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Low Compaction Energy Concrete for Improved Slipform Casting of Concrete Pavements

by Bekir Yilmaz Pekmezci, Thomas Voigt, Kejin Wang, and Surendra P. Shah

The current practice in concrete pavement construction is to use low-slump concrete, which is processed by a slipform paving machine. Extensive vibration, introduced by equally spaced internal vibrators, is required for the concrete to reach proper consolidation. It has frequently been reported that malfunctioning internal vibrators cause over-consolidation of the concrete pavement and lead to premature cracking and durability problems. The research presented in this paper is focused on optimizing the consolidation properties and shape stability of fresh concrete mixtures so that the internal vibration may be eliminated during the slipform paving process. The experimental results have shown that it is possible to design a concrete mixture that can be consolidated without internal or external vibration and at the same time can maintain its slab shape at the end of a slipform paving process. This was achieved by selectively manipulating flowability, consolidation properties, and green strength of fresh concrete through the use of chemical admixtures or the addition of small amounts of fine materials.

Keywords: pavement; slipform; slump.

INTRODUCTION

The current practice in concrete pavement construction is to use low-slump concrete (less than 5 cm [2 in.]), which is processed by a slipform paving machine. Slipform paving is a continuous process and combines placing, casting, consolidation, and finishing the fresh concrete. The paving machine moves with constant speed over fresh concrete, which is placed on the subgrade by concrete trucks or conveyer belts. At the end of this process, the fresh concrete slab can hold its shape without any edge support.

To consolidate the stiff concrete, the slipform paving machine uses extensive vibration, which is introduced by equally spaced internal vibrators. If the vibration frequency is not set correctly or the paving machine moves too slow, these internal vibrators cause over-vibration of the fresh concrete. This leads to segregation of aggregates and a significant reduction of entrained air in the concrete along the path of the vibrators.[1] When such a pavement is subjected to heavy traffic loading and/or freezing-and-thawing cycles during its service life, so-called vibrator trails (Fig. 1) or even longitudinal cracks occur. The vibrator trails are caused by scaling of the pavement surface due to reduced resistance against freezing and thawing. Longitudinal cracking occurs along the path of a vibrator as a result of traffic loading, because over-consolidation has created a weakened plane in the pavement.[2]

To solve these problems, the development of a new concrete technology to eliminate the internal vibration during the slipform paving process is necessary. To make this possible, the concrete to be processed by the slipform paver needs to be modified to exhibit a higher workability without sacrificing its shape stability. Sufficient shape stability is critical because the edges of the fresh pavement stand free without any support after the slipform paver has passed.

The research presented in this paper is focused on optimizing the consolidation properties and shape stability of fresh concrete mixtures to allow for an improvement of the slipform paving process. The goal is to design a concrete mixture that reaches maximum consolidation at a minimum of compaction energy and maintains its shape after the consolidation process. This first requires the investigation of the flowability and consolidation properties of the fresh concrete under the effect of consolidation energy. The second is to study the shape stability of the consolidated fresh concrete, which is largely related to green strength—the strength of the freshly-cast concrete in a plastic state.

The experimental program was designed with the strategy to start with the mixture composition of a conventional self-consolidating concrete (SCC). The rheological properties of this conventional SCC mixture were then modified by different chemical admixtures and fine materials so as to reduce the concrete flowability and increase its green strength. The successful use of fine materials to modify the

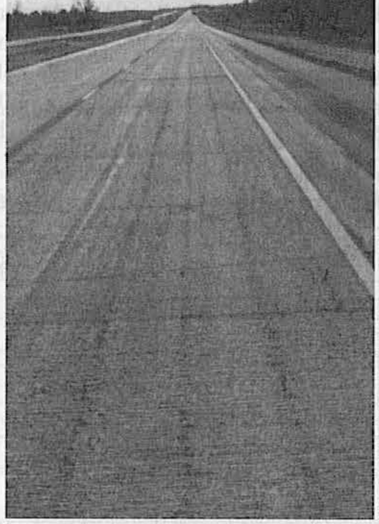

Fig. 1—Vibrator trails on concrete pavements. (Note: photo courtesy of Robert F. Steffes, National Center for Concrete Pavement, Iowa State University, Ames, Iowa.

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fresh state properties of concrete with various workability has been reported in the literature.[3-5]

The modified mixtures were tested by conventional experimental techniques for flowability and consolidation properties. A model paver, a tool specially developed for this research by Iowa State University to simulate the slipform paving process without the application of internal or external vibration, was used to verify the concrete consolidation properties and shape stability.

RESEARCH SIGNIFICANCE

The current practice in slipform casting of concrete pavements involves the use of stiff concrete that is consolidated by the paving machine by means of internal and external vibration. The use of internal vibration potentially leads to localized inhomogeneities in the concrete pavement in the form of reduced air entrainment and segregation of aggregates. During the service life of the pavement, these faults can lead to premature cracking and reduced durability. The presented research investigates possibilities to eliminate the need for internal vibration during slipform paving to overcome these problems. It is shown that the flowability of fresh concrete under the effect of external energy can be significantly increased without sacrificing its shape stability.

EXPERIMENTAL PROGRAM AND TESTED MATERIALS

Concept of investigations

The experimental program was designed with the objective to improve the consolidation properties of concrete without sacrificing its shape stability in a fresh state. As a starting point for the investigations, the mixture proportion of a typical SCC was chosen. The mixture design of this concrete is already optimized to achieve maximum flowability. Within the frame of the research described in this paper, the SCC mixture design was manipulated using fine materials and chemical admixtures to increase its shape stability. The described concept is shown in Fig. 2.

