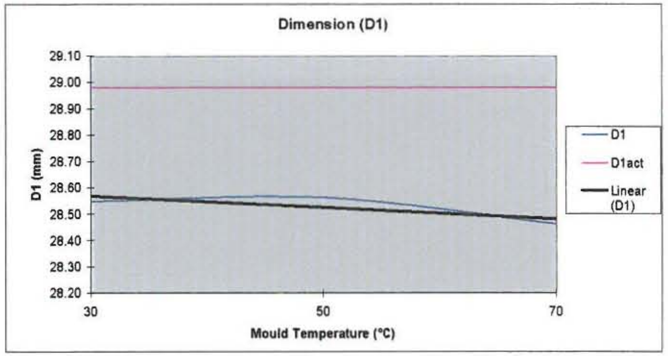
Mould Temp (°C)	Resin Temp (°C)	Curing Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
30	50	30	171.07	172.14	15.93	16.25	139.80	139.95	15.62	16.22	28.55	28.98	28.75	28.96	9.56
50	50	30	170.98	172.14	15.92	16.25	139.83	139.95	15.61	16.22	28.56	28.98	28.74	28.96	9.58
70	50	30	170.38	172.14	16.04	16.25	139.92	139.95	15.69	16.22	28.46	28.98	28.53	28.96	9.54

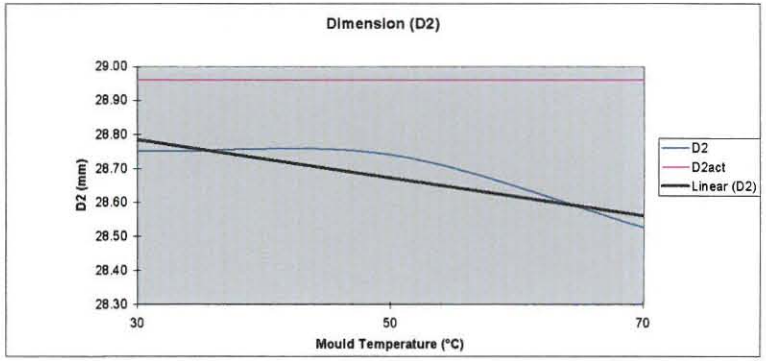


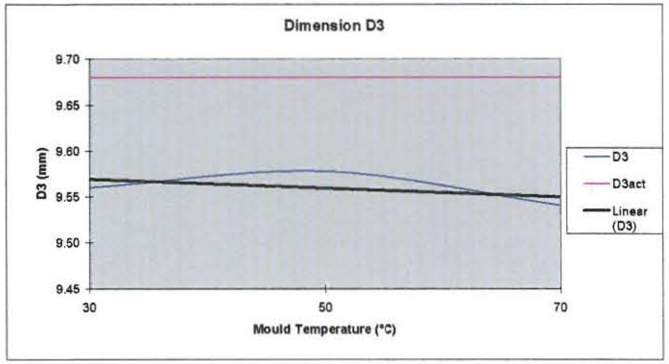


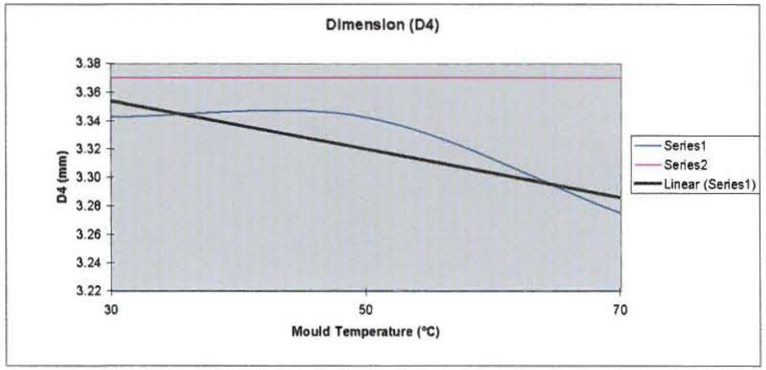


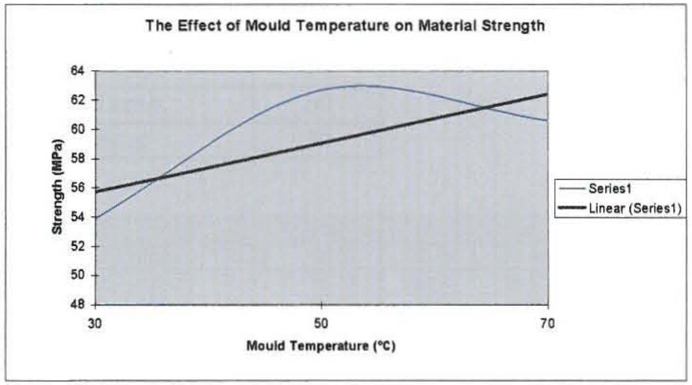


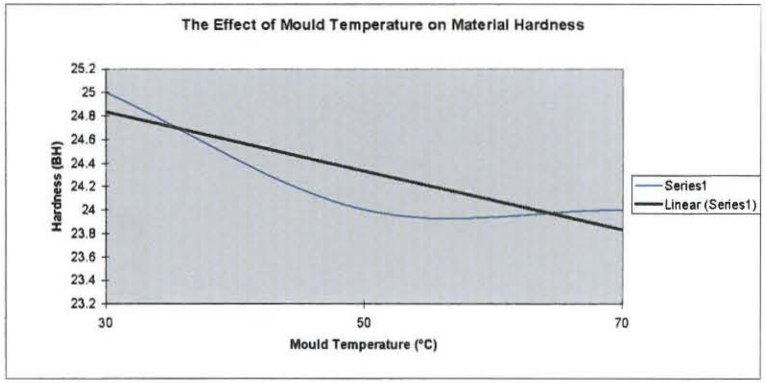

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
30
50
70
Mould Temperature (°C)
D1
D1act
Linear (D1)


Dimension (D2)
D2 (mm)
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
30
50
70
Mould Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.70
9.65
9.60
9.55
9.50
9.45
30
50
70
Mould Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.36
3.34
3.32
3.30
3.28
3.26
3.24
3.22
30
50
70
Mould Temperature (°C)
Series1
Series2
Linear (Series1)


The Effect of Mould Temperature on Material Strength
Strength (MPa)
64
62
60
58
56
54
52
50
48
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
25.2
25
24.8
24.6
24.4
24.2
24
23.8
23.6
23.4
23.2
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

