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Extended summary

MOLD DESIGN IN HIGH STRENGTH CONCRETE FOR THE PROCESS OF INJECTION MOLDING OF PLASTIC MATERIALS

Curriculum: Materials, Waters and Soils Engineering

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Abstract. This thesis is aimed at designing a mold for injection molding of plastic materials made of high strength cement composite. This innovative technique is based on the construction of the mold directly on the plastic model that we want to produce. This feature allows one to avoid several mechanical processes in relation to making a metallic mold consequently obtaining a reduction in production costs. Numerical simulations have been carried out in order to assess the feasibility of the mold process. Two prototypes have been built using different cement mixtures. The mixtures have been cast in a PVC shape containing the model of wheel chocks. Nevertheless in the first experiment we were not able to extract the model, in the second we could extract the model only in the condition of hot mold, i.e. real operating conditions. In both cases we obtained very good finished surface with very low roughness. Thermal conductivity measurements have been also performed on samples of the cement composite. These values are quite satisfactory producing a cost-effective process. However traditional applications, based on metallic molds, show a machine-time that is the half of that obtained in our case. Experimental tests aimed at measuring the breaking stress of the composite have been conducted. Our materials exhibit a breaking stress lower than traditional metal materials (more or less of one order of magnitude). For this reason, an increase in the size of the mold is necessary. The simplicity of the process, its low costs, its reliability on complex shapes and the very good surface roughness of the products make this technique very attractive from the economical point of view. Nevertheless some details need to be improved in the process in order to consider this technique useful for real applications.

Keywords. Injection Molding, Concrete, Filling Process Simulation, Mold Flow.

Introduction

This thesis, carried out in collaboration with AESA Tecnopolimeri, evaulates the possible replacement of steel, with which the molds are commonly made for the industrial production of objects made of polymeric material, with a cementitious composite of high mechanical strength.
The use of a cement mixture to make the molds could produce considerable economic advantage. In fact, taking into consideration only the cost of the concrete, lower than metal alloys one, the use of this new kind of molds would acquire significant interest; if it is considered that in the majority of cases the molds have special and often very complex shapes, further reduction of the costs could be achieved in relation to a smaller number of treatments to be carried out, since the concrete is cast in a form which reproduces exactly the piece to be carried out during molding.
In fact, after casting, curing and the removal of the formwork, a cavity (the negative of the object to be cast) is obtained which does not require subsequent machining.
The problems faced in the research were mainly three: adequate mechanical strength of the cementitious composite, effectiveness in the heat exchange and surface finishing of the object after casting.

Mold design and construction

The object chosen by AESA Tecnopolimeri as test-case for the construction of the prototype of the mold consists of a wedge stops wheels. This item has been conceived and designed with the solutions and the necessary precautions for the parts produced by injection molding.
In the following Figure 1 the wedge is shown with base dimensions of 170 x 170 mm and height of about 100 mm; it may also be noted that the reinforcing ribs generate three compartments helpful in order to eventually allocate the cooling channels of the mold.

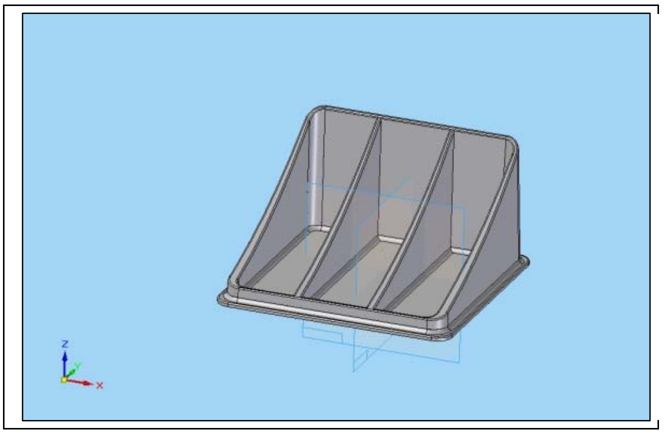


Figure 1 - Wedge stops wheels.

The object designed is very easy to construct because it has no undercuts and has a single draft plan (xy plane), and these characteristics reduce the complexity of the mold to produce.
The drawing was made by using 3D CAD software Solid Edge and then the prototype was made with a resin for rapid prototyping, using a numerically controlled milling machine.

