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ABSTRACT

Permeable concrete soakaways store surface rainwater and let it seep slowly into the soil. This minimizes the risk of flooding, which is an increasingly larger problem due to climate change causing heavier and heavier rainfalls. In the present study, a self-compacting pervious concrete mix design is developed to use for permeable soakaway rings. A self-compacting mix design ensures a more uniform void distribution throughout the soakaway ring compared to the use of a conventional stiff pervious concrete mix design. The study is divided into two main parts: laboratory testing, where the influence of the casting height on the void distribution is also considered, and full-scale casting of a 2.25 m high pervious concrete soakaway ring. The overall conclusion is that a successful self-compacting pervious concrete mix design was developed by carefully balancing the use of superplasticizer and stabilizer. Hereby, it was also possible to perform a successful full-scale casting.

Keywords

Pervious concrete, Self-compacting concrete, Soakaway ring

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Introduction

Due to climate change, it is becoming a global challenge to adapt especially great cities to withstand the increasingly heavier and more frequent rainfalls. During the last centuries, rainfalls in Denmark have become more and more extreme. The total annual rainfall, and also the maximum rainfall per day, have increased steadily since the first rainfall measurements in 1874 [1]. It is expected that the annual average rainfall increases even further during the next several decades [2]. From 2011-2016, Denmark experienced 21 cloudbursts, which is defined as a rainfall of at least 15 mm falling in a maximum of 30 minutes (this number has been informed by the Danish Meteorological Institute and is not to be found in any previous publications). Cloudbursts cause severe flooding, which damages infrastructure and buildings because the ground is not prepared and dimensioned for such great amounts of rain water. The costs involved with the reconstruction process are large; thus, the extreme rainfall is not only of great inconvenience for the citizens but also for municipalities and insurance companies. Hence, in recent years, research in various storm water management tools has gained increasing attention.

An efficient storm water management tool is the construction of permeable pavements capable of storing a great amount of rain water, and slowly letting the water seep into the ground. Hereby the risk of flooding is greatly minimized. The use of Portland cement pervious concrete (PCPC) for permeable pavements is an effective solution due to PCPC's high void content – typically 15-35% – providing a large interconnected void structure which gives the material a large permeability [3]. Typically, the permeability of PCPC ranges from 0.20-0.54 cm/s [3], whereas in Denmark, the maximum intensity of a rain event with a 100-year return period is just 6.5×10^{-3} cm/s [4]. PCPC obtains its large void content by having little or no fines and a well-graded coarse aggregate. The maximum void content is achieved by designing PCPC to have just enough cement paste to coat the aggregates and bind them together in the contact points between the aggregates. Thus, PCPC has a reduced amount of cement paste compared to conventional concrete. Typically, the cement paste has a low water-to-cement ratio of 0.27-0.34, which causes stiff PCPC workability. The strength of PCPC is strongly related to the void content and 28-day compressive strengths between 5.5-32

MPa are reported [5]. PCPC strength can be improved considerably by substituting a small amount of the coarse aggregate with sand and by using chemical admixtures such as superplasticizers and hydration stabilizers [6]. The freeze-thaw durability of PCPC is often a concern because of the larger voids; however, the open void structure is only critical if the voids become water saturated and freeze. The freeze-thaw durability of PCPC can be considerable improved by addition of air entrainment to the cement paste [7]. In the field, several PCPC pavements have already been installed with great success, particularly in the US, and studies show that permeable PCPC pavements can be designed to have sufficient strength and durability to resist the exposure to an outdoor environment – including exposure to freeze-thaw – for several years [8].