To evaluate the improvements of the newly developed mixture proportions, a concrete currently used for concrete pavements in the U.S. is used for comparison. All experiments described in this section were conducted with the modified SCC mixtures and the traditional slipform concrete.

Materials

The mixture proportions of the SCC that were used as the basis of the investigations and the traditional slipform concrete are given in Table 1. Type I portland cement was used for concrete mixture proportions. River sand and gravel with a maximum size of 9.5 mm (3/8 in.) were used as fine

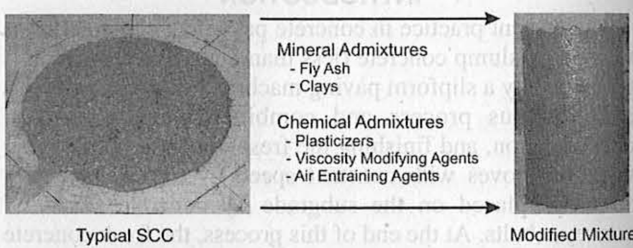

Fig. 2—Basic concept of experimental program.

Table 1—Mixture proportions of concrete

Concrete mixture	Water		Cement		Gravel		Sand		Plasticizer (naphthalene)		Additive		Density		Cylinder shape	Air content, %
	kg/m³	lb/ft³	kg/m³	lb/ft³	kg/m³	lb/ft³	kg/m³	lb/ft³	kg/m³	lb/ft³	kg/m³	lb/ft³	kg/m³	lb/ft³	Stability	
Standard SFC	151	9.4	353	22.0	897	56.0	886	55.3	3.5	0.22	—	—	2266	141.5	Good	8.3
Plain (naphthalene)	197	12.3	517	32.3	861	53.8	794	49.6	2.0	0.12	—	—	2372	148.1	Average	2.3
Plain + AE	194	12.1	509	31.8	847	52.9	781	48.7	2.4	0.15	—	—	2333	145.6	Average	3.9
Plain + VMA	196	12.2	514	32.1	855	53.4	788	49.2	3.6	0.22	—	—	2360	147.3	Good	2.9
Plain + Clay 1 (1.5%)	205	12.8	509	31.8	514	32.1	856	53.4	2.4	0.15	7.6	0.47	2424	151.3	Good	5.2
Plain + Clay 2 (1.5%)	200	12.5	513	32.0	853	53.3	787	49.1	2.4	0.15	7.6	0.47	2362	147.5	Average	2.5
Plain + Clay 3 (1.0%)	206	12.9	513	32.0	854	53.3	787	49.1	2.4	0.15	5.1	0.32	2368	147.8	Good	1.9
Plain + fly ash (10%)	197	12.3	464	29.0	848	52.9	782	48.8	2.4	0.15	51.5	3.2	2360	147.3	Poor	2.1
Plain + fly ash (23%)	195	12.2	409	25.5	851	53.1	784	48.9	2.4	0.15	119.2	7.4	2360	147.3	Average	1.8
Plain + fly ash (33%)	195	12.2	357	22.3	849	53.0	791	49.4	2.4	0.15	167.8	10.47	2351	146.8	Average	1.7

and coarse aggregates, respectively. Class F fly ash and three types of clay were used as mineral additives. The choice of the small-size coarse aggregates is based on the nature of the conducted experiments. The variety of the investigated materials called for quick and efficient experimental methods that use small amounts of material. Larger-size aggregates, as used in regular pavement concrete, would not have allowed the application of these techniques.

The chemical admixtures were plasticizers based on polycarboxylate and naphtaline-sulfonate, a viscosity modifying agent (VMA), and an air-entraining agent (AEA). More details about the admixtures used are given in Table 2. The chemical composition of the cement and fly ash is given in Table 3.

The fine materials that were used for the experiments were also investigated by scanning electron microscopy (SEM). The pictures obtained show that the fine materials cover a wide range of particle shapes and sizes (Fig. 3). The results of the SEM will later be used to find explanations for the effect of the different fine materials on flowability and shape stability of the concrete mixtures. An overview of the concrete mixtures that were designed using the aforementioned chemical admixtures and fine materials is given in Table 1.

Investigated parameters and test methods

Flowability—The influences of different fine materials on the flowability of cement paste and concrete were evaluated by a flow test and a drop table test. The flow test measures the flow diameter of a fresh cement paste or concrete after a brass cone is filled with the material and then lifted. No external force is applied in this test. The drop table test is based on ASTM C 1437.[6] It measured the flow ratio of the test material on a standard table and was subjected to 25 drops. The flow ratio is defined as the ratio of the diameter of the concrete cone at the base before and after the material was subjected to the 25 drops. This test is applied only to the materials that demonstrate the ability to maintain shape after the cone is lifted.

Shape stability and green strength—In addition to determining the material flow property, the drop table was also used to evaluate the shape stability of the tested materials after compaction. This was achieved by loosely filling a 75 x 150 mm (2.95 x 5.91 in.) cylinder with concrete, placing this cylinder on the drop table, and then applying 25 drops. The cylinder was demolded to evaluate its shape stability.

