Design and Application of Low Compaction Energy Concrete for Use in Slip-form Concrete Paving

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Optimization of Self-Consolidating Concrete for Slip-form pavement

A thesis submitted in partial fulfillment for the degree of Master of Science in Civil and Environmental Engineering

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Abstract

The concrete currently used in the slip-form paving process is a low slump concrete that requires both internal and external vibration in order to achieve satisfactory compaction. The use of vibrator fingers for the internal vibration often leads to trails on the surface of the pavement and to segregation around the trails, which cause durability issues. The objective of this project is to overcome these problems by designing a concrete that would not require the use of internal vibrators. The concrete should be workable enough for machine placement, compactable with a minimum of energy and hold its shape for the slip-form process.

Various mix designs based on the concept of Self-Consolidated Concrete were studied, so as to have some flowability and some compactibility, the challenge being to make them shape-stable. Different fine materials were added in the mix design to make the concrete hold its shape. The fine materials used were different types of clays, fly ash and magnesium oxide. The addition of polypropylene fibers was also studied. The flowability of the concrete was evaluated by using the drop table test, while the shape stability was measured by the green strength. A mini-paver was developed in collaboration with Iowa State University so as to simulate the slip-form paving process and was used to test selected mixes. The fresh and hardened state properties of the selected mixes are examined in this paper.
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1 Introduction

1.1 Background and motivation

Concrete has been used in highway construction in the United States since 1913. The invention of the slip-form paver in the 1940’s was a breakthrough as it allowed concrete to be placed continuously, therefore far more efficiently than before. Today, slip-form paving is used worldwide as concrete pavements have greater life expectancies and their maintenance is easier. Slip-form paving differs from fixed-form paving as it does not require the use of any steel or wooden forms. The layer of concrete applied can vary between 2 and 12 inches and its width is ranged from 6 to 20 feet.

The paving process combines concrete placing, consolidation and finishing into one single process. The concrete, which is less than 2 inches slump, is placed in front of the paver as the paver moves forward at a speed up to 15 feet/min. Then, as the concrete is spread in front of the paver, internal electric vibrators consolidate the mixture, which is
then extruded at the back of the paver. The fresh concrete pavement can hold its shape
and is consolidated enough for further surface finishing.

Over the years, longitudinal trails appear on the surface of the pavements; those trails are
parallel to each other and their spacing is similar to the one of the vibrator fingers. The
analysis of cores withheld along the trails revealed that the hardened concrete contains
less than 3% air, compared to 6 to 7% as designed. This explains the durability issues
observed, as the freeze-thaw resistance of the concrete is significantly affected.

Therefore, eliminating the need of internal vibration would solve this recurrent problem
and would constitute a tremendous breakthrough in slip form paving.

![Figure 2: Details of slip-form paving process](image)

![Figure 3: Longitudinal trails](image)
1.2 Objectives

The objectives of this project are to design a new concrete mix for use in slip-form paving. This concrete mixture, based on Self Consolidated Concrete concept, should be workable enough for machine placement, compactable with a minimum of energy and hold its shape for the slip-form process.

This thesis is organized in four chapters. Chapter two reviews the relevant work that has been previously conducted on low-slump concrete. In chapter three, the experimental methods used in this project, as well as the materials involved are described. Chapter four gives the results of the experiments carried out on Slip-Form SCC (SF SCC), analyzes the findings and suggests future work.
2 Literature review

2.1 Introduction

This chapter discusses previous work conducted on improving and studying no-slump concrete. The fundamentals for no-slump concrete optimization are explained, especially the importance of the concept of packing density, then the mechanisms of green state strength of concrete are described. Finally, research studies on the measurement of compactibility of concrete are presented.

2.2 Packing density of no-slump concrete

The packing density can be defined as the ratio:

\[ \text{Packing density(\%) = } \frac{\text{Solids volume}}{\text{Specimen volume}} \times 100 \]

2.2.1 Optimal water content

The common way of finding the optimum water content corresponding to an optimal packing density is called the Proctor test. This optimum water content exists for a given compaction condition, i.e. compaction energy, type and duration. In the following figure, the packing density was measured for different water/cement ratios.
When there is insufficient water, the concrete cannot be well compacted, as the friction between the particles is high. By adding water, the water acts like a lubricant as it forms a film around the particles and the friction is decreased: an optimal packing density is reached. If the water content is increased above the optimum value, the material acts like a hydrostatic incompressible fluid and cannot be further consolidated.

The influence of the water content on the green strength was examined by M. Schmidt et al. (2005). In the next figure, the compressive green strength was plotted for different w/c ratios, and compared to the packing density.
Figure 5: Relation between Green Strength and Packing density for different amounts of Superplasticizer, from Schmidt et al. (2005)

It appears that the packing density and the compressive green strength follow the same course.

2.2.2 Use of ultrafine particles

Another way of improving the green strength and quality of no-slump concretes consists on adding some ultra-fine particles (with a granulometry under 0.25 mm). In this way, the packing density is improved.

An approach similar to the common grading curves was elaborated by Dinger and Funk (1994). Their approach is based on standard grading curves according to German national standard DIN 1045-2 and follows the equation:

\[ K_{PD} = \left( \frac{D^n - D_K^n}{D_G^n - D_K^n} \right) \times 100 \], where

\( K_{PD} \) is the cumulative percent throughput

\( D \) is the examined grain diameter

\( D_G \) = Maximum particle diameter
Dₖ = Minimum particle diameter

n = Distribution module.

According to the standards, the module should stay within the range n = 0.70 and n = 0.22. R. Bornemann (2005) showed that, high packing densities could be achieved by using ultrafine particles < 0.25 mm with a distribution module < 0.35. In order to have some workability, the use of excessive ultrafine particles should be avoided, as that would lead to a sticky material; the module should then not be lower than 0.20. Therefore, for an optimized granular composition, n should be within the range n = 0.35 and n = 0.20 (cf. figure below).

![Figure 6: Granular Composition optimization, from Schmidt et al. (2005)](image)

By optimizing the no-slump concretes using optimum water content and ultrafine particles (limestone flour here), R. Bornemann and M. Schmidt (2005) managed to improve the compressive strength of the specimens tested, compare to a plain concrete with the same paste. In this way, they also demonstrated that the binder content could be significantly decreased, without adversely affecting the strength.
2.2.3 Example of optimization with Concresol

Some experiments were carried to improve the cohesion of no-slump concretes, using a very fine clay like concresol. This work was accomplished by T. Malonn et al. (2005). The mixes studied contained 420 kg/m$^3$ of cement and the base mix design used 1500 kg/m$^3$ of sand. The sand, in one mix, was substituted by Concresol, both having similar densities. The study focused on the effect of varying different parameters: w/c ratio, quantity of superplasticizer, amount of sand and amount of concresol. The experiments carried out measured the apparent specific gravity, the green-state strength, the compressive strength, the surface quality and porosity and the freeze-thaw stability of those mixes. The green strength was determined on cylinders with h=16 cm and d=8 cm. The surface quality was controlled on 20*20*2 cm$^3$ tiles, using magnified photographs.