Mechanical Design

A preliminary design has been made to ensure the mechanical strength of the mold under the action of a press for injection exerting up to 300 t, for which a compressive strength of concrete of 160 MPa was assumed as allowable.
The resistant area required is found to be of approximately 218 x 218 mm whereas the maximum closing force of the mold halves that the press could offer. To make up for a possible decrease in resistance, due to the possible need of inserting the cooling channels, it was decided to increase the dimensions of the base of the first prototype to 370 x 380 mm.

Mold simulations

Software simulations were needed in order to optimize all the parameters involved in the molding.
Numerical simulations allowed to increase the quality of the element built by means of the molding process.
Numerical simulations were conducted in different steps, which can be summarized as:

- Import of geometry and generation of 3D Mesh
- Choice of the polymer to be injected
- Choice of materials with which to make the mold
- Setting the temperature of the molten polymeric material during the injection stage
- Setting the temperatures of the two mold halves

The first results obtained with Moldflow were not very good, since in fact, as shown in Figure 2, the printing presented a significant amount of air inclusions, which are unwanted because they significantly affect the mechanical strength of the object to realized.
Moreover, non-uniformity in the cooling is also shown in Figure 3, which negatively affects the finished object. In fact, a non-uniform cooling causes shrinkage generating differential residual stresses, which can weaken or deform the piece.

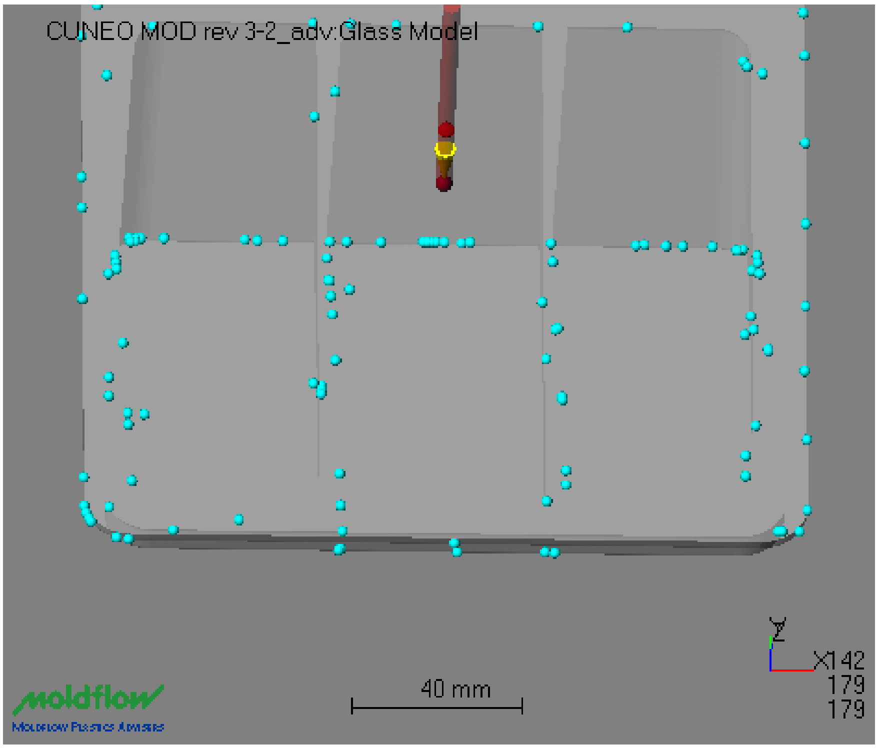


Figure 2 - Moldflow printing.