Immediately after demolding, the green strength of the cylinder was determined by applying a vertical force until the specimen collapsed. The maximum force was used to calculate the green strength of the tested cylinder.

Consolidation properties—The majority of the concrete mixtures were further evaluated for their consolidation properties. This was achieved by simulating the slipform casting process in the laboratory. For this simulation, a model paver (Fig. 4 and 5) has been developed by Iowa State University.

The slipform casting process using the model paver can be described as follows (refer to Fig. 6). The total amount of fresh concrete to be used for the experiment is placed on the (upper) loading level of the model paver. The concrete is then pushed horizontally until it falls through the vertical shaft into the forming channel and reaches the stopping bar.

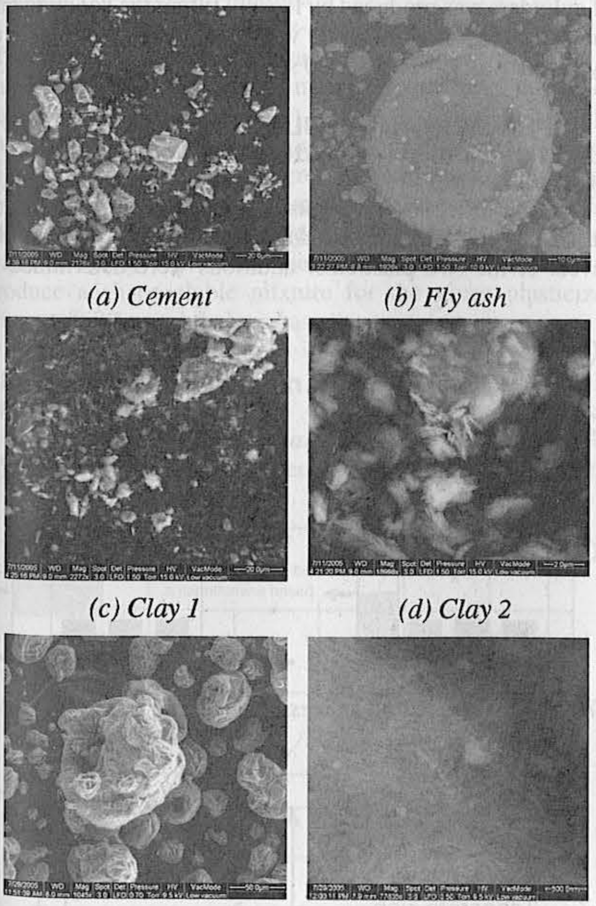

Fig. 3—Scanning electron micrographs of fine materials.

Table 2—Mineral and chemical admixtures used for manipulating flowability of concrete

Material	Description
Fly ash	Class F
Clay 1	Metakaolinite
Clay 2	Kaolinite, illite, silica
Clay 3	Purified magnesium alumino silicate
Plasticizer 1	Based on naphtaline sulfonate
Plasticizer 2	Based on polycarboxylate
Viscosity modifier	Anionic polysaccharide material

Table 3—Chemical compositions of portland cement and fly ash

	Percent	
Chemical data	Fly ash	Cement
SiO_2	49.1	20.3
Al_2O_3	23.88	4.6
Fe_2O_3	12.87	3.0
CaO	5.68	61.8
MgO	0.71	3.4
SO_3	0.92	2.9
Loss on ignition	2.37	1.3
Insoluble residue	—	0.11
Free lime	—	1.0
C_3S	—	57.0
C_3A	—	6.0
Total alkali Na_2O eq.	1.33	0.54

The stopping bar has the function to form a vertical edge of the concrete slab. No vertical force or vibration is applied to the concrete while it is moved into the shaft. The model paver is now pulled by a steel wire in a constant speed of approximately 0.5 m (19.69 in.) per minute. While the model paver moves forward, the fresh concrete passes through the forming channel and is consolidated by static vertical pressure exerted through the self-weight of the model paver. The pressure is applied continuously and uniformly over the length of the forming channel, which is accomplished by a small inclination of the forming plate toward the paving direction. The forward movement of the model paver is maintained until all concrete has moved through and left the forming channel. After the end of the slipform casting process, the produced concrete slab stands free without any edge support.

The consolidation of the concrete, which controls the quality of the concrete slab, mainly depends on: 1) how the concrete flows from the vertical shaft into the forming channel; 2) how it consolidates under the static pressure exerted by the forming plate of the paver; and 3) how it maintains the shape of the free-standing edges after the slipform casting process.

It is not clear if this paving technique could potentially be used in full scale. At this point, it is only intended to use the paver for laboratory investigations because it does not seem viable to eliminate the surface vibration that is also applied to the concrete by the traditional concrete pavers.

Edge stability and surface texture—In addition to the shape stability of the fresh concrete cylinders, the edge stability of the freshly cast concrete slabs was evaluated to obtain a more complete indication about the form stability of the concrete mixtures. The parameter used for this purpose is the edge slump S_E calculated with

$$S_E = t_c - t_{e,avg} \quad (1)$$

where t_c is the thickness of the concrete slab in the center and $t_{e,avg}$ is the average thickness of the slab at the two edges. The general principle of calculating the edge slump is shown in Fig. 7.

The surface quality of concrete slabs was evaluated and expressed in terms of the volume of the voids on the concrete surface. A defined volume of lightly colorized powder was placed on the concrete slab and spread out on its surface. The area that could be covered by powder is related to the roughness of the surface. The surface void volume per unit area was calculated and is labeled as the surface quality index (SQI). It should be noted that the SQI describes the quality of the surface as an immediate result of the slipform casting process. No further finishing techniques were applied.