The results for the apparent specific gravity showed that an addition of concresol improves compactibility and workability of no-slump concretes. The green-state strength, the compressive strength and the surface-quality for the mixes with concresol surpassed the base mix and the stability to freeze-thaw was maintained.

Figure 7: Comparison between base and optimized concresol mixes surfaces from T. Malonn et al. (2005)
2.3 **Origin of the Green Strength**

The Green Strength can be defined as the property of a material to support its own weight in its given shape. This property is essential for numerous concrete applications where form works are not usually used, such as curbs or pavements.

2.3.1 **Interparticle Forces**

Wierig (1971) explained the phenomenon of green strength by the capillary effect of liquid wetted particles. This linking force between particles is perpendicular to the plane of contact of the two particles. Shimada et al. (1993) expressed this linking force \( f_{wi} \) as a function of the particle size \( r_i \), the contact angle of the water membrane \( \phi_i \) and the curvature radii \( r_1 \) and \( r_2 \):

\[
f_{wi} = f_{ws} + f_{wt} = \pi r_i^2 S_u + 2 \pi r_2 \Gamma = \frac{2 \pi r_1 \Gamma}{1 + \tan\left(\frac{\phi_i}{2}\right)}
\]

where \( f_{ws} \) and \( f_{wt} \) are the component of the linking force caused by the suction \( S_u \) and the surface tension \( \Gamma \) of the pore water. \( \Gamma \) is 7.306 Pa at 20°C and is a linear function of the temperature that is expressed by the Ramsay-Shield’s equation:

\[
\Gamma = \alpha \left( \frac{P}{M} \right)^2 \left( T_c - T - 6 \right) \quad \text{(Watanabe et al. 1973)}
\]

Where \( T \) is the temperature, \( T_c \) the critical temperature of water, \( \alpha \) is a constant, \( \rho \) is the density of water and \( M \) is the molecular weight of water.

If the particles in the fresh concrete are assumed to be spherical, with a mean radius of \( r_m \) and a mean water membrane angle of \( \phi_m \), the mean linking force can be expressed as:
\[ f_{wm} = \frac{2\pi r_m \Gamma}{1 + \tan(\frac{\phi_m}{2})}. \]

Figure 8: Interparticle linking forces, from Shimada et al. (1993)

The magnitude of the capillary forces is strongly influenced by the water content, as these forces decrease with an increase in water content until they vanish when the system is saturated.

### 2.3.2 Inner friction of particles

According to Wierig, the inner friction of grain particles is the other effect that explains green strength. This friction appears under external loading, and is due to the formation of a shear plane induced by vertical principal stress \( \sigma_1 \). The no-slump concrete can be considered as a mixed-grained soil, therefore the Mohr-Coulomb’s model which asserts that a material will yield by shearing when horizontal shear stresses \( \tau \) reach the value:

\[ \tau = \sigma \tan \varphi + c, \]

where \( \sigma \) are compressive stresses, \( c \) are cohesive shear stresses and \( \varphi \) is the angle of inner friction, which depends on distribution, roughness and shape of the particles.
The cohesion stresses are due to the attractive forces between the particles. Both $c$ and $\varphi$ values follow the same trend as the packing density, reaching a maximum value when the packing of the solids is optimal. This is explained by the fact that the packing increases the number of contact points.

Freimann (2001) studied the effects of compaction on the cohesion of fresh concrete. The figure below shows that, during compaction, as the structure of the particles is redefined, both the cohesion and the shear force of the material are increased.

Figure 9: Effect of consolidation on cohesion of fresh concrete, from Freimann (2001).
2.4 Measurement of workability for no-slump concrete

A standard procedure to study the effects of different additives on the workability of flowable concrete and compare them to a reference mix is based on maintaining the slump constant and comparing some properties such as compressive strength or durability. However, such a standardized procedure is not established with no-slump concrete.

2.4.1 Use of gyratory tester

A method to measure the workability of stiff concrete was established in Finland by A. Käppi and E. Nordenswan (1988). This method is based on the development of a gyratory compactor called Intensive Compaction Tester (IC-tester). The IC-tester is equipped with a test cylinder, a piston and an electronic pressure device. The IC-tester measures the height of the piston during the compaction of the concrete in the cylinder, as a function of the compaction cycles and calculates the density of the specimen. It is also equipped with a shear force measurement that evaluates the force that resists compaction.

Figure 10: Intensive Compaction Tester m-100R, from Käppi et al. (1988).
In order to measure and compare workability of different specimens, a typical density is targeted and workability corresponds to the number of compaction cycles needed to achieve the required density.

In the following figure, three samples from a same concrete batch are compacted to a targeted density value of 2430 kg/m³. The two later samples require more compaction to achieve the desired density, as they are stiffer than the first specimen. For the shear force, the stiffer is the material, the higher is the internal friction.

![Figure 11: Effect of compaction on Density and Shear Stress, from Käppi et al. (1988).](image)

The effect of “aging” on concrete was also studied. The IC test measured a loss of workability starting around 30 to 50 minutes after adding water in the mix (figure below), depending on the type of cement and its fineness.
Those results of the influence of aging of concrete on workability are confirmed by the results of the compressive strength at 3 days (Figure 13). Up to about 50 minutes from adding water (the samples being subjected to constant compaction energy after the time shown), the compressive strength remains almost constant, and then it decreases.
The IC-tester was also used to examine the effect of various factors such as w/c ratio on workability of cement.

The IC-tester that is now used in the field has it weights around 200 lbs and can be lifted and moved as wanted.

2.5 Conclusion

Many studies have been carried out on no-slump concrete. Research has been focused on optimizing its properties, especially the green strength. The optimization of the green strength was made possible thanks to a better understanding of the forces responsible for this shape stability, i.e. cohesion and capillary forces. This process is based on using ultrafine particles and an optimized amount of water, in order to improve the packing density of the concrete, which is directly responsible for green strength. Among the fine particles used, a nano-clay called concresol revealed very interesting characteristics, as it improved compactibility, workability, green strength and surface quality.