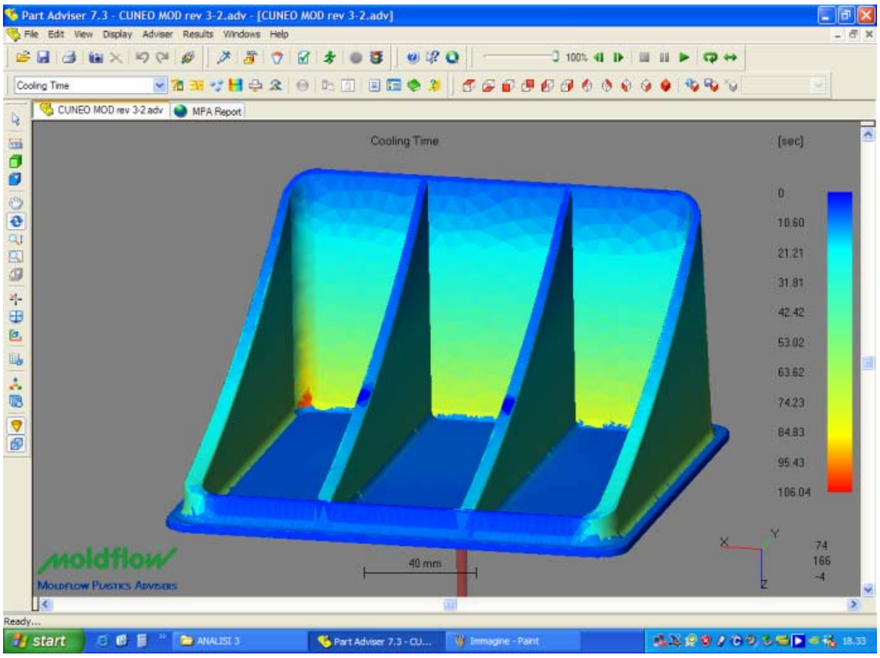


Figure 3 - Cooling time.

Figure 4 shows the quality of the wedge, where the yellow colored areas are those showing poorer quality.

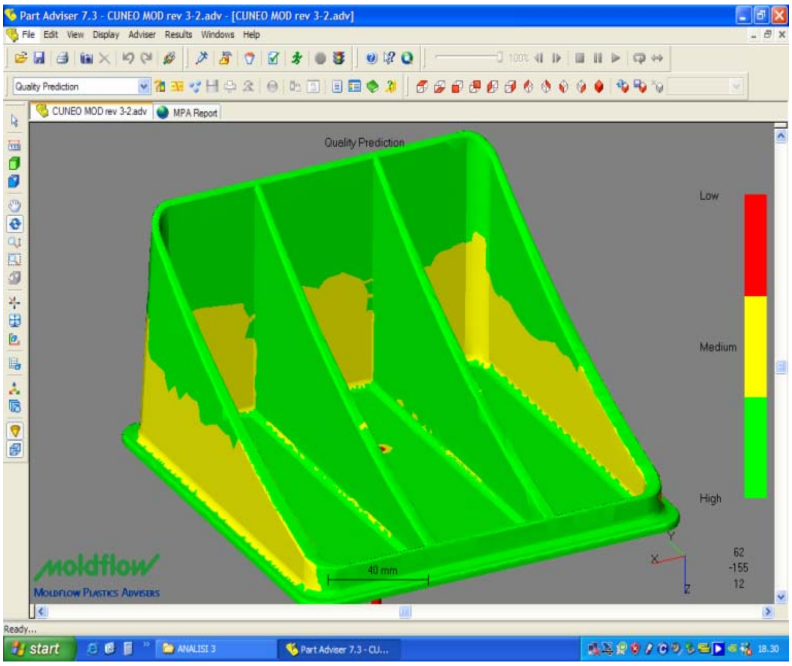


Figure 4 - Quality prediction.

In order to improve the quality of the wedge, cooling channels as shown in Figure 5, have been added in the simulation and after various modifications of the channel diameter, of the cooling water flow and its inlet temperature, a good overall quality of the object has been achieved, as shown in Figure 6.

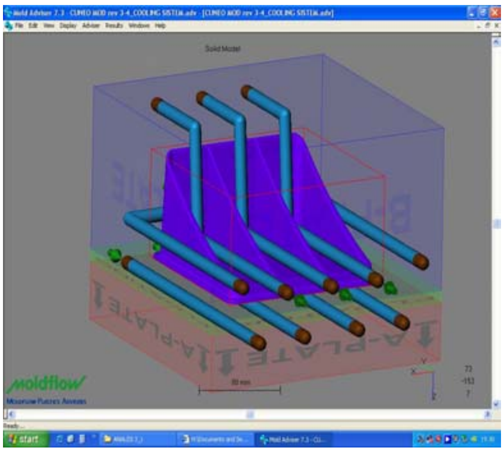


Figure 5 - Cooling channels.

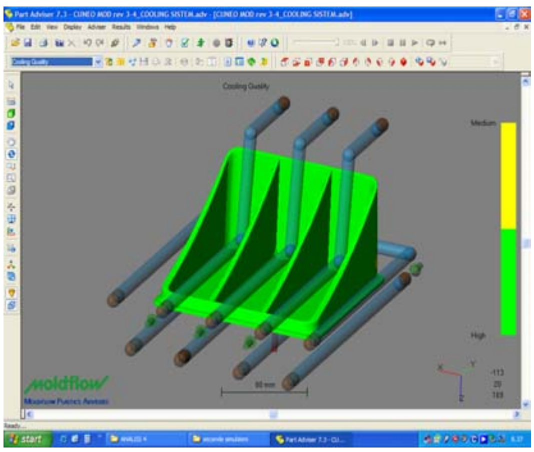


Figure 6 - Quality prediction with cooling channels.