Experiment 2.2

Mould Temp.	**30**
Curing Temp.	**50**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.80	16.02	139.89	15.48	28.75	28.57	9.66	3.43
	2	170.90	16.12	139.90	15.45	28.58	28.63	9.39	3.32
	3	170.85	15.73	139.86	15.60	28.47	28.68	9.44	3.24
	4	171.20	15.77	139.82	15.47	28.46	28.78	9.52	3.35
	5	171.20	15.77	139.89	15.52	28.74	28.81	9.56	3.28
	6	171.20	15.81	139.89	15.71	28.55	28.78	9.65	3.42
	7	171.20	15.95	139.90	15.62	28.37	28.6	9.33	3.32
	8	171.00	16.11	139.92	15.60	28.43	28.63	9.39	3.38
	9	170.95	16.15	139.88	15.50	28.57	28.78	9.47	3.30
	10	171.85	15.75	139.81	15.50	28.72	28.62	9.57	3.31
Cast2	1	171.30	15.92	139.86	15.70	28.48	28.56	9.57	3.33
	2	171.20	15.89	139.79	15.61	28.51	28.72	9.75	3.37
	3	171.25	15.90	139.76	15.71	28.58	28.94	9.82	3.38
	4	171.30	15.89	139.65	15.83	28.64	29.1	9.73	3.32
	5	171.20	16.09	139.78	15.69	28.65	29.09	9.57	3.37
	6	171.20	16.03	139.80	15.69	28.58	28.9	9.75	3.31
	7	171.20	15.99	139.80	15.74	28.51	28.8	9.82	3.31
	8	171.10	15.97	139.79	15.89	28.55	28.84	9.60	3.26
	9	171.20	15.97	139.86	15.68	28.64	29.09	9.57	3.36
	10	171.20	16.02	139.85	15.63	28.53	28.86	9.71	3.31
Cast3	1	170.90	15.91	139.78	15.57	28.62	28.61	9.46	3.36
	2	170.90	15.99	139.75	15.54	28.55	28.6	9.49	3.41
	3	170.90	15.81	139.73	15.50	28.34	28.62	9.50	3.37
	4	170.95	15.87	139.75	15.53	28.48	28.73	9.52	3.42
	5	170.95	15.88	139.69	15.57	28.57	28.78	9.53	3.33
	6	170.95	15.85	139.69	15.50	28.59	28.72	9.47	3.38
	7	170.85	15.85	139.72	15.68	28.43	28.64	9.49	3.24
	8	170.75	16.02	139.75	15.76	28.42	28.59	9.52	3.38
	9	170.80	15.88	139.78	15.76	28.55	28.77	9.50	3.33
	10	170.85	15.86	139.77	15.66	28.60	28.68	9.45	3.39
Average Value		171.07	15.93	139.80	15.62	28.55	28.75	9.56	3.34
Std deviation		0.23	0.11	0.07	0.11	0.10	0.15	0.13	0.05

Central University of Technology, Free State

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	171.07	15.93	139.80	15.62	28.55	28.75	9.56	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.62	1.98	0.11	3.70	1.50	0.71	1.24	0.87
Experiment 2.1.1	170.98	15.92	139.83	15.61	28.56	28.74	9.58	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.67	2.00	0.09	3.80	1.45	0.74	1.06	0.88
Experiment 3.1.1	170.38	16.04	139.92	15.69	28.46	28.53	9.54	3.27
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	1.02	1.27	0.03	3.29	1.79	1.48	1.44	2.89
Av Shrinkage (%)	0.77	1.75	0.07	3.60	1.58	0.97	1.25	3.36

Experiment 2.2

Mould Temp.	**50**
Curing Temp.	**50**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.90	16.00	139.92	15.46	28.74	28.59	9.32	3.34
	2	170.90	15.75	139.95	15.52	28.59	28.64	9.40	3.36
	3	171.00	15.77	139.89	15.49	28.38	28.82	9.48	3.31
	4	171.00	15.77	139.94	15.49	28.44	28.77	9.65	3.31
	5	171.00	15.98	140.06	15.54	28.72	28.62	9.66	3.41
	6	171.20	16.13	140.00	15.66	28.67	28.62	9.51	3.40
	7	170.80	15.76	139.91	15.49	28.51	28.74	9.51	3.40
	8	170.80	15.85	139.91	15.52	28.29	28.83	9.63	3.33
	9	170.75	15.86	139.93	15.46	28.55	28.75	9.66	3.32
	10	170.80	15.94	139.93	15.56	28.71	28.56	9.32	3.38
Cast2	1	171.20	15.99	139.92	15.61	28.63	28.53	9.56	3.34
	2	171.20	15.95	139.87	15.77	28.50	28.8	9.70	3.29
	3	171.10	15.96	139.62	15.83	28.54	29.04	9.83	3.35
	4	171.25	16.03	139.79	15.68	28.63	29.09	9.85	3.29
	5	171.20	16.01	139.84	15.71	28.63	29.02	9.78	3.41
	6	171.20	16.15	139.82	16.28	28.52	28.84	9.56	3.29
	7	171.00	15.98	139.74	15.85	28.58	28.53	9.75	3.29
	8	171.20	15.99	139.83	15.59	28.60	28.79	9.85	3.27
	9	171.20	15.99	139.83	15.58	28.64	28.74	9.83	3.37
	10	171.20	15.96	139.63	15.70	28.64	29.08	9.56	3.35
Cast3	1	170.80	15.91	139.79	15.57	28.61	28.63	9.46	3.41
	2	170.80	15.89	139.74	15.52	28.48	28.61	9.49	3.36
	3	170.90	15.77	139.77	15.58	28.43	28.76	9.51	3.34
	4	170.95	15.93	139.77	15.46	28.59	28.78	9.51	3.35
	5	171.00	16.00	139.76	15.52	28.59	28.7	9.48	3.34
	6	170.80	15.94	139.74	15.54	28.41	28.58	9.50	3.37
	7	170.80	15.74	139.77	15.57	28.49	28.64	9.52	3.38
	8	170.80	15.89	139.77	15.57	28.57	28.75	9.46	3.27
	9	170.80	16.04	139.78	15.57	28.62	28.73	9.49	3.37
	10	170.80	15.77	139.78	15.54	28.57	28.66	9.50	3.27
Average Value		170.98	15.92	139.83	15.61	28.56	28.74	9.58	3.34
Std deviation		0.17	0.11	0.10	0.16	0.10	0.15	0.15	0.04