A different use of PCPC as a storm water management tool is to apply it to permeable concrete soakaway rings. Permeable concrete soakaways store surface runoff water and allow the water to disperse into the surroundings through the sides of the soakaway. This solution requires that the pavement is capable of directing the surface water to the PCPC soakaway rings through, for example, road soakaways. Because the permeable concrete soakaways are not directly connected to the sewer system, this reduces the pressure on it. Instead, the seeping water is dispersed locally in the surrounding filter sand [9]. If the sand reaches its infiltration capacity, water will start flowing into the soakaway. Due to their large volume, the soakaway rings can store a significant amount of water. When the surrounding filter sand becomes less infiltrated with water, the water inside the soakaway rings can again start seeping into the surroundings. An example of the soakaway system is shown in Fig. 1a where PCPC soakaway rings are placed directly below the road surface; however, in other types of construction the permeable concrete soakaway rings can be laid out next to the road instead as seen in Fig. 1b. Regardless of the type of construction, the PCPC soakaway rings are installed below the frost line and thereby frost deterioration of the PCPC is not considered a concern. Conventional concrete soakaway rings are used for the top part of the construction where freeze-thaw occurs.

Fig. 1. a) Principle in the use of PCPC soakaway rings which allow rain water to disperse into the surrounding soil. Drainpipes below the roadbed are used to lead the rain water to the soakaway. The soil around the vicinity of the

soakaway rings must be sufficiently permeable to drain the water. b) Installation of permeable concrete soakaway rings next to roadbed. From: [9].

The casting procedure of PCPC soakaway rings can be divided into two different methods:

1) *Dry casting:* PCPC has a low w/c-ratio giving it a reduced workability which means that excessive vibration is needed to compact the PCPC. This is typically done by use of a handheld electric concrete vibrator in a number of layers which depend on the total height of the soakaway. After vibration, the PCPC soakaway rings are so stable that they can be directly removed from the molds and cured under plastic until they reach the desired maturity.

2) *Wet casting:* PCPC has a low w/c-ratio but is mixed with a superplasticizer which increases its workability, reduces the construction effort, and eliminates the need for vibration; however, the PCPC soakaway rings need to remain in the molds overnight before the molds can be split and the soakaway rings can be moved to a position where they can cure under plastic until they reach the desired maturity.

PCPC soakaway rings produced in Denmark come in two sizes with an internal diameter of either 60 cm or 125 cm. Both types have a wall thickness of 10 cm. The height varies between 1-2.25 m and depends on which casting procedure is applied. Because the high void content causes the PCPC skeleton to be weaker than that of conventional concrete, it is only possible to cast the soakaway rings in heights of up to 1 m when using the dry casting method in which the mold is removed immediately after casting; however, when applying the wet casting method, the height can be increased because the soakaway rings are left in the mold overnight. An increased height of the soakaway rings is typically preferred because hereby less soakaway rings need to be assembled and because it requires less effort than when handling a larger number of soakaway rings. However, the main advantage by applying the wet casting procedure for PCPC soakaway rings is the reduced construction effort and the reduced risk for operational deviations during the compaction procedure. It is well-known that vibration of PCPC layers from above causes the void content to be inhomogeneous [10], which causes the permeability of the soakaway rings to vary with the height.

Moreover, there is a risk of over-vibration or too little vibration which all together leaves the properties of the PCPC soakaway rings very much up to the personnel placing them. Finally, due to health related considerations, handheld vibration is not desired.

In order to apply the wet casting procedure, the PCPC mix design needs to be self-compacting. Because research on self-compacting pervious concrete (SCCPC) is still limited, the use of SCCPC is also still relatively limited; however, SCCPC has several advantages compared with conventional PCPC such as the reduction in construction effort. The main challenges when working with SCCPC are to avoid the paste draining off the aggregates, and to have a uniform distribution of the voids after filling the mold without additional compaction [11].

In this study, a SCCPC mix design is developed for permeable soakaway rings. The study is divided into two main parts. In the first part, the mix design is developed and tested in a laboratory and in the second part, the mix design is used to cast a SCCPC soakaway ring in full-scale by applying the wet casting method. In the laboratory experiments, it is also considered how the casting height influences paste runoff and distribution of voids.