In the following table all the output values that the program provides after the simulation are reported, among which of particular interest are the maximum compressive force that the press exerts on the two mold halves, equal to about 33 t, and the cycle time, i.e. the time that elapses between the closure and reopening of the mold after solidification of the molded part. In particular, the cycle time, which results to be of 148 seconds, although it is almost double compared to the times which are obtained with the traditional metal molds, is satisfactory for batches of medium-small production.

Material Grade:	PP Generic Estimates
Max Injection Pressure:	180.00 MPa
Mold Temperature:	75.00 deg.C
Melt Temperature:	230.00 deg.C
Model Suitability:	Part model was suitable for analysis.

Runner Adviser Results	CUNEO MOD rev 3-4_COOLING SISTEM_adv
Gates Largest Percentage Change	-58.07%
Gates Average Percentage Change	-58.07%
Number of Altered Gates	1
Runners Largest Percentage Change	0
Runners Average Percentage Change	0
Number of Altered Runners	0

Filling Analysis	CUNEO MOD rev 3-4_COOLING SISTEM_adv
Moldability:	Your part can be easily filled
Confidence:	Medium
Injection Time:	5.34 sec
Injection Pressure:	9.35 MPa
Weld Lines:	Yes
Air Traps:	Yes
Shot Volume (cavity, runner):	317.00 cu.cm (316.86, 0.15)
Filling Clamp Force:	6.98 tonne
Packing Clamp Force Estimate @20%:	(1.87)MPa 5.50 tonne
Packing Clamp Force Estimate @80%:	(7.48)MPa 21.99 tonne
Packing Clamp Force Estimate @120%:	(11.23)MPa 32.98 tonne
Clamp Force Area:	288.14 sq.cm
Cycle Time:	148.00 sec

Realization of the first prototype

In the light of the results obtained from the analysis described above, after a further phase of CAD design, which is necessary to have a view of the whole and realize all the components to be assembled, we proceeded by preparing a formwork (Figure 7), which was realized in such a way that allowed to accommodate both the model of the wedge and the cooling channels, and at the same time allowed the operations of pouring the concrete.
The formwork and the model have been previously sprayed with an oil release agent in order to facilitate the removal of the walls of the formwork and the extraction of the model after the solidification occurred.
Once the cast was performed with a mixture of very fine aggregate, silica fume, 42.5 limestone blended cement, superplasticizer and water, specimens for mechanical testing and thermal properties were also prepared with the same mixture, all the cast concrete was adequately vibrated and finally allowed to harden under wet curing conditions.

Figure 7 - Formwork set up.

Unfortunately, after 28 days of aging, despite the ease with which it was possible to remove the walls of the formwork, it was not possible to extract the model of the wedge, probably because of its shape characterized by a high ratio of surface to volume.
Excellent results have been obtained with regard to the surface finish of the mold both in the part immediately visible that forms the interface of contact between the fixed and mobile half-mold (Figure 8) and in the cavity formed by the model (Figure 9), whose aspect could be observed only after breaking the cast piece for the extraction of the model itself. To facilitate this extraction in subsequent experiments it was decided to use other types of release agents, such as mold release waxes used for the laminations in the fiber reinforced composite production.

Figure 8 - Draft plan.

Figure 9 - Internal surface finish.

Mechanical and Thermal Tests

To evaluate the mechanical strength of the concrete tests were carried out under bending (Figure 10) and compression (Figure 11).

Figure 10 - Flexural test.