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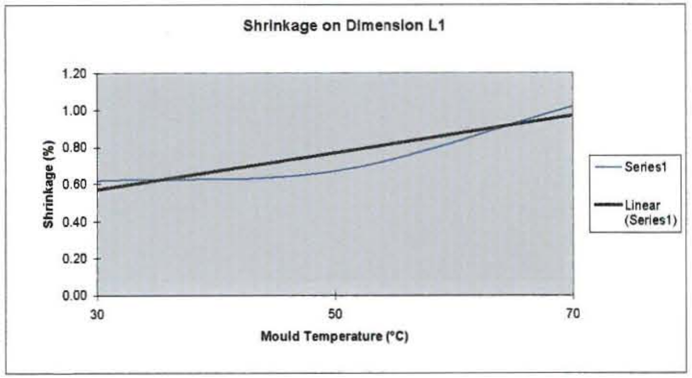
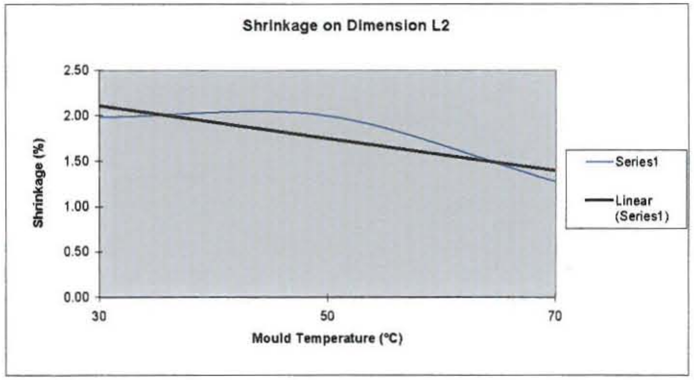
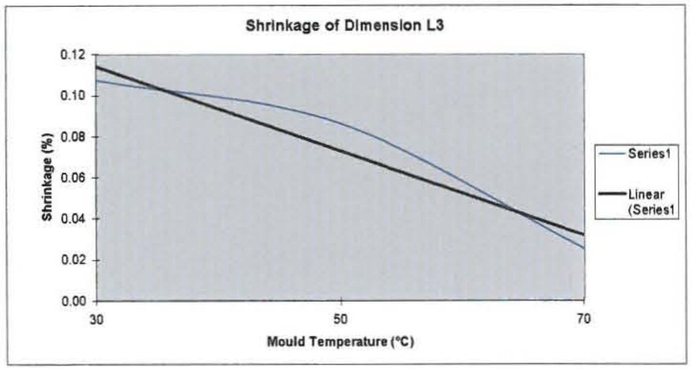
Experiment 2.2

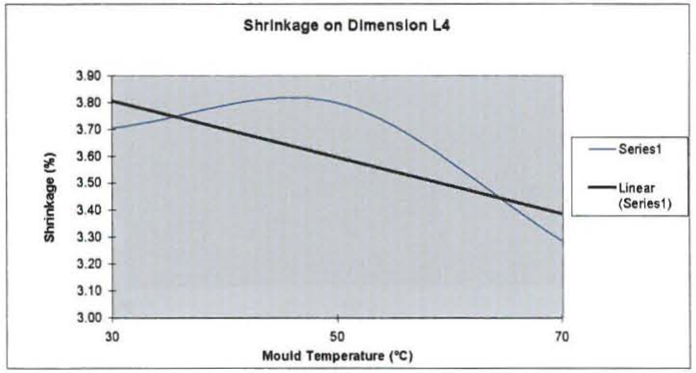
Mould Temp.	70
Curing Temp.	50
Resin Temp	30

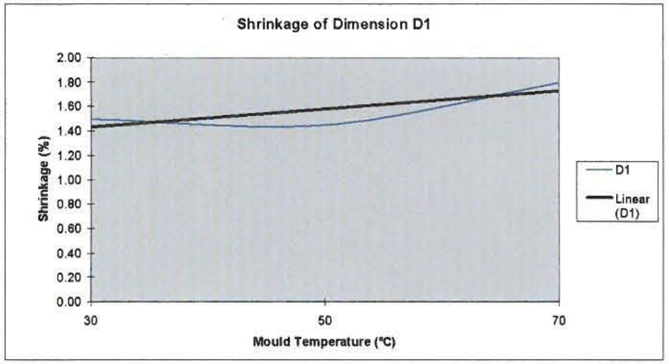
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	170.30	16.08	139.88	15.61	28.34	28.49	9.51	3.25
	2	170.30	16.07	139.88	15.62	28.26	28.28	9.46	3.28
	3	170.30	16.09	139.85	15.69	28.53	28.62	9.51	3.29
	4	170.30	16.02	139.79	15.67	28.51	28.64	9.49	3.30
	5	170.35	16.01	139.93	15.69	28.37	28.63	9.51	3.14
	6	170.30	16.08	139.89	15.64	28.20	28.25	9.58	3.18
	7	170.30	16.08	139.85	15.87	28.51	28.51	9.56	3.18
	8	170.30	16.07	139.74	15.65	28.49	28.64	9.51	3.22
	9	170.30	16.02	139.80	15.65	28.35	28.66	9.50	3.24
	10	170.35	16.05	139.90	15.74	28.30	28.35	9.51	3.13
Cast2	1	170.60	16.04	140.18	15.72	28.39	28.42	9.52	3.30
	2	170.70	16.07	140.16	15.78	28.47	28.58	9.56	3.29
	3	170.70	16.13	140.11	15.78	28.64	28.81	9.58	3.22
	4	170.70	15.97	140.05	15.71	28.71	28.62	9.58	3.27
	5	170.70	16.21	140.01	15.71	28.55	28.42	9.58	3.28
	6	170.50	16.13	140.06	15.73	28.41	28.52	9.52	3.33
	7	170.50	16.04	139.97	15.73	28.57	28.77	9.54	3.30
	8	170.50	16.00	140.08	15.68	28.70	28.76	9.58	3.31
	9	170.60	16.03	140.16	15.67	28.66	28.49	9.58	3.30
	10	170.60	16.07	140.17	15.76	28.43	28.39	9.60	3.34
Cast3	1	170.10	16.05	139.74	15.65	28.62	28.36	9.53	3.35
	2	170.10	16.12	139.72	15.63	28.58	28.52	9.54	3.31
	3	170.20	15.96	139.73	15.65	28.27	28.69	9.56	3.30
	4	170.30	15.88	139.82	15.65	28.31	28.61	9.57	3.33
	5	170.30	15.93	139.83	15.57	28.65	28.38	9.53	3.29
	6	170.30	15.94	139.94	15.74	28.43	28.36	9.53	3.35
	7	170.30	16.10	139.92	15.66	28.21	28.56	9.54	3.31
	8	170.35	16.08	139.81	15.74	28.31	28.71	9.57	3.26
	9	170.20	16.05	139.82	15.66	28.43	28.4	9.56	3.28
	10	170.10	15.87	139.77	15.68	28.67	28.37	9.51	3.31
Average Value		170.38	16.04	139.92	15.69	28.46	28.53	9.54	3.27
Std deviation		0.18	0.07	0.14	0.06	0.15	0.15	0.03	0.06

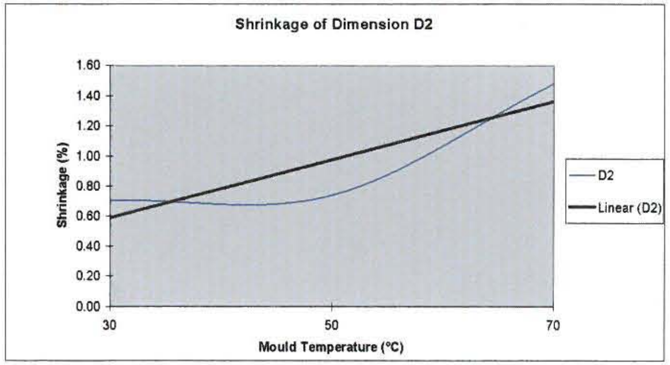

Shrinkage on Dimension L1
Shrinkage (%)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