Some research also focused on the way to measure the compactibility of no-slump concrete. New equipments such as the Intensive-Compaction Tester were elaborated that measured not only the workability, but also the shear stress corresponding to a given compaction energy.
3 Experimental methods and tested materials

The influence of adding different types of fine materials in a Self-Consolidating Concrete based mix was studied, in both fresh and hardened states.

3.1 Testing fresh state properties

3.1.1 Flowability (Drop Table)

The Drop Table was used in order to measure the flowability of the concrete under some external compaction energy. The material, cement paste or concrete, is placed in a brass cone that is filled, and then lifted. According to ASTM C1437, this test measures the flow ratio of the tested material, after the table that supports the material is subjected to 25 drops. The diameter of the base of the cone is 4in. The flow diameter was recorded every 5 drops. This test requires that the material tested is shape stable, ie. Its flow diameter at 0 drop is 4in.

Figure 14: Drop table
3.1.2 Green Strength and Shape Stability

This drop table was also used to evaluate the shape stability of the tested concrete. A 75x100 mm cylinder (3x6 in.\(^2\)) was loosely filled by the concrete and then was placed on the drop table and subjected to 25 drops. The cylinder was then demolded and a vertical force applied on the fresh demolded cylinder until it collapsed. The maximum force at which the cylinder collapsed corresponded to the Green Strength of the tested cylinder.

![Image of Green Strength Test](image)

Figure 15: Green Strength Test

3.1.3 Consolidation properties (Mini paver)

3.1.3.1 Description

After testing several different mixes and determining their flowability with the drop table test and their green strength, the best mixes were tested with the mini paver, which simulates the slip-form paving process. The mini-paver (figure below) was developed by the Iowa State University Research team and it has the following dimensions:

Length=35.4 in. = 900 mm, Width= 18in. = 457 mm. The height of the mini pavement obtained was: 4.1 in. = 104 mm. As it was highly probable that the Slip-form SCC would
need some pressure to consolidate, the design of the mini-paver was based on an L-box concept. The mini paver is composed of two compartments that are filled with concrete during the experiment: a vertical and a horizontal one. The concrete was placed in the vertical compartment of the paver and the paver was pulled so as the concrete would get under the paver, in the horizontal compartment. The concrete was compacted due to a slight slope of the upper plate of the horizontal compartment of the paver and due to some weights placed on that upper plate which applied pressure on the concrete.

![Figure 16: Mini-Paver](image)

The result of this test was an extruded concrete pavement which had the form of a parallelepiped with a cross section of 457mm x 104mm. Its length depended on the amount of concrete mixed. Typically, the amount of concrete mixed was around 10 gallons (37.8 dm³), which corresponded to pavements of about 750 mm long.
3.1.3.2 Edge Slump

The slump at the edges of the mini-pavement was measured, after cutting it into slabs.

The edge slump is measured as indicated below:

![Image of edge slump measurement]

Figure 17: Edge slump measurement

3.1.4 Viscosity and Yield Stress (Rheology)

A Haake Rheometer was used to determine the flow parameters of the paste of the mixes that were tested with the flow table. The viscosity and the yield stress were obtained according to the Bingham model. This model gives a relation between the shear stress, the shear rate, the yield stress and the plastic viscosity:

\[ \tau = \tau_B + \eta_P D \]

where

- \( \tau \) = shear stress (Pa)
- \( \tau_B \) = Bingham yield stress (Pa)
- \( \eta_P \) = Bingham plastic viscosity (Pa.s\(^{-1}\))
- \( D \) = shear rate (s\(^{-1}\))

The main purpose was a better understanding of the role of viscosity and yield stress on the result of the mini paver test. For this reason, both mixes for which the mini paver test was successful and mixes for which it failed were studied here.
The lab protocol is plotted below. After filling the cup of the rheometer with cement paste, it was mixed at a shear rate that increased linearly from 0 to 70 s\(^{-1}\) for 15 seconds. Then the shear rate was stepped from 70 to 10 s\(^{-1}\), in 10 s\(^{-1}\) increments. At each shear rate, the shear stress reached a steady state after a few seconds. The shear stress that was used for the corresponding shear rate to plot the flow curves (shear stress vs. shear rate) was the average shear stress of the last 15 data. A linear regression was then used to determine the Bingham equation.

Figure 18: Rheological lab protocol
3.2 Testing Hardened state properties

The pavements obtained with the mini-paver test were then mechanically tested in both flexion and compression, after being cured in the laboratory in ambient conditions. Their surface texture and their shape stability were both examined.

3.2.1 Flexural Strength

The pavements were cut transversally in 3.5 in. slabs in order to test them in flexion with a 3-points bending test, thanks to a 20kips capacity MTS machine. The surface of the slabs (457 mm x 88.9 mm x 104 mm) was smoothed so as to avoid any imperfection that would have affected the results. Three slabs were tested for each pavement and the flexural strength of each pavement was taken as the average of the three slabs.
The flexural strength was calculated using the maximum force at which the specimen collapsed by:

\[
MOR = \frac{3}{2} \frac{P_{\text{max}} \cdot L}{b \cdot d^2}
\]

Where,

- \(MOR\) = Modulus Of Rupture in MPa
- \(P_{\text{max}}\) = Maximum load in kN
- \(L\) = Length of the specimen = 457 mm
- \(b\) = Width of the specimen = 88.9 mm
- \(d\) = Height of the specimen = 104 mm

Figure 20: 3-points bending test

### 3.2.2 Compressive Strength

The slabs used for the 3-points bending test were then cut in 3.5x3.5x3.5 in.\(^3\) = 88.9x88.9x88.9 mm\(^3\) cubes and their faces ground in order to get very smooth surfaces. These cubes were then tested in compression with a 1000 kips capacity MTS machine.
3.2.3 **Surface texture**

The surface texture of the pavements was also studied. The test used consisted of spraying a certain amount of powder of a given volume on the surface of the pavements and measure the total area covered by the powder. The powder used is a clay called Actigel which density is 1.55 g/dm$^3$. The idea is that the powder fills all the surface voids of a certain area. This test led to a Surface Quality Index (SQI) expressed in cm$^3$/cm$^2$. The lower is this index, the better is the surface texture.

3.3 **Materials**

The cement used in all the experiments was Ordinary Type I Portland Cement provided by Lafarge. The two superplasticizers used were a Naphtalene based and Polycarboxylate based ones.

3.3.1 **Mix design**

The starting point of this study was a Self-Consolidating Concrete (SCC) that was modified by changing the type and amount of superplasticizer in order to make it shape...
stable. The mix design of the SCC used is given below. The Iowa mix corresponds to the mix that is currently used in the slip-form process for highways.