Compressive and flexural strength of hardened concrete—The concrete slabs produced by the model paver were cut into smaller specimens (beams) and used for the determination of flexural strength at the age of 7 days after casting. After the flexural bending test, two cubes (9 x 9 x 9 cm [3.54 x 3.54 x 3.54 in.]) were cut from the two parts of each beam and tested in compression at the ages of 7 and 40 days.

The compressive strength of the hardened concrete made with the investigated mixtures was also tested on cylinders (7.5 x 15 cm [2.95 x 5.9 in.]) at the ages of 1, 7, and 28 days. To determine the influence of the placing condition, one set of cylinders was produced by loosely filling the concrete into the cylindrical mold with no vibration, while another set of cylinders was vibrated for 30 seconds on a vibrating table.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Effect of chemical admixtures on flowability and green strength

Type of plasticizer—Two types of plasticizer (polycarboxylate-based and naphthalene-based) were investigated. First, the levels of the two plasticizer additions were determined to

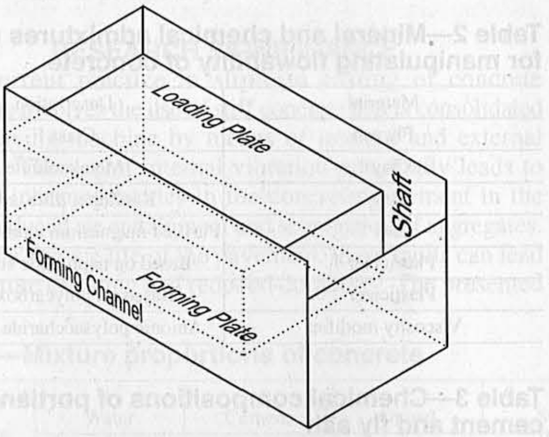

Fig. 4—Schematic of model paver developed by Iowa State University.

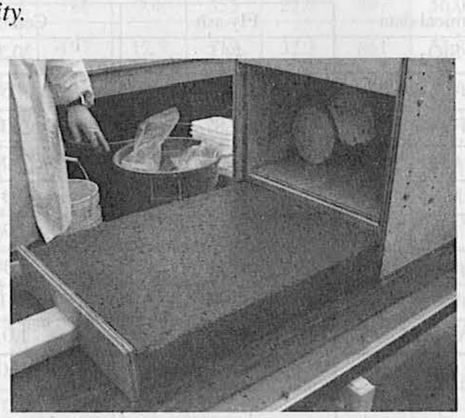

Fig. 5—Concrete slab produced by model paver.

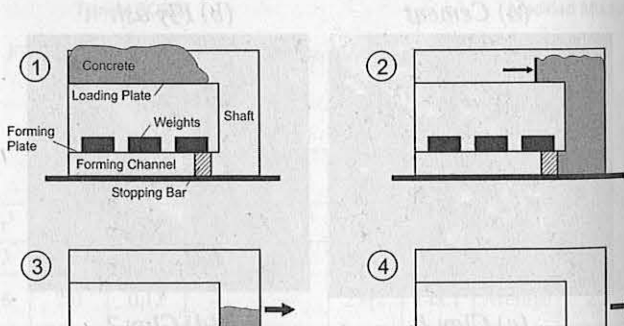

Fig. 6—Slipform casting process conducted with model paver.

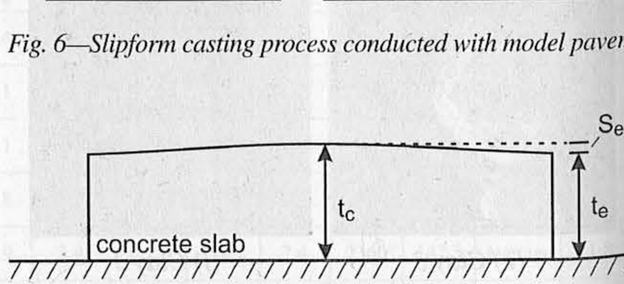

Fig. 7—General determination of edge slump.

bring a conventional SCC to a shape stable condition. This was accomplished by varying the content of the plasticizers and determining the flow ratio of these mixtures with the flow test. The results are shown in Fig. 8. By starting with a flow ratio typical for a SCC, the amount of plasticizer addition was gradually reduced until the flow ratio reached a value of zero. For the polycarboxylate-based plasticizer, the added amount was 0.1% (of cement weight), and for the naphthalene-based plasticizer, it was 0.47%. The significant difference in the amount of addition rates demonstrates the much higher effectiveness of the polycarboxylate-based plasticizer.

The second step was to investigate the effect of the plasticizer type on the flow behavior of the concrete as determined with the drop table. The tests were performed on the drop table with the two shape stable mixtures containing polycarboxylate- and naphthalene-based plasticizers, 0.10 and 0.47%, respectively, in the appropriate contents and the standard slipform mixture for comparison. From the results shown in Fig. 9, it is clear that for a given number of drops, that is, a given amount of applied external compaction energy, the flow ratio of the mixture containing naphthalene-based plasticizer is significantly higher than that of the two remaining mixtures. Despite the high flowability, the concrete containing the naphthalene-based plasticizer has an acceptable green strength and shape stability when compared with the polycarboxylate-based mixture. Due to the better flowability of the mixture containing naphthalene-based plasticizer under the effect of external energy, this mixture was then used as a reference and labeled as plain. As shown in Table 1, the later investigations in the research focused on improving the properties of this plain mixture.