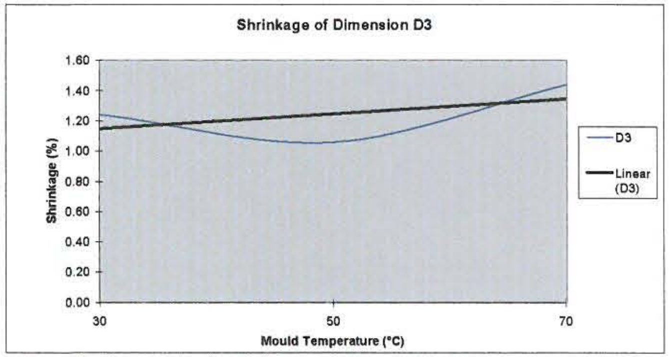

Shrinkage on Dimension L2
Shrinkage (%)
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

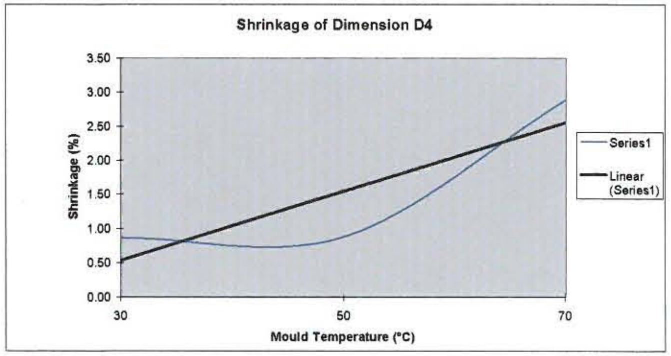

Shrinkage of Dimension L3
Shrinkage (%)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1


Shrinkage on Dimension L4
Shrinkage (%)
3.90
3.80
3.70
3.60
3.50
3.40
3.30
3.20
3.10
3.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage of Dimension D1
Shrinkage (%)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
D2
Linear (D2)

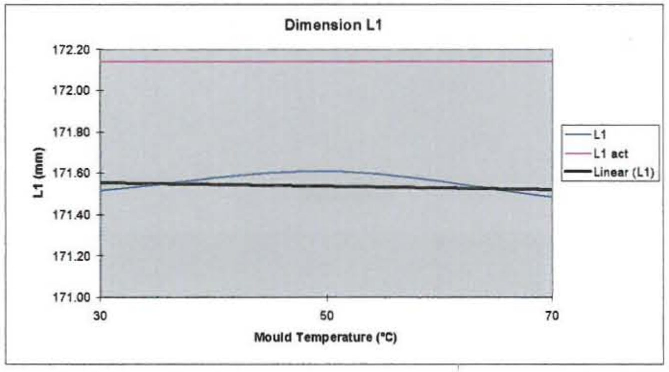

Shrinkage of Dimension D3
Shrinkage (%)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
D3
Linear (D3)

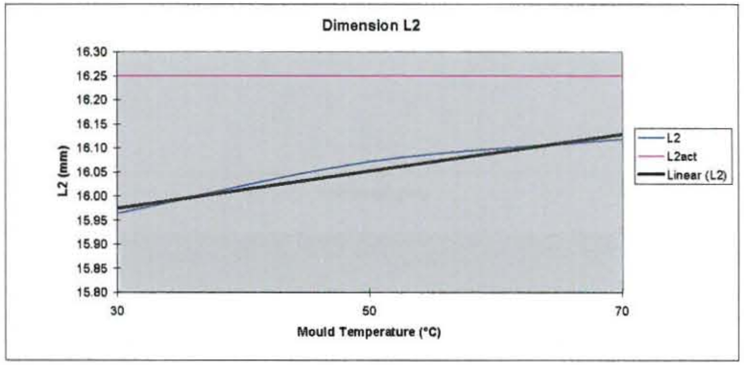

Shrinkage of Dimension D4
Shrinkage (%)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

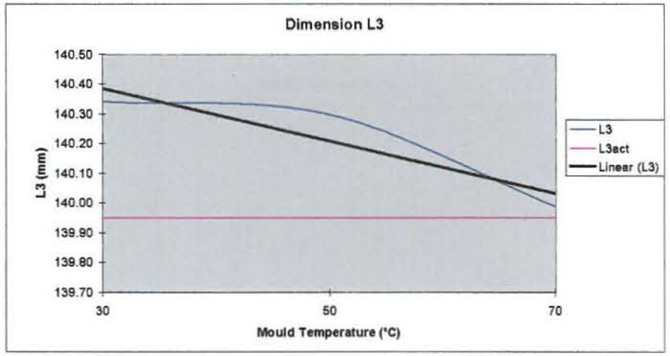
DATA OF EXPERIMENT 2.3

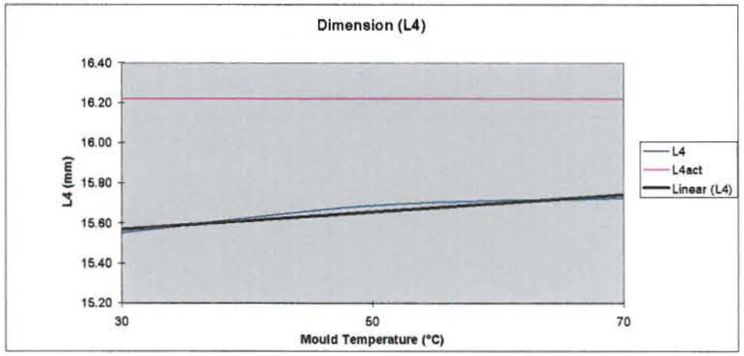
APPENDIX F : EXPERIMENT 2.3

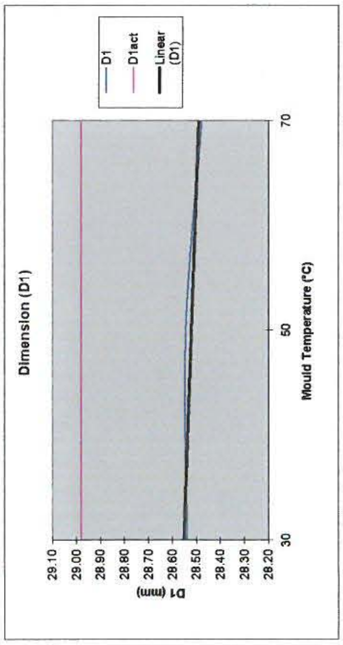
Mould Temp (°C)	Resin Temp (°C)	Curing Temp (°C)	Dimensions (mm)												
			L1	L1 act	L2	L2act	L3	L3act	L4	L4act	D1	D1act	D2	D2act	D3
30	70	30	171.52	172.14	15.96	16.25	140.34	139.95	15.55	16.22	28.54	28.98	28.68	28.96	9.49
50	70	30	171.61	172.14	16.07	16.25	140.30	139.95	15.69	16.22	28.55	28.98	28.68	28.96	9.49
70	70	30	171.48	172.14	16.12	16.25	139.99	139.95	15.73	16.22	28.48	28.98	28.50	28.96	9.54