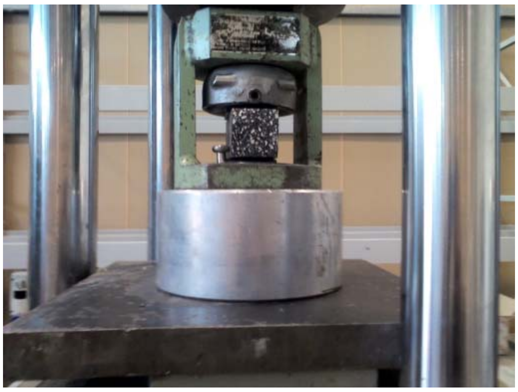
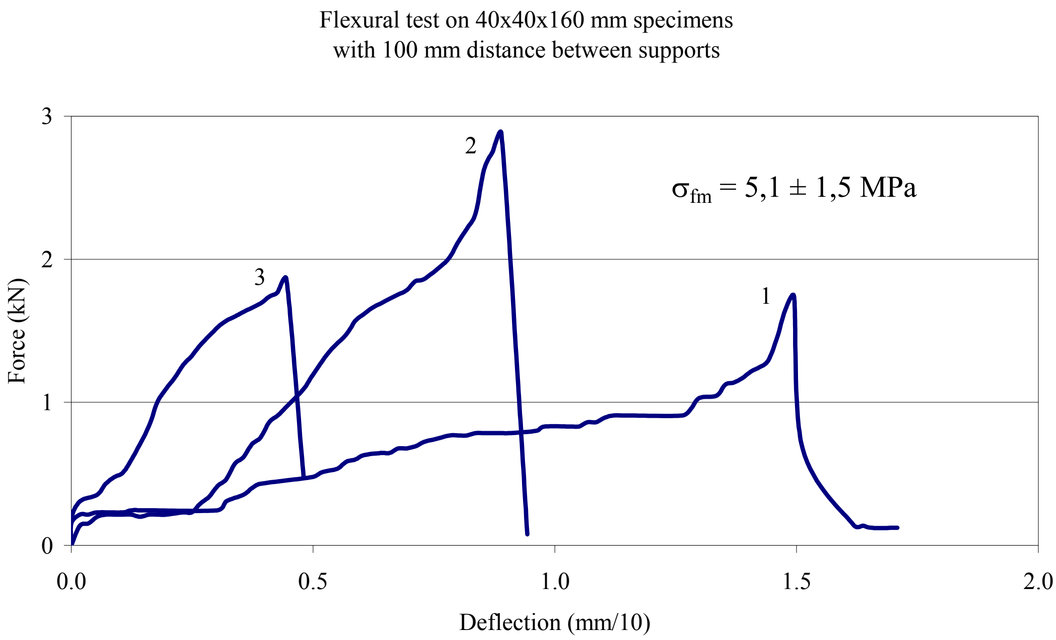
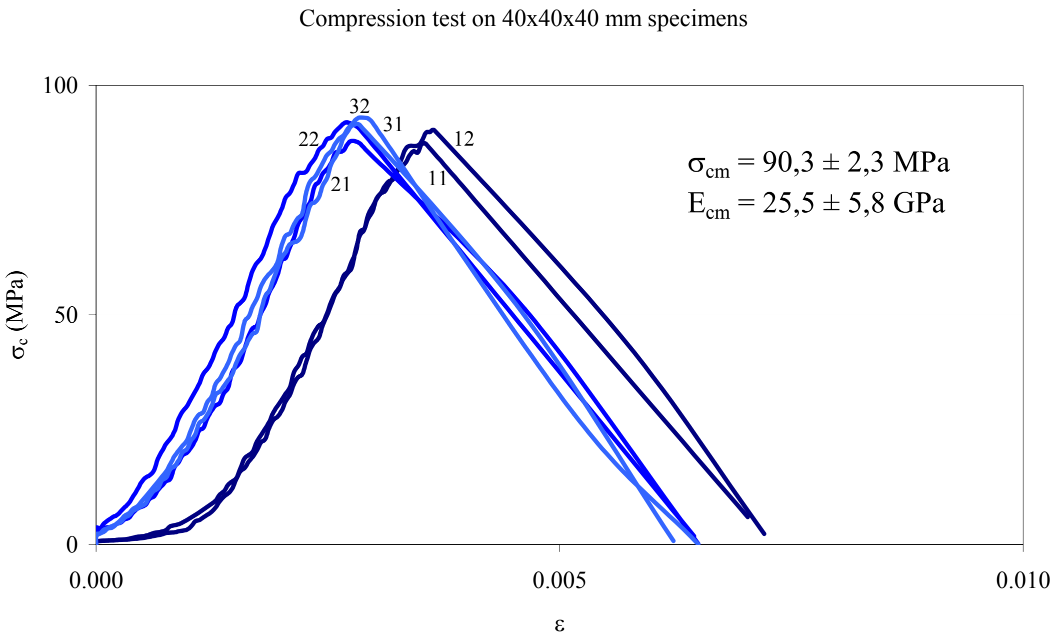


Figure 11 - Compression test.

From the mechanical tests a compressive strength of about 90 MPa was obtained; this value is almost halved compared to that expected from the mixture design, assumed to be equal to 160 MPa, so that a change in the mixture design of the concrete is necessary in order to increase its mechanical strength.
In order to evaluate the thermal characteristics of the mixture, a test instrument with a hot plate guard ring (Figure 12) was carried out on two disk-shaped specimens, with 200 mm diameter and 20 mm thick (Figure 13), which were previously dried.