Viscosity modifying and air-entraining agent—The effect of VMA and AEA on flowability and green strength is shown in Fig. 10. The plain mixture (containing 0.47% of naphthalene-based plasticizer) and the plain + AEA mixture show very similar flow ratios and green strength values. Significant improvement in green strength can be achieved by adding VMA to the plain mixture. The amount of VMA added to the plain mixture (dry powder form; 0.072% of water content) represents the amount that is needed to produce a shape stable mixture for the given plasticizer content (0.7%; naphthalene based).

Effect of fine materials on flowability and green strength

General effect of fine materials—To obtain a better understanding about the general effect of fine materials on the fresh state properties of concrete, different clays and additional cement were added to the SCC mixture and fly ash was used to replace cement with an incremental amount, as shown in Table 1. After each addition step, the flow ratio of the resulting mixture was measured at the flow table (no external force applied). The content of the individual fine materials was increased until a shape stable condition (flow ratio of zero) was measured.

The experiments have shown that the efficiency of the fine materials in reducing the flowability of the SCC mixture differs significantly. The relationship between the water-to-fine material ratio and the flow ratio is given in Fig. 11. It can

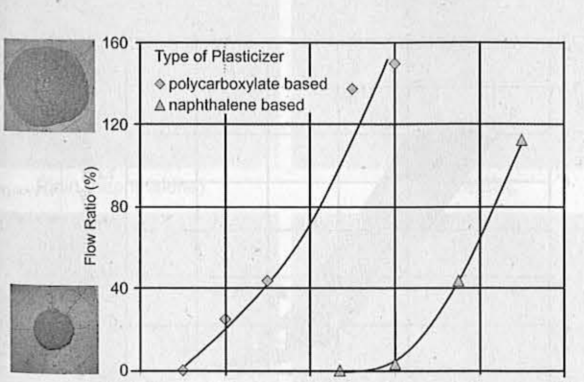

Fig. 8—Effect of plasticizer type on flowability of fresh concrete (flow test).

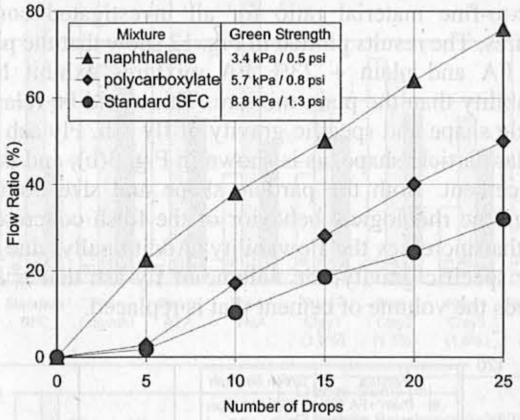

Fig. 9—Effect of plasticizer type on flowability and green strength (drop table test).

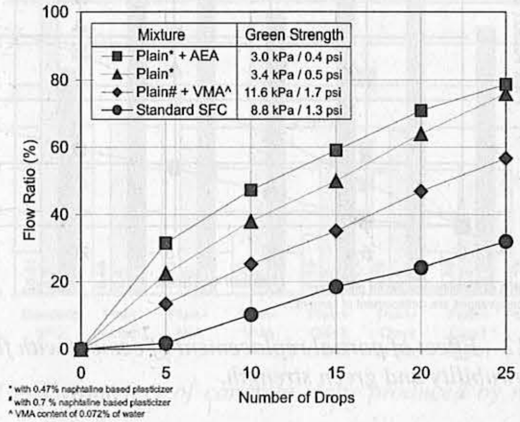

Fig. 10—Effect of air-entraining agent and viscosity modifying agent on flowability and green strength.

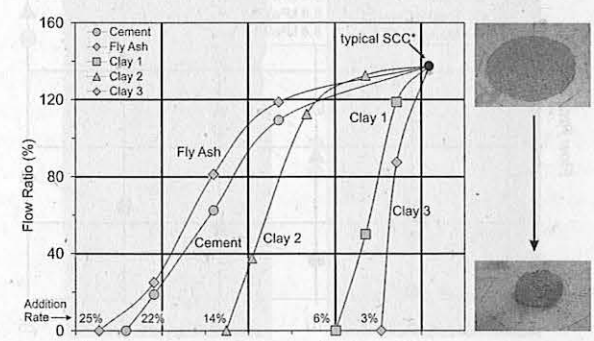

Fig. 11—Effect of different fine materials on flowability of concrete (flow test).

be seen that the addition of a very small amount of Clay 1 and Clay 3 (3 and 6% weight of the cement) causes a reduction of the flow ratio to zero, whereas the addition of a relatively large amount (14, 22, and 25%) was required if Clay 2, fly ash, and cement were used. This is attributed to the combined effect of the water absorption of the fine materials (no additional water has been added) and the particle size and particle shape of these materials.