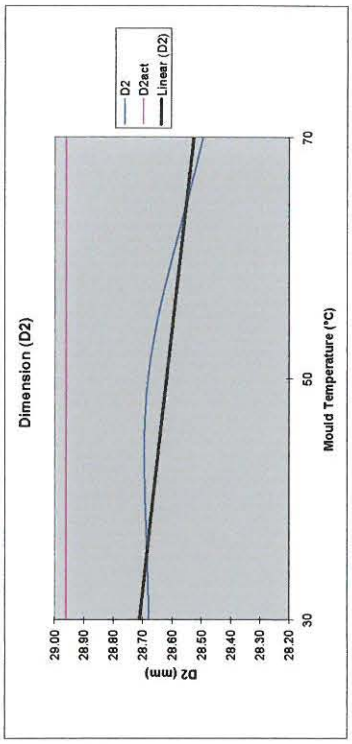


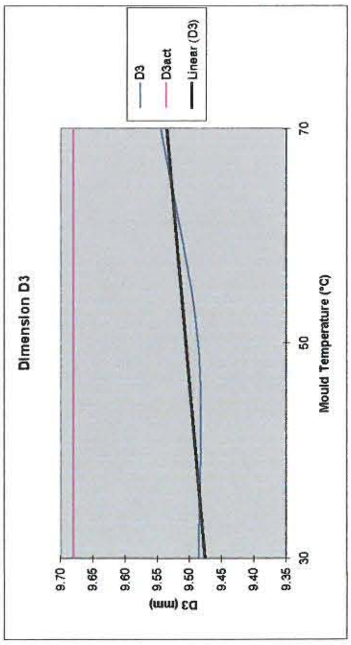


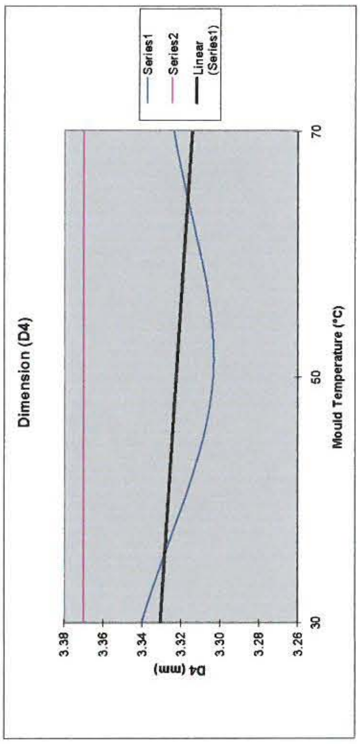


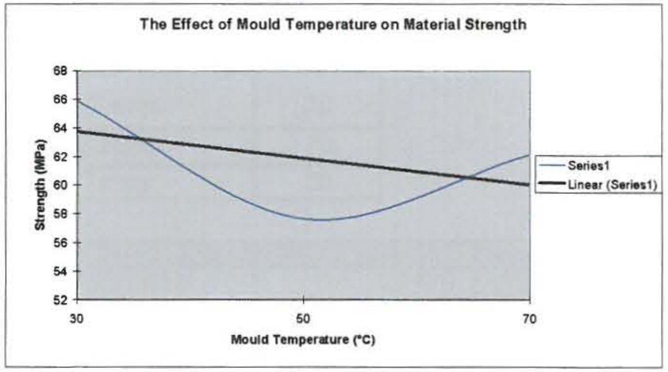


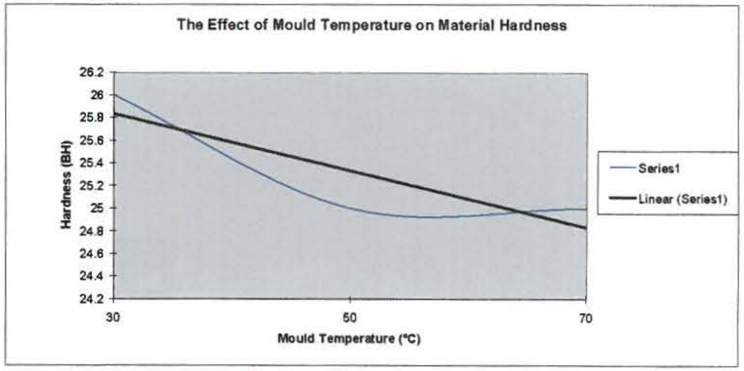

Dimension (D1)
D1 (mm)
29.10
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
30
50
70
Mould Temperature (°C)
D1
D1act
Linear (D1)


Dimension (D2)
D2 (mm)
29.00
28.90
28.80
28.70
28.60
28.50
28.40
28.30
28.20
30
50
70
Mould Temperature (°C)
D2
D2act
Linear (D2)


Dimension D3
D3 (mm)
9.70
9.65
9.60
9.55
9.50
9.45
9.40
9.35
30
50
70
Mould Temperature (°C)
D3
D3act
Linear (D3)


Dimension (D4)
D4 (mm)
3.38
3.36
3.34
3.32
3.30
3.28
3.26
30
50
70
Mould Temperature (°C)
Series1
Series2
Linear (Series1)


The Effect of Mould Temperature on Material Strength
Strength (MPa)
68
66
64
62
60
58
56
54
52
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


The Effect of Mould Temperature on Material Hardness
Hardness (BH)
26.2
26
25.8
25.6
25.4
25.2
25
24.8
24.6
24.4
24.2
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