<table>
<thead>
<tr>
<th></th>
<th>SCC (kg/m³)</th>
<th>Iowa (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>516</td>
<td>353</td>
</tr>
<tr>
<td>Water</td>
<td>197</td>
<td>151</td>
</tr>
<tr>
<td>Gravel</td>
<td>861</td>
<td>897</td>
</tr>
<tr>
<td>Sand</td>
<td>794</td>
<td>886</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>2.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 22: Mix design of SCC and Iowa DOT concrete for pavement

The granulometry of the aggregates used is given in the chart below. The ones used in this part of the study are the sand and the gravel. The limestone coarse aggregates will be used later in the study.
As can be see from Figure 23, the minimum particle size was 0.2 mm for the sand and 2.4 mm for the gravel. The maximum particle size was 4.8 mm for the sand and 9.5 mm for the gravel.

The influence of the type of Plasticizer on the flowability was also investigated for the conventional SCC mix design (see Figure 22). The flow diameter of the conventional SCC with a Polycarboxylate-based Plasticizer was compared to the same concrete mixture for which the plasticizer had been replaced by a Naphtaline based one.

### 3.3.2 Fine materials

The conventional SCC mix was also made shape stable by adding various types of fine materials.
The fine materials used to make the base mix shape stable were Fly Ash class F and three different types of clays: Actigel, Metamax and Concresol. They were gradually added to the base mix until the concrete reached a shape stable state. This state corresponded to an initial flow diameter of 4 inch, after lifting the cone of the drop table. The reason for adding fine particles was to improve the particle packing of the concrete so as to obtain a denser concrete.

The Magnesium Oxide tested is produced by Baymag and is called Baymag 40.

The properties of the fine materials used are listed in the table below:

<table>
<thead>
<tr>
<th>Name</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actigel</td>
<td>Purified magnesium Alumino Silicate</td>
</tr>
<tr>
<td>Metamax</td>
<td>Kaolinite</td>
</tr>
<tr>
<td>Concresol</td>
<td>Kaolinite, Illite, Quartz</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Class F (SiO2, Al2O3, Fe2O3, CaO, MgO, SO3, LOI)</td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>MgO</td>
</tr>
</tbody>
</table>

Figure 24: Fine materials tested

### 3.3.3 Other materials

The same investigation was performed for other types of materials: Viscosity Modifying Agent (VMA) and Polypropylene fibers.

#### 3.3.3.1 VMA

The VMA used in this part of the study is an anionic polysaccharide material called Welan Gum, produced by Kelco.
3.3.3.2 Effect of Polypropylene fibers addition

The fibers used were made of polypropylene; they were 5 to 15 mm long with a diameter less than 0.05 mm and an aspect ratio of 100-300.

4 Experimental results and analysis

The effect on concrete of the addition of the materials cited above will be examined in this chapter. The properties, on which the selection of mixes was based, were the flowability, measured by the drop table test, and the green strength. The selected mixes were then tested with the mini-paver.

4.1 Effect of tested materials on flow properties

4.1.1 Effect of type of superplasticizer

The mix design for SCC given above was modified in order to make it shape stable. The first parameter examined was the amount and type of superplasticizer. The two mixtures, corresponding to the two types of superplasticizer, that were shape stable for the flow test, i.e. the one with 0.1% polycarboxylate and the one with 0.47% naphtaline were then tested with the drop table and their green strength measured (see Figure 25 below).

It can be noticed that, at a given number of drops, the concrete with the naphtaline based plasticizer exhibits a higher flow diameter than the one with the polycarboxylate based plasticizer. This is the reason why this concrete mixture will be considered as our reference mix.
4.1.2 Effect of fine materials

Figure 26 shows that the fine materials tested have very different effects on the flow of the concrete. The clays are more effective than the fly ash and cement powder, which is due to the fact that their particle size is finer. The plasticizer used in those experiments was a Polycarboxylate based one.
As shown above, actigel is more efficient in reducing the flow as a 3% addition is enough to make the mix shape stable. Fly ash appears to be the least efficient as a 25% addition is necessary to reach a 4 inch flow diameter. The effectiveness of each fine material will be discussed later, in the last part of this thesis and related to the shape and size of the particles.

4.1.2.1 Effect of Fly Ash addition

Three different amounts of Fly Ash were added to the reference mix and their flowability and Green Strength were compared to the reference mix ones. The addition rates studied (in percent of cement weight) were 10%, 20% and 30%.
The 10% and the 20% addition rates mixes had a higher flow than the reference, while their green strength was lower (respectively 0 and 1.1 kPa as opposed to 3.4 kPa for the base mix). The 30% addition rate mix had a slightly lower flow than the base mix and a lower Green Strength, but was still shape stable. As the main reason of studying Fly Ash mixes was to decrease the cement content in our mix design (516 kg/m³ as opposed to 350 kg/m³ for the concrete mixture used now for slip-form paving), the 30% addition rate was chosen for further work.

The mix with the lowest flow was the Iowa DOT mix, i.e. the mix that is currently used in slip-form paving. Its low workability explains the need for vibration; this can be also
noticed from the physical aspect of the corresponding cylinder, the surface of which shows the presence of many air voids, compared to the other mixes, which are better consolidated.

4.1.2.2 Effect of Actigel addition

Different amounts of Actigel were added to the reference mix.

![Acti-gel addition](image)

Figure 28: Effect of actigel addition

As it can be noticed, the flowability of the reference mix is increased by adding both 1% and 2% of actigel (addition rate in percent of cement weight). However, the green strength is improved just for the 1% addition rate. The 2% addition rate mix has a lower green strength than the reference mix. So does the 3% addition rate mix, which has also a
lower flow diameter at 25 drops than the reference mix. For these reasons, it seemed to be appropriate to investigate further the 1% addition rate concrete mixture has it has both a higher flow and a higher green strength than the reference mix.

### 4.1.2.3 Effect of Metamax addition

As it was done above for the actigel, the addition of different amounts of Metamax to the reference mix was studied.

![Admixture: Naphtaline](image)

**Figure 29: Effect of Metamax addition**

All three addition rates of metamax (1.5%, 3.0% and 4.5%) increased the flow. The best flow at 25 drops was obtained with the 1.5% addition rate. This mixture, by improving the flow, kept the green strength of the concrete constant (3.4 kPa), while the other
addition rates decreased the green strength of the base mix. This shows that the 1.5% addition rate mix should be further investigated.

4.1.2.4 Effect of Concresol addition

The effect of the addition of three different amounts of concresol is shown below. Those addition rates were 1.5%, 3% and 4.5%.