Effect of fly ash—To investigate the effect of fly ash on flowability and green strength, the plain mixture (containing 0.47% of naphthalene-based plasticizer) was modified by replacing 10, 23, and 32% of the cement weight with fly ash. The mixture proportions were adjusted to obtain an identical water-to-fine material ratio for all investigated concrete mixtures. The results plotted in Fig. 12 show that the plain + 10% FA and plain + 23% FA mixtures exhibit higher flowability than the plain mixture. This could be related to particle shape and specific gravity of fly ash. Fly ash has a circular particle shape, as is shown in Fig. 3(b), and is finer than cement. Both the particle shape and size obviously change the rheological behavior of the fresh concrete in a way that increases the flowability. Additionally, due to its lower specific gravity, the volume of fly ash that is added exceeds the volume of cement that is replaced.

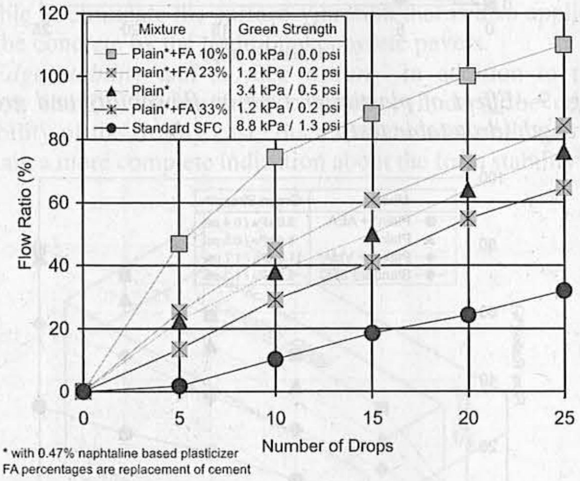

Fig. 12—Effect of partial replacement of cement with fly ash on flowability and green strength.

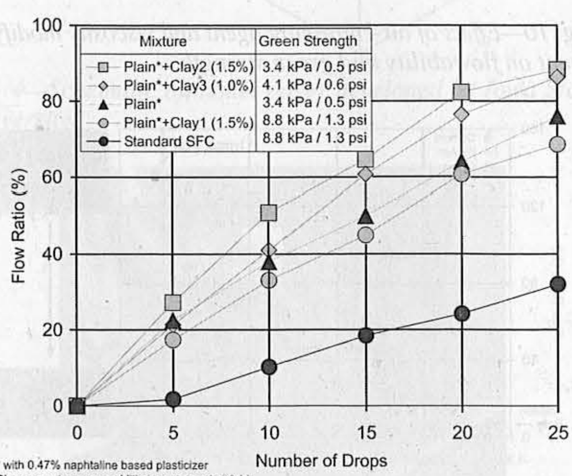

Fig. 13—Effect of clay addition (per weight of cement) on flowability and green strength.

Fly ash replacement also has detrimental effects on the green strength of concrete. At a low level of fly ash replacement (plain + 10% FA), no shape stability could be achieved, where as at a high level of fly ash replacement (plain + 23 or 33% FA), green strength of the concrete was improved.

The observed influence of partial cement replacement with fly ash is of particular interest because reducing the cement content of the mixture will be necessary for practical application. The mixture with a cement replacement rate of 33% has a similar cement content as the standard SFC mixture and will, therefore, not cause a major increase in material cost.

Effect of clay—The effect of different types of clay on flowability and green strength of fresh concrete is investigated in this section. Three different types were used in addition ratios of 1 and 1.5% of cement weight. The results plotted in Fig. 13 show that two different mechanisms can be identified. Clay 2 and 3 increase the flowability compared with the plain mixture. Despite the better flowability, the green strength is maintained at the same level. The addition of Clay 3 causes even a slight increase of the green strength. For Clay 1, on the other side, a slight decrease in flowability is accompanied by an increase of the green strength to the level of the much stiffer standard SFC mixture.

Relationship between flowability and green strength

In the previous sections, the influences of chemical admixtures and fine materials on the flowability and green strength of fresh concrete were presented. To obtain a better understanding of the principles that govern the fresh state properties of concrete, it is important to analyze the relationship between those parameters. Green strength and flow ratio measured for the mixtures discussed in the previous sections are plotted in Fig. 14. Note that the figure also includes some mixtures that are not discussed in the paper to the benefit of a better observation of the relationship.

As observed in Fig. 14, the majority of the data points follow the expected general trend that describes a sharp decrease in green strength with an increase in flow ratio. After a certain threshold value of flow ratio, the green strength becomes zero. Some mixtures do not follow this main trend, however, and exhibit higher green strength values for a given flow ratio than the general trend would predict. This is the case for the plain mixture (containing naphthalene-based plasticizer), the mixtures containing additional fine materials (clay and fly ash), and mixtures

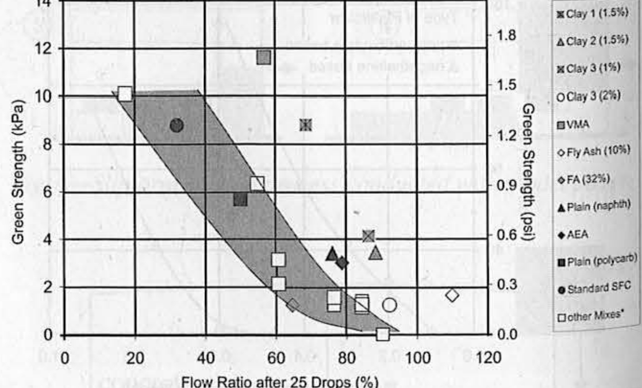

Fig. 14—Relationship between flowability and green strength for range of investigated mixtures.

with additional chemical admixtures (VMA and AEA). Further research is needed on this subject.