Experimental Method

MATERIAL PROPERTIES

All mixes were prepared with Portland cement CEM II A-LL 52.5 R with a density of 3,100 kg/m^3. The mixes used 0-4 mm fine aggregate and 8-16 mm coarse aggregate, with the gradation curves shown in Fig. 2 and the properties shown in Table 1. Both types of aggregates belonged to environmental class P [12]. Finally, two chemical admixtures were used: a polycarboxylate superplasticizer (SP), and a stabilizer (viscosity modifying agent, VMA).

Fig. 2. Gradation curves for aggregates.

Table 1. Aggregate properties.

Material	Density, kg/m^3	Water absorption, %
Sand, 0-4 mm	2,610	0.5
Coarse aggregate, 8-16 mm	2,530	2.2

MIXTURE PROPORTIONS

The mix design prepared for the laboratory tests, mix design L, had a w/c-ratio of 0.35, and a mix design void content of 20%. To improve strength, and because sand also works as VMA, 11% of the coarse aggregate was replaced by fine aggregate [11,13]. The SP dosage was 0.6% of the mass of cement, and the VMA dosage was 0.3% of the mass of cement. The dosage of SP and VMA was found by careful balancing, because too large a dosage of superplasticizer, and too small a dosage of stabilizer, caused paste runoff which is undesired. Table 2 shows the mixture proportions of mix design L.

Table 2. Mixture proportions of PCPC mix design L (laboratory specimens) and mix design F (full-scale specimens).

Material	Mix L	Mix F-1	Mix F-2
Cement, kg/m³	250.0	250.0	250.0
Water, kg/m^3	85.7	85.2	85.0
SP, kg/m³	1.50	2.30	2.50
VMA, kg/m³	0.75	0.75	0.75
Sand, kg/m^3	159.6	159.5	159.5
Granite, kg/m^3	1,392.3	1,391.9	1,391.8

The mix design prepared for full-scale implementation took its point of origin in mix design L; however, in order to achieve a satisfying workability, the SP dosage was first increased to 0.9% of the mass of cement (mix design F-1) and subsequently to 1.0% of the mass of cement (mix design F-2). Otherwise, the mix

design was similar to mix design L, as can also be seen from Table 2, which shows the mixture proportions of mix designs F-1 and F-2.

MIXING AND SAMPLE PREPARATION

Mixing and Sample Preparation of Laboratory Specimens

The mixes were prepared by first mixing the aggregates and 5% of the cement in a rotating drum mixer for two minutes to coat all aggregates with cement and thereby improve the PCPC strength [13]. Next, the remaining cement, and the water in which SP was diluted, was added to the mix and mixed for 30 seconds. Finally, VMA was added and mixed for 2.5 minutes. The mixture was allowed to rest for 3 minutes and then mixed for an additional 2 minutes before preparing the samples. Fig. 3 shows the visual appearance of the fresh SCCPC. The paste appears wet and uniform and covers the aggregates completely without draining off. Conventional PCPC typically appears much drier and rougher [11].

Fig. 3. Visual appearance of fresh SCCPC.

The specimens were prepared in 300 mm-high cylinder molds with a diameter of 150 mm. Two different placing techniques were used. In the first method, the mass of SCCPC that corresponded exactly to the volume of the mold was determined from the mix design density and placed in the mold in one layer by pouring it from the top edge of the mold. No vibration was added but the sides of the mold were hit 25 times with a rubber mallet to make the SCCPC settle. In the second method, different casting heights were considered to investigate its influence on the distribution of the voids and the paste runoff. Three different casting heights were considered: 0 cm, 80 cm, and 150 cm. The specimens referring to these casting heights are subsequently denoted "L0", "L80", and "L150", respectively. Acrylic tubes with a diameter of 150 mm and a height of either 80 cm or 150 cm were used to ensure the desired casting height by pouring the PCPC mix from the top of the tube as shown in Fig. 4.