Experiment 2.3

Mould Temp.	**30**
Curing Temp.	**70**
Resin Temp	**30**

		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.25	15.97	140.12	15.58	28.34	28.43	9.41	3.33
	2	171.30	15.96	140.14	15.53	28.51	28.53	9.46	3.38
	3	171.30	15.83	139.98	15.63	28.57	28.66	9.46	3.31
	4	171.25	15.88	140.02	15.68	28.39	28.75	9.46	3.27
	5	171.25	15.85	139.99	15.00	28.29	28.79	9.43	3.24
	6	171.45	16.10	139.99	15.54	28.32	28.73	9.41	3.18
	7	171.30	16.07	140.01	15.45	28.54	28.65	9.46	3.22
	8	171.25	16.03	140.08	15.50	28.57	28.44	9.46	3.18
	9	171.20	16.07	140.17	15.64	28.52	28.72	9.44	3.28
	10	171.25	16.18	140.18	15.49	28.28	28.66	9.42	3.26
Cast2	1	171.85	16.06	140.66	15.54	28.42	28.49	9.48	3.32
	2	171.90	16.10	140.68	15.68	28.36	28.82	9.59	3.31
	3	171.95	16.02	140.55	15.60	28.61	28.96	9.58	3.39
	4	171.95	16.06	140.53	15.57	28.77	28.96	9.57	3.34
	5	171.75	15.95	140.51	15.70	28.55	28.72	9.54	3.34
	6	171.70	15.97	140.52	15.59	28.36	28.55	9.50	3.35
	7	171.70	15.88	140.47	15.68	28.42	28.53	9.60	3.38
	8	171.80	16.18	140.58	15.80	28.70	28.97	9.57	3.40
	9	171.90	16.01	140.71	15.58	28.73	28.9	9.54	3.36
	10	171.95	15.93	140.63	15.63	28.49	28.63	9.49	3.38
Cast3	1	171.30	16.02	140.28	15.49	28.86	28.51	9.45	3.42
	2	171.35	15.94	140.28	15.53	28.59	28.56	9.47	3.39
	3	171.40	15.72	140.33	15.45	28.25	28.65	9.50	3.36
	4	171.45	15.78	140.37	15.48	28.77	28.74	9.48	3.42
	5	171.45	15.88	140.47	15.48	28.79	28.76	9.44	3.44
	6	171.60	16.00	140.54	15.49	28.55	28.72	9.50	3.43
	7	171.60	15.87	140.51	15.58	28.30	28.64	9.49	3.39
	8	171.40	16.00	140.39	15.53	28.73	28.51	9.44	3.39
	9	171.40	15.88	140.27	15.56	28.86	28.77	9.43	3.32
	10	171.30	15.73	140.25	15.53	28.78	28.6	9.48	3.42
Average Value		171.52	15.96	140.34	15.55	28.54	28.68	9.49	3.34
Std deviation		0.26	0.12	0.23	0.13	0.19	0.15	0.05	0.07

Steel Specimen

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
1	172.15	16.22	139.96	16.30	28.99	28.95	9.69	3.38
2	172.15	16.26	139.94	16.23	28.98	28.96	9.70	3.38
3	172.15	16.26	139.98	16.21	28.99	28.95	9.69	3.38
4	172.10	16.33	139.96	16.25	28.98	28.95	9.70	3.38
5	172.10	16.28	139.99	16.19	28.98	28.96	9.69	3.36
6	172.10	16.19	139.96	16.21	28.98	28.95	9.69	3.37
7	172.15	16.29	139.97	16.25	28.98	28.96	9.68	3.37
8	172.15	16.19	139.89	16.22	28.98	28.96	9.69	3.36
9	172.20	16.20	139.95	16.18	28.98	28.96	9.69	3.38
10	172.10	16.26	139.94	16.20	28.98	28.95	9.68	3.36
Average Value	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Std deviation	0.03	0.05	0.03	0.04	0.00	0.01	0.01	0.01

Shrinkage

Measurement	L1	L2	L3	L4	D1	D2	D3	D4
Exp 1.1.1	171.52	15.96	140.34	15.55	28.54	28.68	9.49	3.34
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.36	1.75	-0.28	4.15	1.52	0.96	2.01	0.95
Experiment 2.1.1	171.61	16.07	140.30	15.69	28.55	28.68	9.49	3.30
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.31	1.09	-0.25	3.31	1.51	0.95	2.00	2.04
Experiment 3.1.1	171.48	16.12	139.99	15.73	28.48	28.50	9.54	3.32
Original	172.14	16.25	139.95	16.22	28.98	28.96	9.68	3.37
Shrinkage (%)	0.38	0.80	-0.02	3.08	1.74	1.59	1.40	1.43
Av Shrinkage (%)	0.35	1.21	-0.18	3.51	1.59	1.16	1.81	3.36

Experiment 2.3

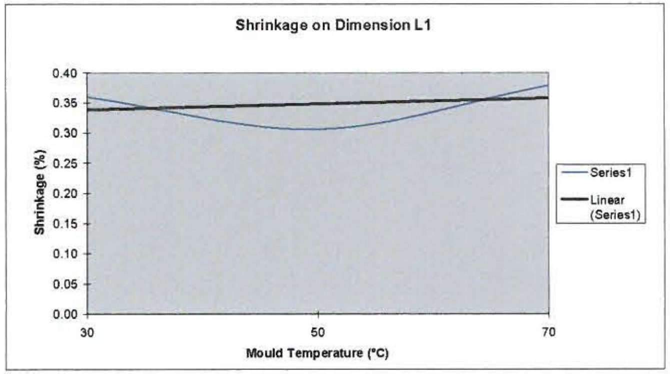
Mould Temp.	50
Curing Temp.	70
Resin Temp	30

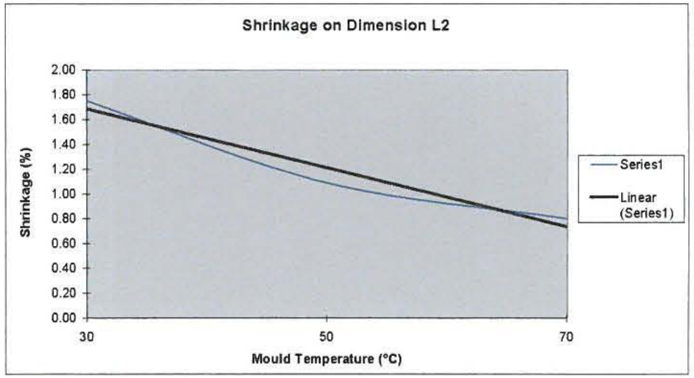
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.40	16.10	140.18	15.60	28.57	28.45	9.44	3.28
	2	171.35	16.11	140.19	15.69	28.43	28.61	9.51	3.32
	3	171.30	16.20	140.17	15.76	28.32	28.79	9.53	3.30
	4	171.30	16.16	139.93	15.85	28.35	28.7	9.50	3.23
	5	171.40	16.07	139.96	15.73	28.49	28.58	9.48	3.17
	6	171.45	15.94	139.95	15.58	28.57	28.57	9.43	3.18
	7	171.45	17.01	139.83	15.76	28.50	28.61	9.52	3.16
	8	171.50	16.14	140.21	15.84	28.34	28.78	9.52	3.32
	9	171.35	16.12	140.21	15.57	28.32	28.7	9.49	3.20
	10	171.30	16.16	140.13	15.72	28.55	28.59	9.45	3.22
Cast2	1	172.00	15.91	140.75	15.66	28.69	28.51	9.48	3.33
	2	172.10	16.09	140.71	15.74	28.40	28.78	9.47	3.27
	3	172.10	16.08	140.71	15.81	28.39	28.92	9.58	3.38
	4	172.10	16.07	140.69	15.93	28.78	28.99	9.57	3.34
	5	172.20	16.11	140.68	15.69	28.57	28.86	9.55	3.36
	6	172.10	16.11	140.68	15.70	28.38	28.49	9.51	3.38
	7	172.15	16.08	140.70	15.65	28.59	28.76	9.48	3.35
	8	172.05	15.98	140.75	15.72	28.77	28.98	9.57	3.41
	9	172.00	16.05	140.68	15.82	28.64	28.83	9.52	3.32
	10	172.10	16.16	140.73	15.87	28.53	28.53	9.48	3.38
Cast3	1	171.40	15.90	140.10	15.50	28.53	28.49	9.48	3.38
	2	171.50	15.88	140.08	15.59	28.67	28.68	9.39	3.30
	3	171.45	15.90	140.09	15.57	28.86	28.76	9.44	3.25
	4	171.40	16.00	140.09	15.61	28.76	28.73	9.46	3.22
	5	171.20	16.13	140.09	15.68	28.53	28.7	9.48	3.27
	6	171.25	15.90	140.15	15.63	28.27	28.5	9.48	3.33
	7	171.25	15.90	140.16	15.57	28.78	28.66	9.38	3.39
	8	171.35	15.97	140.12	15.53	28.84	28.77	9.44	3.41
	9	171.35	15.99	140.09	15.71	28.69	28.59	9.48	3.33
	10	171.40	15.92	140.11	15.54	28.25	28.53	9.48	3.32
Average Value		171.61	16.07	140.30	15.69	28.55	28.68	9.49	3.30
Std deviation		0.35	0.20	0.31	0.11	0.18	0.15	0.05	0.07