![Concresol addition](image)

**Figure 30: Effect of Concresol addition**

It can be noticed that all the addition rates resulted in slightly decreasing the flow diameter of the concrete. The green strength increased for the 1.5% and 3% addition
rates, while it decreased for the 4.5% addition rate. This explains why, with nearly the same flowability as the reference mix and with much better green strength (8.8 kPa as opposed to 3.4 kPa for the reference mixture), the 1.5% addition rate mix was selected for further work.

4.1.2.5 Effect of Magnesium Oxide addition

Different addition rates of MgO were investigated: 1%, 2%, 3% and 4%, while the water/cement ratio was also varied from 0.4 to 0.41.

![Figure 31: Effect of Magnesium Oxide addition](image)

The best combination appeared to be the 2% addition rate with w/c=0.41 as it had a better flowability than the reference mix and also a higher green strength (4.1kPa).
4.1.3 Effect of VMA and Polypropylene fibers

4.1.3.1 Effect of VMA addition

Three different addition rates of VMA were used: 0.155%, 0.072% and 0.039% in percent of water weight. All the three addition rates mixes exhibit a lower diameter flow than the reference mix, while the green strength was improved. The best compromise appeared to be the 0.039% addition rate as it had a better green strength than the reference mix (3.7 kPa) while having a slightly lower flowability.

Figure 32: Effect of VMA addition
4.1.3.2 Effect of Polypropylene fibers addition

The addition rate tested was 0.1% in percent of the total volume of the concrete. Different amounts of water/cement ratios were investigated (See below).

According to the results of the drop table and the green strength tests, the mix that gives the best results is the one with a water/cement ratio of 0.41. This mix will be examined.

![Figure 33: Effect of Polypropylene fibers addition](image)

4.1.4 Optimization of Fly Ash mixes

As said above, the main reason for using Fly Ash was to decrease the cement content in our mix design; It was chosen to improve the fly ash mix design by adding the three types of clays mentioned, in order to keep the flow properties of the fly ash mix and combine them with the green strength of the clays mixes.
At this point of the study, the cement batch was changed and therefore, the flow properties slightly changed. Especially, the flow diameter was lowered, compared to the previous results. Therefore, in order to match the results obtained before, the water/cement ratio was increased from 0.38 to 0.40. This explains why some results differ a bit from previous ones.

4.1.4.1 Effect of Concresol addition

The fly ash mixes which gave the best results in both the drop table and the green strength tests are plotted below in Figure 34. It appears that the 30% Fly Ash replacement rate had a better flow than the reference mix, but a lower green strength (0.9 kPa). This mix was then changed by adding some Concresol. This was also examined for the 10% and the 20% fly ash mixes.

Figure 34: Effect of Concresol addition on Fly Ash mixes
It appears that the FA 30% + 0.5% Concresol has the higher flow, while its Green Strength (2.8 kPa) is comparable to that of the reference mix (3.4kPa). The other fly ash mixes exhibit a lower flow diameter and a lower Green Strength than the reference mix. In conclusion, the FA 30% + 0.5% Concresol mixture seems very promising and will be further investigated.

4.1.5 Summary of effects of materials tested

Below are summarized the effect on flow and green strength of the different materials used.

<table>
<thead>
<tr>
<th>Name</th>
<th>Effect on Flow</th>
<th>Effect on Green Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actigel</td>
<td>Increases</td>
<td>Increases</td>
</tr>
<tr>
<td>Metamax</td>
<td>Increases</td>
<td>Same</td>
</tr>
<tr>
<td>Concresol</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>Increases</td>
<td>Decreases</td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>VMA</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
<tr>
<td>PP fibers</td>
<td>Decreases</td>
<td>Increases</td>
</tr>
</tbody>
</table>

Figure 35 Summary of addition effect of materials
4.2 *Experiments with 10 mm coarse aggregates*

4.2.1 *Green Strength vs. Flow*

For all the mixes described above, the relationship between the Green Strength and the Flow is shown in Figure 36 below. For the majority of the mixes, it can be noticed a general trend, i.e. the higher is the flow at 25 drops, the lower is the Green Strength. However, a few mixes do not follow this general trend and have both a high green strength (>2 kPa) and a high flow after 25 drops (>6.5 inch). These mixtures should then be investigated further and tested with the mini-paver test as they may correspond to low compaction energy concrete.

![Figure 36: Green Strength vs. Flow at 25 drops](image)
4.2.2 Yield Stress vs. Viscosity

A rheological study was carried out to study how the Bingham parameters, i.e. Yield Stress and Viscosity would vary for the mixes that we tested so far. The results are plotted below.

The results, as expected, differed significantly from one mix to the other. The range of the viscosity was: 0.11 Pa*s\(^{-1}\) – 0.77 Pa*s\(^{-1}\), whereas the yield stress varied from 0 to 6.7 Pa.

The mixes that could be potential candidates for use in low compaction energy concrete correspond, in figure 37 below, to the mixes that are in the middle part of the chart, i.e. exhibit a viscosity between 0.38 and 0.59 Pa*s\(^{-1}\), while their yield stress is in the range 4-5.8 Pa. In conclusion, mixtures that combine good flow properties and a high green strength have a yield stress and a viscosity that fits in the rectangular area defined above and represented in Figure 37.
4.2.3 Self-compactibility of selected concrete mixes (loose vs. vibrated)

So far, seven mixes were selected as they could require low compaction energy. Those mixes were compared to the Iowa mixture and are listed below:

1. Iowa
2. Reference mix
3. Reference mix + Air Entrainer
4. Reference mix + 1% Actigel
5. Reference mix + 1.5% Concresol
6. Reference mix + 1.5% Metamax
7. Reference mix + 0.039% VMA
8- 30% Fly Ash (replacement weight of cement in the reference mix)

In order to determine how compactable those mixes are, 6 cylinders were cast for each mix, where 3 cylinders were filled with loose concrete and 3 cylinders were filled with loose concrete and vibrated for 30 seconds on a vibration table. All the cylinders (8*3*2=48) were then cured in a 100% humidity curing room. The compressive strength of the two sets of cylinders was then measured at 1, 7 and 28 days.