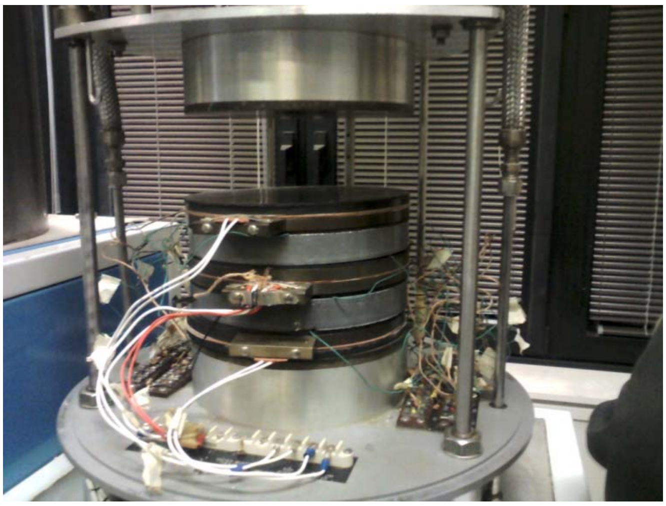


Figure 12 - Thermal testing set up.

Figure 13 - Disk-shaped specimen.

The test report shows that the thermal conductivity of the specimen, 0.739 W/mK, is very low but in any case of the expected order of magnitude. An improvement of the mixture in order to raise this coefficient would bring the advantage of further lowering the production cycle time.

Verification of the mechanical behaviour

In the light of the data obtained by the simulations with Moldflow and from the values obtained by means of the tests, it was possible to verify the resistance of the mold to the loads to which it would actually be subjected during molding.
This test was done using the finite element Ansis setting the following values as input data:

MAXIMUM CLAMPING FORCE ……………………..……......…..……… 33,0 t

COMPRESSION LIMIT STRESS....…………………...................………...… 88,0 MPa

BENDING LIMIT STRESS ....………………….......................................…… 3,6 MPa

YOUNG'S MODULUS ……………………………….…..….……..….…. 20,0 GPa

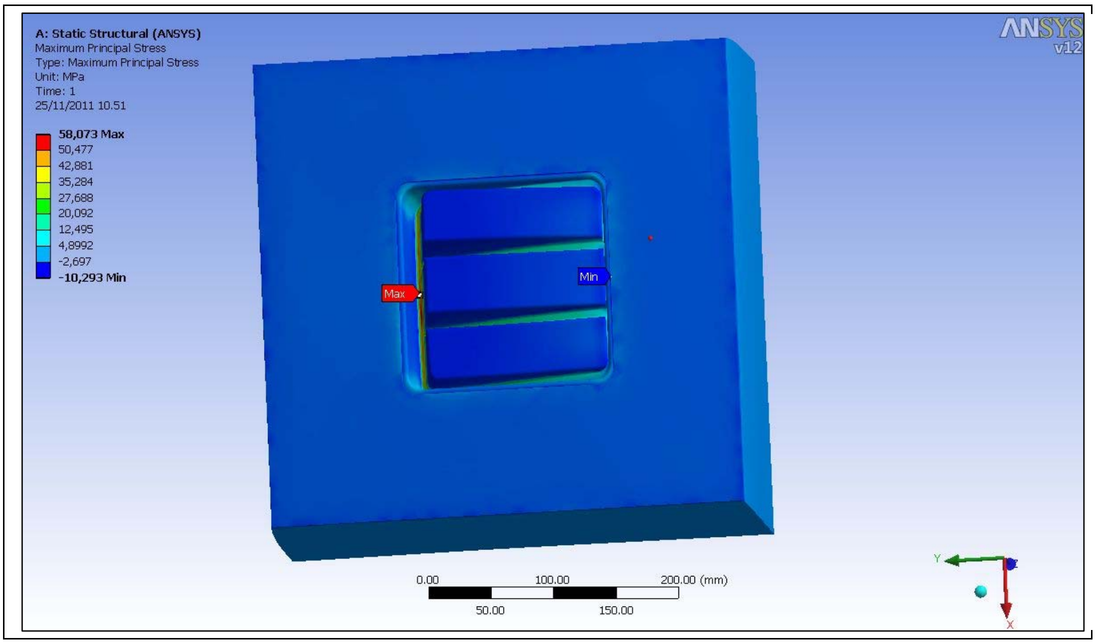


Figure 14 - Maximum principal stress.