Consolidation properties and flexural strength

The mixtures that exhibited desirable flowability and shape stability were further analyzed in regard to their consolidation properties. This was done using the model paver (developed by Iowa State University) that simulates the slipform casting process without the use of internal and external vibration.

Photographs of the concrete slabs (fresh state) produced with the model paver are shown in Fig. 15. It can be seen that, in the absence of internal or external vibration, the newly developed concrete mixtures exhibit good surface quality and sharp edge formation indicating proper consolidation, whereas the currently used slipform paving concrete mixture (standard SFC) has poor surface quality and edge formation. The static pressure exerted by the forming plate of the model paver was not sufficient for the standard SFC to reach proper consolidation.

Edge slump, surface roughness, and flexural strength values (at the age of 7 days) of the concrete slabs produced by the model paver are given in Fig. 16. As expected from the photograph in Fig. 15, the standard SFC mixture exhibits a very high surface roughness and the lowest flexural strength. The plain (naphthalene), plain + AEA, and plain + VMA mixtures show somewhat higher values of edge slump or surface roughness, respectively. This indicates that these mixtures mark the borderline for concrete mixtures suitable for slipform casting without the use of vibration. The remaining mixtures show similar results of edge slump, surface roughness, and flexural strength.

Self-consolidatability and compressive strength

This section investigates the relationship between the consolidation properties and compressive strength of the tested materials. The compressive strength was determined on cylinders (7.5 x 15 cm [2.95 x 5.91 in.]) after 1, 7, and 28 days and for two conditions of consolidation. For one set of cylinders, no external consolidation was applied after the cylinder mold was filled with the fresh concrete. The material consolidated solely under self-weight and the parameters measured for this group of cylinders indicate the performance of the individual mixtures under the condition of self-consolidation. The second set of cylinders was subjected to

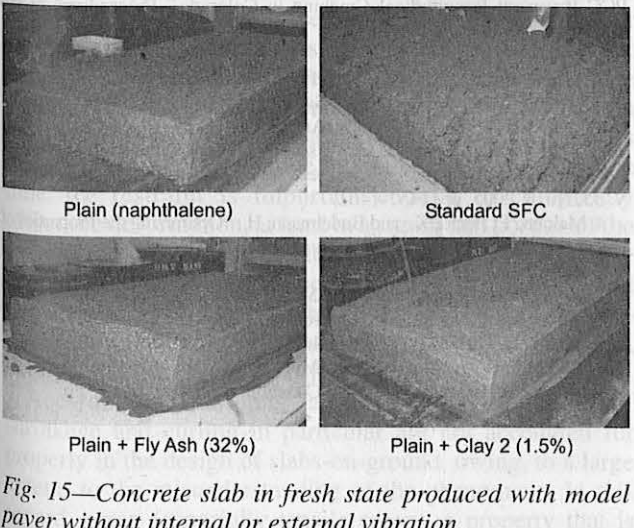

Fig. 15—Concrete slab in fresh state produced with model paver without internal or external vibration.

external vibration on a vibrating table for 2 minutes after filling the molds.

The concrete mixtures were also visually evaluated concerning their surface quality when still in a fresh state. Figure 17 shows the photographs of the standard and newly developed slipform casting concrete. The new mixture

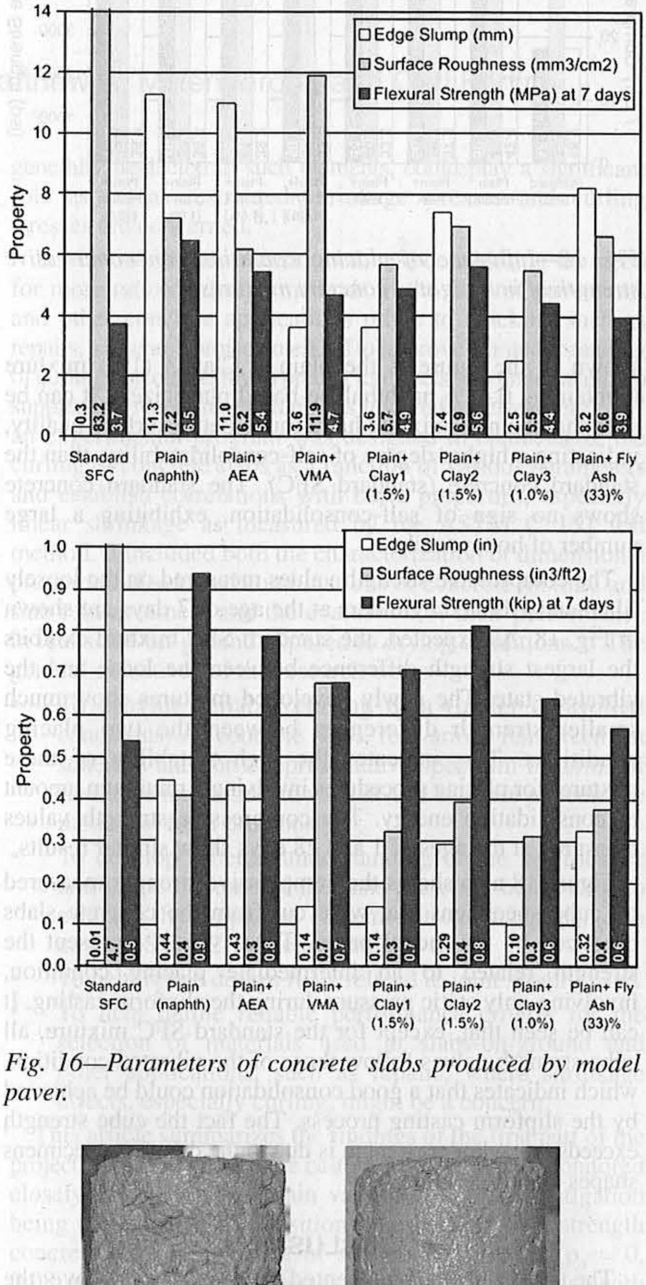

Fig. 16—Parameters of concrete slabs produced by model paver.