![Figure 38: 1 day compressive strength for loose and vibrated cylinders](image)
As it was expected, for most of the mixes, the compressive strength was higher for vibrated cylinders than for loose ones. However, it is important to notice that the difference between loose and vibrated cylinders is more than twice for the Iowa mix, while it is much less for the selected mixtures (cf. figure table below). The ratio of compressive strength Loose/Vibrated is close to 1 for the selected mixes, which indicates...
a low compaction energy requirement, as the compressive strength is directly related to the packing density of the concrete.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Ratio Loose/vibrated at 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>0.44</td>
</tr>
<tr>
<td>Ref</td>
<td>1.06</td>
</tr>
<tr>
<td>AE</td>
<td>0.99</td>
</tr>
<tr>
<td>Actigel</td>
<td>0.80</td>
</tr>
<tr>
<td>Concresol</td>
<td>0.90</td>
</tr>
<tr>
<td>Metamax</td>
<td>1.06</td>
</tr>
<tr>
<td>VMA</td>
<td>0.77</td>
</tr>
<tr>
<td>FA 30%</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Figure 41: Ratio of compressive strengths Loose/ vibrated at 28 days

The fact that the compressive strength of some mixes is higher for loose cylinders can be due to some inaccuracy in the testing process, but mainly indicates that the mixes have very low compaction energy requirements. The best mixes, by considering this parameter, are the Reference + 1.5% Concresol, the Fly Ash 30%, the Reference + Air Entrainer, the Reference and the Reference + 1.5% Metamax ones.

All the mixes, but the Iowa one, exhibited a “loose” compressive strength higher than 38 Mpa. The highest values of compressive strength were obtained for the base mix, the base mix + 1.5% Metamax and the Fly Ash 30% mix.

Those results, which are directly related to the packing density and to the binder of the concrete studied, should be related to the particle size and shape of the fine materials tested, in the last part of this thesis.
4.3 Experiments with 25 mm limestone coarse aggregates

4.3.1 Drop table and Green strength tests

To measure the flowability of the concrete mixtures containing limestone coarse aggregates, another drop table was used. This drop table which has a rectangular form of 700mm x700mm is shown below in Figure 42.

![Drop table test for mixes with 25mm limestone aggregates](image)

**Figure 42: Drop table test for mixes with 25mm limestone aggregates**

It is made of two plates. The top plate can be lifted and moved up and down. The concrete is placed on the top plate, in a cone. Then the cone is lifted, the slump of the concrete measured, as well as its initial diameter. Then 15 drops are applied by lifting and dropping from 40mm height the top plate and the final diameter of the concrete is then measured.

The first step here was to determine the amount of limestone coarse aggregates to put in the mix, in order to get the same flow and shape stability properties as for the 10 mm aggregates.

The plots below show the results of the drop table, the slump and the shape stability tests for limestone aggregates mixtures and those results are compared to the 10 mm aggregates results.
The challenge was to get to similar properties than the ones obtained with the 10 mm aggregates. With the same amount of limestone aggregates, the flow was comparable for the Fly Ash mix (48 cm compared to 50 cm) but the mix was not shape stable.

Then in order to make the Fly Ash mix shape stable, the mix design was slightly changed by adding some limestone aggregates (in order to keep the same paste): 5% more and 10% more aggregates (in weight) than in precedent mixes. The results are given below:

**Figure 43:** Drop table test for same mix design: same amount of limestone aggregates (in weight)

**Figure 44:** Drop table and Green Strength tests with limestone aggregates (10% more).
Figure 45: Drop table and Green Strength tests with 25mm aggregates (5% more)

Figure 46: Improvement of the Fly Ash mix with clays and MgO.
Figure 47: Improvement of the Fly Ash mix with PP fibers.

By adding more coarse aggregates, the flow diameter decreased for the Fly Ash mix, while it became shape stable. For this mix and for 5% coarse addition, the flow at 15 drops is equal to 46 cm (compared to 50 cm) and the green strength is 0.8 kPa (compared to 0.9 kPa). Those values are, for 10% coarse addition, respectively 43 cm and 0.8 kPa. The best mix appears to be the 5% addition, as it has comparable flow and green strength to the Fly ash mix with 10 mm coarse aggregates. The values of the slump are also comparable.

The addition of the clays and MgO to the fly ash mix increased the Green Strength. The highest value was obtained for the actigel mix (2.4 kPa), while the lowest value was obtained for the Metamax mix (1.3 kPa). The highest flow value was reached with the concresol mix (44 cm) when the lowest one was measured with the MgO mix (41 cm). The best compromise Flow/Green Strength was obtained with the actigel mix (43 cm/ 2.4 kPa), followed by the concresol mix (44 cm/ 1.4 kPa).
The addition of polyprolyne preserved the flow, when the Green Strength increased significantly (1.6 kPa compared to 0.8 kPa for the plain fly ash).

4.4 Results of consolidation test

The selected mixes were then tested with the mini-paver, which corresponds to our most important and last test. The experiments were carried out in two phases, according to the type of coarse aggregates used.

4.4.1 Mini-paver test with 10 mm coarse aggregates

4.4.1.1 Selected mixes based on Reference mix

Ten concrete mixtures were tested with the mini-paver, i.e. 1-Reference mix, 2- 1+ Air Entrainer, 3- 1+ 1% Actigel, 4- 1 + 1.5% Metamax, 5- 1 + 1.5% Concresol, 6- 1 + 0.039% VMA, 7- Iowa, 8- 30% Fly Ash, 9- 1 + 2% MgO, 10- 1 + 0.1% Polypropylene fibers.

In this paving simulation process, all the selected mixes have succeeded, except the Iowa mix, which could be expected as it was not designed for slip-form paving.

Pictures of the pavements obtained as well as results of tests on hardened state pavements are given below.
Figure 48: Reference

Figure 49: Fly Ash 30%

Figure 50: VMA

Figure 51: Iowa
Figure 52: Metamax 1.5%  
Figure 53: Concresol 1.5%  

Figure 54: Actigel 1%  
Figure 55: Reference Air Entrained
The Iowa mix exhibits the worst surface quality, as it has the highest SQI (83.2 cm$^3$/cm$^2$). This is due to the reason given above. However, it has the best shape stability, as it exhibits the lowest Edge Slump.

Considering the flexural strength, the Iowa Department Of Transportation (DOT) requirements are 4 MPa for the Modulus Of Rupture (MOR). This is fulfilled for eight of
our mixtures. The only ones that are below this value are the Iowa mix (3.7 MPa, due to the lack of vibration) and the 30% Fly Ash mix (3.92 MPa). The best compromises are obtained with the Actigel and the concresol, as they both have low edge slump, the best surface quality and they both meet the DOT MOR requirements.

In conclusion, the selected mixes were successful at the mini-paver test. They were shape stable (their edge slump was acceptable) and their surface was smooth enough. All of them, but the Fly Ash mix, fulfilled the mechanical requirements. The Fly Ash mix requires further work.