As shown in Figure 14, the allowable stress is exceeded at the edge of the wedge, and this would lead to the collapse of the mold. The explanation of the fact that the stress dramatically increases at the edge of the wedge is most likely due to a very low radius of curvature, thus leading to stress concentration.

Realization of the second prototype

In light of the problems encountered with the first prototype of the mold, a change in the formwork was made by using six extractors in order to facilitate the extraction of the model of the wedge, and were also inserted threaded bars to fix four eyebolts necessary for the mold handling because of its considerable weight.

Figure 15 - Second Formwork set up.

Differently from the first, for this second prototype a silicone oil spray as release agent has been used before pouring concrete. Moreover, in this case a cement type 52.5 R has been used without changing all the other components of the mixture.
After maturation, it was decided to release the prototype from the mold, but as in the first case the wedge could not be pulled out. To facilitate the extraction, the mold was connected to a thermostatic bath allowing the circulation of water at 70°C in the channels of thermal conditioning. This idea was successful, since the mold heating brings it under the temperature conditions in which it will be after the molding cycle, in the opening phase and extraction; in fact, at this temperature the polymer of which the wedge is made is less rigid, and, therefore, lower force is exerted on the walls of the mold and the lubricating oil is considerably less viscous, thus facilitating the model extraction.

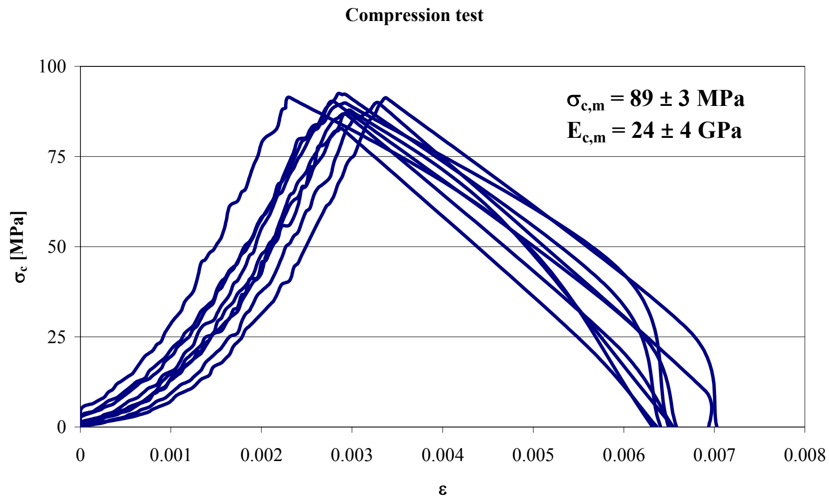
Figure 16 - Mold conditioning.

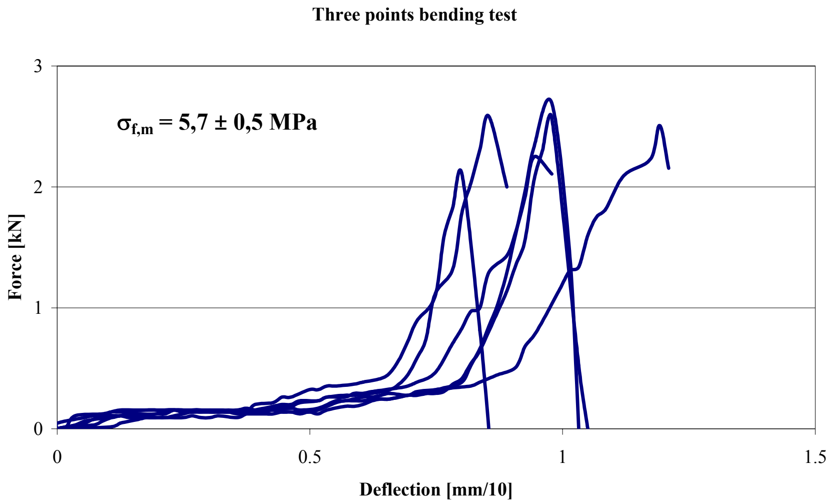
The surface finish was again excellent in everywhere, even if during the extraction the edges of the cavity model were partly damaged.