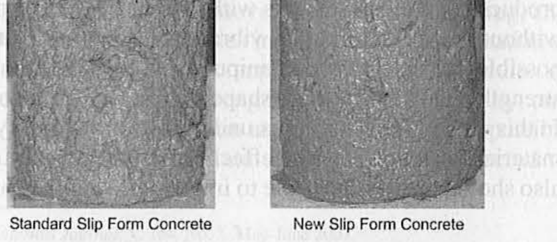

Fig. 17—Comparison of self-consolidatability of standard and new slipform casting concrete (new concrete is plain + Clay 3 [1%]).

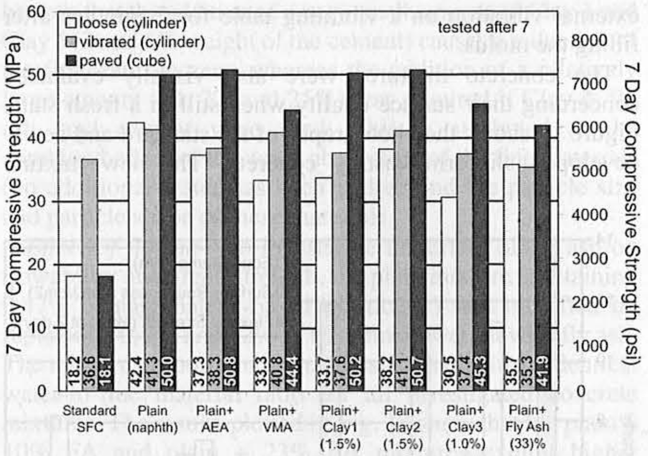

Fig. 18—Influence of placing conditions on compressive strength of investigated concrete mixtures.

shown in the figure is the plain + Clay 3 (1%) mixture (containing 0.47% naphthalene-based plasticizer). It can be seen that the new mixture has a much better surface quality, indicating a higher degree of self-consolidatability, than the standard concrete (standard SFC). The standard concrete shows no sign of self-consolidation, exhibiting a large number of honeycombs.

The compressive strength values measured on the loosely filled and vibrated cylinders at the age of 7 days are shown in Fig. 18. As expected, the standard SFC mixture exhibits the largest strength difference between the loose and the vibrated state. The newly developed mixtures show much smaller strength differences between the two placing conditions. This indicates the high suitability of these mixtures for placing procedures involving a minimum amount of consolidation energy. The compressive strength values measured at the ages of 1 and 28 days show similar results.

Figure 18 also shows the compressive strength measured on cube specimens that were cut from the concrete slabs produced by the model paver. These values represent the strength related to an intermediate placing condition, involving only static pressure during the slipform casting. It can be seen that, except for the standard SFC mixture, all cube strength values follow those of the vibrated condition, which indicates that a good consolidation could be achieved by the slipform casting process. The fact the cube strength exceeds the cylinder strength is due to the different specimens shapes and dimensions.

CONCLUSIONS

The investigations presented in this paper prove the feasibility of designing concrete mixtures that can be used to produce concrete pavements with a slipform casting process without the use of internal vibration. It is shown that it is possible to selectively manipulate flowability or green strength, which is related to shape stability, of fresh concrete. In this context, flowability is understood as the ability of the material to flow under the effect of external energy. It was also shown that it is possible to improve flowability or green strength by maintaining the other parameter at a moderate level. The following specific conclusions can be drawn:

1. The flowability can be increased while the green strength of the concrete is maintained at the same or a moderate level by using naphthalene-based plasticizer or adding Clay 2 and Clay 3;

2. The green strength can be increased while the flowability of the concrete is maintained at the same or a moderate level by using VMA or adding Clay 1;

3. Flowability and green strength of concrete can be maintained at same or moderate levels by using an AEA to achieve improved air-void structure or partial replacement of fly ash for cement;

4. The concrete mixtures modified as mentioned previously can be consolidated without the use of internal or external vibration. The self-consolidibility of the mixtures was also confirmed by the minimal differences in the compressive strength values of the concrete cylinders that were produced with and without external consolidation; and

5. By tailoring the concrete mixture proportions, a concrete mixture can be designed that can be consolidated without internal or external vibration, and, in addition, can also maintain its slab shape right after a slipform paving process. The shape stability of the concrete mixtures has been verified in the paper using the model paver that simulates slipform casting process.

FUTURE WORK

Future work to be conducted in this area needs to investigate the effect of the different additives used in combination. This may lead to further improvements of flowability and green strength. Emphasis should also be placed on the effect of the clays used on long-term mechanical properties and durability.

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