4.4.1.2 Improvements of the Fly Ash mix

As it was discussed in section 4.1.4, the Fly Ash mix was optimized in order to improve its shape stability. The non-optimized Fly Ash mix did not perform as well as the other mixes for the flexural strength.

The optimized mix was (according to figure 30 in section 4.1.4): 30% Fly Ash + 0.5% Concresol. The mini-paver test was successful, as shown in the picture and the chart below:
Figure 59: Improved Fly Ash properties

As it can be noticed, this improved mix exhibits better shape stability (lower Edge slump), better surface texture (lower SQI) and better flexural strength than the 30% Fly Ash mix.

4.4.2 Mini-paver test with 25 mm coarse aggregates

4.4.2.1 Mixes tested:

Seven concrete mixtures were selected for the mini-paver test. They are:

1- Fly Ash 30%, w/b=0.39 (+ 5% coarse aggregates),
2- Fly Ash 30% + 0.5% Actigel, w/b=0.4 (+5% coarse aggregates)
3- Fly Ash 30% + 1.5% Metamax, w/b= 0.39 (+5% coarse aggregates)
4- Fly Ash 30% + 0.5% Concresol, w/b=0.39 (+5% coarse aggregates)
5- Fly Ash 30% + 2% MgO, w/b=0.4 (+5% coarse aggregates)
6- Fly Ash 30% + 0.1% PP fibers, w/b=0.4 (+5% coarse aggregates)
7- Fly Ash 30%, w/b= 0.39 (+10% coarse aggregates)

The pictures of the mixes are given below, as well as their hardened state properties.

Figure 60: FA 30%

Figure 61: FA 30% + Concresol 0.5%

Figure 62: FA 30% + Metamax 1.5%

Figure 63: FA 30% + Actigel 0.5%
4.4.2.2 Properties of the mini-pavements

In the following chart (Figure 66) are presented the results of the Surface Quality test, the 3-point bending test and the edge slump for the mini-pavements mentioned above. All the mixes tested met the Iowa DOT flexural strength requirements (MOR > 4 MPa). The highest MOR was obtained for the MgO mix (6.26 MPa), and the lowest for the Metamax mix (4.38 MPa). The most stable mix in terms of edge slump was the actigel mix (1.1mm edge slump) and the best surface quality was obtained with the metamax mix.

As it appears, the best compromises are obtained for the concresol, the metamax and the MgO mixes.
4.5 Relationship between consolidation properties and hardened state properties

4.5.1 Compression of cubes from mini-pavements

The cubes obtained from the mini-pavements were tested in compression, at 7 and 40 days. As shown in the charts below, the results were in the same range for all the mixes but the Iowa one (41 MPa-51 MPa at 7 days and 61 MPa- 81 MPa at 40 days). The Iowa mix, at it was expected, exhibited much lower compressive strengths: 18 MPa at 7 days and 30 MPa at 40 days. The highest strength at 40 days was obtained with the Concresol mix: 81 MPa. This was completely expected as this mix had the highest Green Strength among all the mixes selected for the mini-paver test.
4.5.2 Comparison of cylinders vibrated-loose to cubes

The following plots (Figures 67 to 69) compare the results of the compressive tests for cylinders (loose and vibrated) vs. the ones for the cubes from the pavements.

![7-day compressive strengths](chart)

**Figure 67:** Compressive strength for Loose/ vibrated cylinders and paved cubes at 7 days
The compressive strength of the paved cubes is higher than the one of the cylinders (except for the Iowa mix) due mainly to the size effect. Since paved specimens are cubic and have smaller dimensions, their compressive strength is higher than well vibrated specimens.

The chart below compares the ratios of compressive strengths: $f_c$ paved/ $f_c$ loose and $f_c$ paved/ $f_c$ vibrated for the eight mixes.
Figure 69: Ratio of compressive strengths for paved, loose and vibrated specimens

Those ratios demonstrate the suitability of selected concrete mixture for slip-form paving. The higher the ratios $f_{c, paved} / f_{c, vibrated}$ and $f_{c, paved} / f_{c, loose}$ are, the more suitable the mixes are. The mixes with the three clays appeared to be the most satisfactory for slip-form paving process.

4.6 Relation between Flow and Shape Stability (Green Strength, Flow, Edge Slump, Air Content, Yield Stress, Viscosity)

The purpose of this section is to relate the rheological parameters (Yield Stress and viscosity) of the studied mixes as well as their edge slump and air content to their
flowability and Green Strength. In the following charts, a correlation was found between the yield stress, the viscosity and the green strength.

4.6.1 Relation between Yield Stress, Viscosity and Green Strength

The mixes that were selected exhibited an interesting property: the higher was their viscosity, the greater was their yield stress and these parameters varied linearly. A correlation was also established between yield stress, viscosity and green strength. Therefore, it appears that, for the selected mixtures, these three parameters are linked. The higher are yield stress and viscosity, the greater is the green strength. Such a correlation could not be established with the flow diameter.

![Yield Stress vs. Viscosity](image)

**Figure 70: Yield Stress vs. Viscosity**
Yield Stress vs Green Strength

$$y = 0.2803x + 3.8927$$
$$R^2 = 0.7143$$

Figure 71: Yield Stress vs. Green Strength

Viscosity vs. Green Strength

$$y = 0.0447x + 0.3028$$
$$R^2 = 0.8162$$

Figure 72: Viscosity vs. Green Strength
4.6.2 Air content

The air content of the seven mixes with limestone aggregates was measured. The procedure used was the following: after filling the cylinder used to measure the green strength, the concrete inside the cylinder was compacted by 20 drops. Before demolding the cylinder, the height of the concrete inside the cylinder was measured. This value enabled to calculate the volume of the compacted concrete. Knowing its mass, which was also measured, the air content of the concrete was determined.

The results for the seven mixes are given below:

<table>
<thead>
<tr>
<th>Mix</th>
<th>Air content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>0.5%</td>
</tr>
<tr>
<td>Actigel</td>
<td>2%</td>
</tr>
<tr>
<td>MgO</td>
<td>1.5%</td>
</tr>
<tr>
<td>PP fibers</td>
<td>0.5%</td>
</tr>
<tr>
<td>Meta</td>
<td>0.1%</td>
</tr>
<tr>
<td>Concresol</td>
<td>0.5%</td>
</tr>
<tr>
<td>FA 30%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

![Air content of compacted concrete after 20 drops](image)

Figure 73: Air content of compacted concrete after 20 drops

It appears that the mixes which had the best compromise surface quality/edge slump (Metamax, Concresol and MgO) have a air content in the range 2%-3.6%.
4.7 Microstructural analysis

4.7.1 Scanning Electron Microscopy (SEM)

The Scanning Electron Microscope is a type of electron microscope which is capable to produce high resolution images of a sample. Electron microscopes use electrons instead of light and glass lenses for conventional light microscope to magnify images. The images obtained with SEM have a large depth of field (can focus on rough surface) and are more detailed than the ones obtained with light microscopes as the magnifications used can be much higher.