Fig. 4. Test setup used to place SCCPC cylinders with a casting height of 80 cm. With a casting height of 0 cm, no acrylic tube was used and with a casting height of 150 cm, the acrylic tube was elongated to a height of 150 cm.

For a casting height of 0 cm, no acrylic tube was used but the SCCPC mix was poured directly from the top of the mold. When the mold was filled, the sides of it were hit 25 times with a rubber mallet to make the SCCPC settle.

For both placing techniques, the molds were split after 24 hours. Subsequently, the specimens were stored in a 20°C water basin until their maturity reached the desired level. In total, five cylinder specimens were cast for each casting height.

Mixing and Sample Preparation of Full-Scale Specimens

A 2.25 m high SCCPC soakaway ring with a diameter of 1.25 m and a wall thickness of 10 cm was cast at a Danish concrete mixing plant by using the wet casting procedure, see Section 1. The mixing plant was not set up for automatic addition of VMA; thus, VMA was added manually. The SCCPC soakaway ring was cast upside down in four steps: First, the mold was filled with approximately 15 cm conventional concrete in order to shape the very top of the soakaway ring. Secondly, the mold was filled with two layers of SCCPC of mix design F-1. Each of the layers had a thickness of approximately 0.8 m. Next, the mold was filled with one layer of SCCPC of mix design F-2, giving the soakaway ring a total height of 2.25 m. Finally, a bottom of the mold was cast with conventional concrete. When casting the soakaway ring, the SCCPC easily shoved into the mold because of its highly workable consistency. It required only one worker and a shovel to place the SCCPC. No vibration or other type of compaction was applied. The casting procedure is shown in Fig. 5. Two days after casting the SCCPC soakaway ring, it was removed from the mold without any complications.

Fig. 5. Casting procedure of SCCPC soakaway ring. a) SCCPC was shovelled into the mold. Beforehand, the bottom 15 cm of the mold was filled with conventional concrete. b) The SCCPC soakaway was cast in three layers each with a height of approximately 80 cm. c) Finishing of the third SCCPC layer. d) Placement of reinforcement mesh before the bottom of the soakaway ring was cast with conventional concrete.

To estimate the void content and compressive strength of mix design F-1 and F-2, three d150/h300 mm cylinder specimens were cast with each mix design by placing SCCPC in the cylinder mold in one layer and subsequently impacting the sides of the mold 25 times with a rubber mallet.

TESTING PROCEDURES

Flow Test

A slump flow test was performed according to DS/EN 12350-8 [14] to determine the fluidity of the SCCPC mix. The SCCPC mix was poured into a 30 cm high cone in one operation without any tamping. Next, the surplus from the top of the cone was struck off and any spilled concrete was removed from the baseplate. Finally, the cone was lifted and the diameter of flow of the SCCPC was measured when the flow had stabilized.

Determination of Void Content and Hardened Unit Weight

The distribution of voids throughout the hardened specimens cast in the laboratory was determined by cutting each cylinder into four equally long specimens of approximately 75 mm. The void content of each specimen was determined from ASTM C1754-12 *Standard Test Method for Density and Void Content of Hardened Pervious Concrete*, Drying Method A [15]. The specimens were dried at 38°C until constant weight, and then subsequently submerged in water for 30 minutes while trapped air was released by tapping the sides of the specimen 10 times with a rubber mallet. It was then possible to determine the void content, P [%], from the equation:

$$P = \left(1 - \frac{m_{38°C} - m_{sw}}{\rho_w \cdot V_{tot}}\right) \times 100\% \tag{1}$$

where:

$m_{38°C}$ = constant mass of the oven-dried specimen, kg

m_{sw} = mass of the specimen submerged in water, kg

ρ_w = density of water, kg/m^3

V_{tot} = total volume of the specimen, m^3

The hardened unit weight (UW) was determined as the ratio between $m_{38°C}$ and V_{tot}.