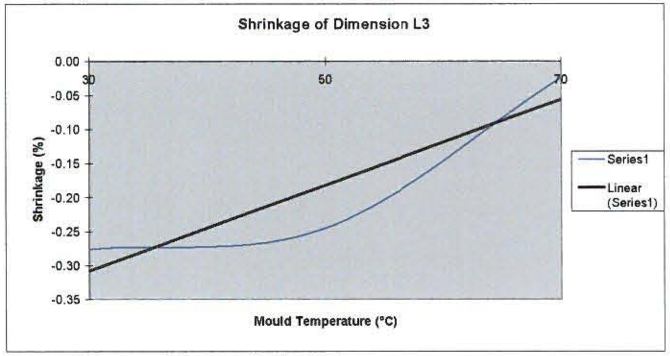
Experiment 2.3

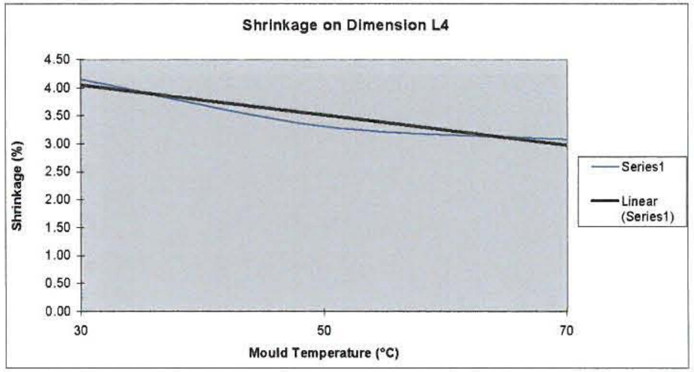
Mould Temp.	70
Curing Temp.	70
Resin Temp	30

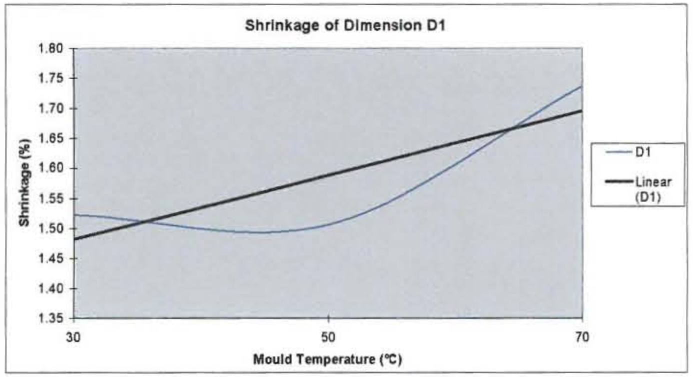
		L1	L2	L3	L4	D1	D2	D3	D4
Cast1	1	171.20	16.42	139.63	15.65	28.75	28.37	9.54	3.23
	2	171.00	16.21	139.65	15.73	28.70	28.47	9.55	3.33
	3	171.00	16.05	139.68	15.73	28.46	28.65	9.55	3.32
	4	171.20	16.04	139.58	15.71	28.36	28.68	9.52	3.28
	5	171.15	16.16	139.63	15.62	28.23	28.41	9.49	3.15
	6	171.10	16.28	139.75	15.62	28.32	28.23	9.54	3.19
	7	171.15	16.22	139.68	15.61	28.72	28.47	9.55	3.19
	8	171.25	16.25	139.38	15.76	28.55	28.72	9.54	3.19
	9	171.10	16.16	139.55	15.73	28.25	28.35	9.52	3.28
	10	171.25	16.36	139.64	15.68	28.65	28.23	9.49	3.20
Cast2	1	171.80	16.03	140.26	15.76	28.61	28.44	9.57	3.34
	2	171.80	16.24	140.31	15.72	28.69	28.54	9.52	3.32
	3	171.75	16.15	140.26	15.75	28.50	28.64	9.57	3.38
	4	171.80	16.19	140.18	15.78	28.46	28.7	9.58	3.37
	5	171.80	16.08	140.25	15.78	28.68	28.53	9.56	3.37
	6	171.70	15.96	140.24	15.71	28.62	28.48	9.51	3.33
	7	171.70	16.03	140.21	15.63	28.46	28.5	9.56	3.33
	8	171.70	16.11	140.23	15.83	28.45	28.7	9.58	3.38
	9	171.75	16.24	140.25	15.81	28.57	28.51	9.55	3.34
	10	171.75	16.27	140.27	15.93	28.61	28.44	9.49	3.39
Cast3	1	171.50	15.97	140.10	15.61	28.30	28.23	9.54	3.40
	2	171.50	15.89	140.11	15.64	28.14	28.53	9.59	3.33
	3	171.60	16.01	140.12	15.66	28.19	28.68	9.60	3.43
	4	171.50	16.03	140.02	15.68	28.55	28.63	9.56	3.26
	5	171.50	16.06	140.11	15.68	28.63	28.36	9.52	3.36
	6	171.50	16.09	140.10	15.77	28.35	28.27	9.59	3.41
	7	171.60	16.04	140.05	15.74	28.18	28.57	9.58	3.44
	8	171.60	15.96	140.07	15.93	28.39	28.72	9.55	3.38
	9	171.65	16.02	140.16	15.73	28.66	28.57	9.51	3.36
	10	171.60	16.02	140.15	15.77	28.33	28.24	9.51	3.43
Average Value		171.48	16.12	139.99	15.73	28.48	28.50	9.54	3.32
Std deviation		0.27	0.13	0.28	0.08	0.18	0.16	0.03	0.08

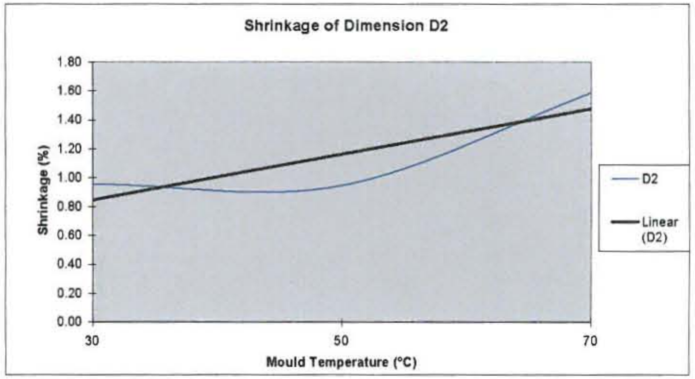

Shrinkage on Dimension L1
Shrinkage (%)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