The sample is placed inside the microscope’s vacuum chamber, and the air inside the chamber is pumped out.

Then, an electro-gun located at the top of the chamber emits a beam of high energy electrons. The electrons emitted are condensed by the condensing lenses and the objective focuses the scanning beam onto the desired part of the specimen. Some electrons are knocked loose from the surface of the sample and a detector counts these electrons. This information is then sent to an amplifier and the final image is built up from the number of electrons detected.
4.7.2 Shape and size of particles

The following fine materials were analyzed with SEM: Actigel, Concresol, Metamax, Fly Ash class F and Magnesium Oxide. The following images were obtained and show the particles shape and size.

Actigel:

As it can be observed, the particles have a spherical shape, with an uneven surface texture. Some of them have a hole in the middle. Their size varies from 10µm to 100µm. The second picture is a 100x close-up of one particle surface. It appears that its surface is made of innumerable needles; it will be referred to this characteristic in the next section, to understand some flow properties of Actigel mixes.
Figure 75: Actigel particles

Figure 76: Close view of an actigel particle

Conresol:

The following picture illustrates the cottony aspect of Conresol particles, with a particle size of about 5 to 15µm. It can be noticed that some particles are slimmer than others.
Figure 77: Concresol particles

Metamax:

Metamax particles are about 5µm long, with some needles on their surface.

Figure 78: Metamax particles

Fly Ash:

The particles are spherical, with a size ranged between 5 and 20µm. Their surface is characterized by its smoothness.
Figure 79: Fly Ash particles

Magnesium Oxide:

The following picture shows a cottony aspect of the particles, with a size of about 10 µm.

Figure 80: Magnesium Oxide particles
Summary of materials properties:

<table>
<thead>
<tr>
<th>Name</th>
<th>Average particle size</th>
<th>Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actigel</td>
<td>65 µm</td>
<td>Spherical; Surface made of innumerable needles</td>
</tr>
<tr>
<td>Concresol</td>
<td>13 µm</td>
<td>cottony</td>
</tr>
<tr>
<td>Metamax</td>
<td>3.5 µm</td>
<td>Some needles on their surface</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>24 µm</td>
<td>Spherical</td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>13 µm</td>
<td>cottony</td>
</tr>
</tbody>
</table>

Figure 81: Materials properties

4.7.3 Effect of processing on Actigel mixes

The effect of mixing time on the flowability of Actigel mixes was studied, both on mortar and concrete. The mixer used had a 5 dm³ capacity bowl, and the coarse aggregates used for the concrete mix were the 10 mm ones.

For the mortar study, three different mixing times were examined: 2, 4 and 6 minutes.

The material used was different for each experiment.

As shown below, the flow increased with the mixing time. For a 2 minutes mixing, the flow at 25 drops was 6.5 in, whereas it was about 8.25 in for 4 minutes and 8.5 in for 6 minutes.
For the concrete study, two different mixing times were analyzed: 4 and 6 minutes. The same trend was noticed: for 4 minutes, the flow at 25 drops was around 5.65 in. compared to 5.9 in. for 6 minutes.

This behavior can be explained by the texture of the Actigel particles surface. The needles that constitute this surface (cf. figure ?) require a certain amount of shear in order to dissociate, which explains why the flow increases with the mixing time. This shows that the actigel mix requires more mixing time than the other selected mixes, the flow properties can be different, depending on the mixing conditions: amount of material, mixing time and mixing speed.

Figure 82: Mixing time effect on actigel mixes (mortar)
4.7.4 Understanding of flow properties of mixes

The flow properties of actigel mixes depend on the mixing time as discussed above. The presence of bigger particles (up to 100 µm), compare to ≈15 µm for cement particles and 5 to 20 µm for fly ash and other clays) could explain why, when not sufficiently mixed, actigel mixes exhibit such a low flow.

The spherical aspect of fly ash explains why it contributes to improve the flow, when added to concrete. The finer size of concresol and metamax particles (5-10 µm) could explain why, combined to cement and fly ash, they contribute to a better shape stability. The size (10 µm) of magnesium oxide particles also enable to understand the positive effect on shape stability.
5 Conclusion and further work

5.1 Summary of project

The main objective of this project was to design a concrete mix that would be shape stable and that would not require any vibration. For this reason, the project started by studying the effect of the addition of ultrafine particles on the shape stability of Self-Consolidated Concrete, in order to take profit from the flow properties of SCC. The fine particles added were three types of nanoclays – Actigel, Metamax and Concresol – and fly ash.

Once the SCC based mixes were made stable, the study focused on the optimization of the flow and shape stability of the concrete mixes, based on the results of the drop table and the green strength tests. This optimization consisted in selecting the best amount of each material to be added, in order to obtain the best compromise in terms flow and green strength.

The rheology of numerous mixes was also examined, so as to relate the results of consolidation tests on concrete to the Bingham parameters.

5.2 Main conclusions

The main conclusions of this study can be summarized into the following points:

1. The nanoclays tested successfully improved the flow and shape stability properties of our mixes.
2. Adding Fly Ash to the base mix increased the flowability, whereas VMA, Magnesium Oxide and polypropylene fibers improved the green strength.

3. The mini-paver test was successful for the selected mixes and demonstrated that a minimum of 6.2 in. flow diameter was required at 25 drops for 10 mm aggregates and 40 cm (16 in.) at 20 drops was required for limestone aggregates.

4. The higher is the flow diameter for a given mix, the higher should be the required green strength for a successful mini-paver test.

5. Studying the rheology of cement paste for SF SCC mixes revealed a range for the yield stress (4 Pa-5.8 Pa) and for the viscosity (0.38 Pa.s⁻¹-0.59 Pa.s⁻¹) required for mini-paver test success.

6. SEM pictures enabled to relate size particle and shape of nanoclays to flow properties of corresponding mixes.

5.3 Future work

Future work should include the study of the size effect of the pavement, especially its depth and possibly its width, by realizing field testing. A better understanding of the addition effect of nanoclays on concrete should be aimed, by SEM observations on wet clay samples. The rheological study on cement paste should be completed by a study on the rheology of concrete, for a better understanding of the effect of nanoclays in concrete mixes. Finally, as one of the Iowa DOT requirements deals with durability, the freeze-thaw resistance of the optimized mixes should be examined.
6 References