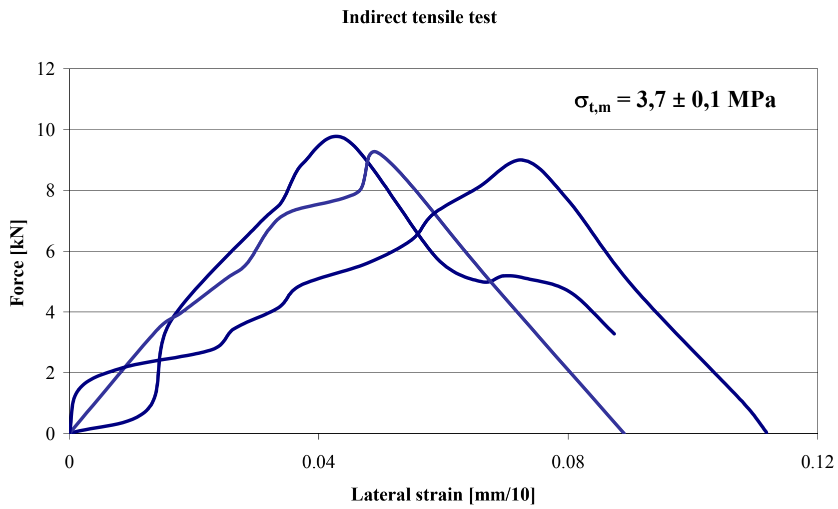
Figure 17 Cavity

8.4.1 Mechanical and Thermal Tests

Also in this second experiment specimens have been prepared necessary to carry out the measurements of the mechanical and thermal characteristics of the new mixture. The results obtained are reported in the following figures.


Compression test
$\sigma_{c,m}$ = 89 ± 3 MPa
$E_{c,m}$ = 24 ± 4 GPa
100
75
50
25
0
σ_c [MPa]
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
ε


Three points bending test
$\sigma_{f,m}$ = 5,7 ± 0,5 MPa
3
2
1
0
Force [kN]
0
0.5
1
1.5
Deflection [mm/10]


Indirect tensile test
$\sigma_{t,m}$ = 3,7 ± 0,1 MPa
12
10
8
6
4
2
0
Force [kN]
0
0.04
0.08
0.12
Lateral strain [mm/10]

As shown by the graphs, no improvement of the mechanical properties is obtained compared to the mixture previously used.
The report of the thermal measurement made on specimens of the new mixture shows that the thermal conductivity is somewhat improved by assuming the value 0.750 W/mK.

Conclusions

The aim of the research, partly carried out in collaboration with AESA Tecnopolimeri, is the design of a mold for injection molding of plastic materials to be carried out by using mixtures of high-strength concrete.
This innovative technique consists in realizing the mold by casting the concrete mixture directly on a polymer model of the prototype to be molded, thereby avoiding many machining operations related to the realization of a metal mold, and therefore the cost rise.
Numerical simulations and laboratory tests were conducted in order to verify the mechanical strength of the molds so realized, the ability of quick heat disposal and the surface finish obtained.
Within this thesis, after a long preliminary phase of numerical simulation of the molding process required for a first check of applicability of the technique, two prototypes have been realized by using two concrete mixtures, different for the cement type, portland cement 42.5R and 52.5R respectively. These mixtures were poured in a form made of PVC containing the model, which in both cases was a wedge stops wheels.
In both cases excellent results were obtained as regards to the surface finish, although it was not possible to extract the model of the wedge from the first prototype, probably because of its shape characterized by a high ratio between surface area and volume, while in the second it has been proved that a hot mold, such problems can be overcome. The measurements of thermal conductivity of both mixtures revealed a low but sufficient heat exchange capacity. This feature significantly influences the machine times.and output; despite these effects are double compared to those obtainable with the traditional metal molds, this new production technique is still economically viable.
Mechanical resistance tests were also conducted on some specimens prepared during the casts: the values of the maximum measured stresses are of an order of magnitude lower than those of metals, and this results in an increase in size of the cement molds compared to the traditional metallic in order to withstand the injection loads.
We conclude, therefore, that the ease of implementation, the low cost of materials used, the ease with which even complex shapes can be reproduced with good surface finish, make this technique economically very advantageous and technologically promising, even though it is still to be much refined.
Certainly, improvements of the concrete mixture are necessary, obtainable by introducing into the mixture reinforcing fillers and other elements to increase mechanical strength and thermal conductivity. The principles underlying the design of the molds should be adjusted on the base of the values of draft angles to give the plastic components in order to take account for any shrinkage that may occur in the cast

prototype. Further experimentation and testing directly on actual presses would, of course, be necessary for the completion of this work.

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