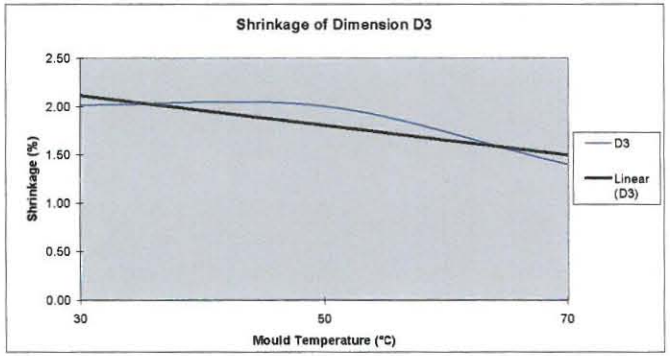

Shrinkage on Dimension L2
Shrinkage (%)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

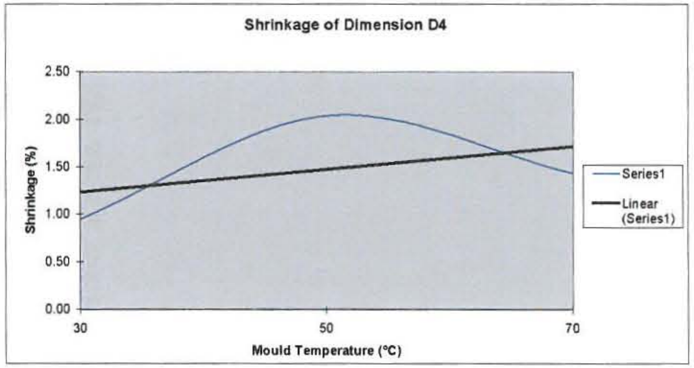

Shrinkage of Dimension L3
Shrinkage (%)
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage on Dimension L4
Shrinkage (%)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)


Shrinkage of Dimension D1
Shrinkage (%)
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
1.40
1.35
30
50
70
Mould Temperature (°C)
D1
Linear (D1)


Shrinkage of Dimension D2
Shrinkage (%)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
30
50
70
Mould Temperature (°C)
D2
Linear (D2)


Shrinkage of Dimension D3
Shrinkage (%)
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
D3
Linear (D3)


Shrinkage of Dimension D4
Shrinkage (%)
2.50
2.00
1.50
1.00
0.50
0.00
30
50
70
Mould Temperature (°C)
Series1
Linear (Series1)

APPENDIX G

MATERIAL STRENGTH TEST RESULTS

TENSILE TEST RESULTS

Experiment	1.1.1	1.1.1	1.1.1	Av	1.2.1	1.2.1	1.2.1	Av	1.3.1	1.3.1	1.3.1	Av
Cast	1	2	3		1	2	3		1	2	3	
Young's Modulus (Mpa)	1619.500	1619.500	1619.500	**1619.500**	1561.600	1606.100	1642.000	**1603.233**	1584.500	1485.600	1584.500	**1551.533**
Maximum Force (N)	3863.000	4103.200	2863.000	**3609.733**	2908.700	4763.100	3864.100	**3845.300**	4762.800	4566.100	4762.800	**4697.233**
Tensile Strength (Mpa)	53.369	57.524	53.369	**54.754**	40.778	66.775	54.171	**53.908**	66.771	64.014	66.771	**65.852**
Elongation at Fracture (mm)	10.827	12.644	10.827	**11.433**	3.985	8.835	5.768	**6.196**	9.602	10.218	9.602	**9.807**
Percentage Elongation	10.827	14.376	10.827	**12.010**	4.580	10.155	6.630	**7.122**	10.979	11.745	10.979	**11.234**

Experiment	2.1.1	2.1.1	2.1.1	Av	2.2.1	2.2.1	2.2.1	Av	2.3.1	2.3.1	2.3.1	Av
Cast	1	2	3		1	2	3		1	2	3	
Young's Modulus	667.770	677.500	698.590	**681.287**	1380.300	1609.000	1575.700	**1521.667**	1558.800	1580.200	1531.700	**1556.900**
Maximum Force	377.300	4670.800	4706.800	**3251.633**	4584.000	4735.900	4095.900	**4471.933**	3649.700	4106.100	4578.000	**4111.267**
Tensile Strength	52.955	65.481	65.985	**61.474**	64.264	66.393	57.421	**62.693**	51.165	57.564	64.180	**57.636**
Elongation at Fracture	7.018	9.034	8.550	**8.201**	12.768	8.969	9.151	**10.296**	6.284	6.368	11.336	**7.996**
Percentage Elongation	8.064	10.384	9.827	**9.425**	14.676	10.309	10.519	**11.835**	7.205	7.319	12.071	**8.865**

Experiment	3.1.1	3.1.1	3.1.1	Av	3.2.1	3.2.1	3.2.1	Av	3.3.1	3.3.1	3.3.1	Av
Cast	1	2	3		1	2	3		1	2	3	
Young's Modulus	665.280	665.280	674.670	**668.410**	637.570	637.570	657.790	**644.310**	790.280	740.890	790.280	**773.817**
Maximum Force	4776.300	4776.300	4444.100	**4665.567**	4246.400	4246.400	4469.700	**4320.833**	4515.800	4264.100	4515.800	**4431.900**
Tensile Strength	66.960	66.960	62.303	**65.408**	59.531	59.531	62.662	**60.575**	63.308	59.780	63.308	**62.132**
Elongation at Fracture	10.779	10.779	7.502	**9.687**	7.786	7.786	9.819	**8.464**	8.284	6.935	8.284	**7.834**
Percentage Elongation	11.343	11.343	8.623	**10.436**	8.948	8.948	11.286	**9.727**	9.522	7.971	9.522	**9.005**

APPENDIX H

MATERIAL HARDNESS TEST RESULTS

HARDNESS TEST RESULTS

Experiment	1.1.1	1.1.1	1.1.1	Av	1.2.1	1.2.1	1.2.1	Av	1.3.1	1.3.1	1.3.1	Av
Cast	1	2	3		1	2	3		1	2	3	
Rockwell Hardness	25	25	25	**25**	25	24	26	**25**	25	24	20	**23**

Experiment	2.1.1	2.1.1	2.1.1	Av	2.2.1	2.2.1	2.2.1	Av	2.3.1	2.3.1	2.3.1	Av
Cast	1	2	3		1	2	3		1	2	3	
Rockwell Hardness	22.000	26.000	23.000	**24**	27.000	25.000	22.000	**25**	26.000	26.000	28.000	**27**

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