Determination of 28-Day Compressive Strength

There are no standards on how to evaluate the compressive strength of PCPC; thus, inspiration was found in DS/EN 12390-3 [16], which relates to conventional concrete. The compressive strength was determined on a TONI 3000 kN machine with a load rate of 7 kN/s when the specimens had a maturity of 28 days. Fibreboards with a thickness of 3 mm were placed between the cylinder specimen ends and the testing machine during testing. Before the compressive strength test was carried out, the specimens were dried at 38°C until constant weight, as described in Section 2.4.2, to determine their void content.

Results and Discussion

FLUIDITY OF SCCPC MIX DESIGNS

Table 3 shows the diameter of the flow of SCCPC mix design L, F-1, and F-2.

Table 3. Diameter of the flow, d [cm], of SCCPC mix design L, F-1, and F-2.

Mix design	L	F-1	F-2
d, cm	39	36	42

During the full-scale casting it was assessed that it was necessary to increase the amount of SP compared to that of the laboratory casting to achieve the same workability. Thus, mix design F-1 and F-2 contain 0.9% and 1.0% SP of the mass of cement, respectively, compared with 0.6% SP of mix design L. Table 3 shows that the diameter of flow for all mix designs was in the same order of magnitude; however, for mix design F-2 the visual appearance showed that the layer of paste covering the aggregates was thinner than that of mix design F-1, which could indicate paste runoff.

INFLUENCE OF CASTING HEIGHT ON DISTRIBUTION OF VOIDS

Fig. 6 shows the variation in void content throughout the laboratory specimens placed with three different casting heights. Two specimens were tested for each mix design.

Fig. 6. Variation in void content through specimens cast with a casting height of 0 cm (L0), 80 cm (L80), or 150 cm (L150). Two specimens were tested for each casting height.

Fig. 6 shows that the specimens placed with the lowest casting height (0 cm) have the greatest variation in void content throughout the specimen height, and that an increased casting height has a positive effect on the homogeneity of the cylinder specimens. The average void content is greater for a casting height of 0 cm than for a casting height of 80 cm or 150 cm. This is believed to be because SCCPC packs better when the fall energy is larger. The difference in the distribution of voids is greater when comparing a casting height of 0 cm with that of 80 cm and 150 cm; however, no significant difference is observed between a casting height of 80 cm and 150 cm.

When placing the SCCPC soakaway rings, the casting height varies between 0-225 cm because the height of the soakaway ring is 225 cm and SCCPC is poured into the mold from the top of the mold; hence, the casting height decreases when filling the mold. The results in Fig. 6 indicate that the main part of the soakaway ring can be expected to have a fairly homogenous void distribution but that the top ~30 cm (which becomes the bottom of the soakaway ring after demolding) is less homogenous and has a higher void content than the remaining soakaway ring.

COMPRESSIVE STRENGTH OF HARDENED SCCPC SPECIMENS

Table 4 shows the 28-day compressive strength of the laboratory specimens placed with three different casting heights of 0 cm, 80 cm, and 150 cm, and the specimens made when casting the SCCPC soakaway ring.

Table 4. 28-Day compressive strength, f_c, cylinder void content, P, and hardened UW of laboratory specimens (mix design L) and specimens made at full-scale casting (mix design F). The laboratory specimens were placed with three different casting heights of 0, 80, and 150 cm. Both average values and standard deviations are given. Each value in the table is based on an average of three specimens.

Mix design	L0		L80		L150		F-1		F-2	
	Av.	Std.	Av.	Std.	Av.	Std.	Av.	Std.	Av.	Std.
f_c, MPa	9.8	1.6	10.6	4.0	14.1	1.8	19.8	2.6	14.8	6.7
P, %	32.6	2.6	29.6	8.3	26.5	0.9	22.8	3.0	25.9	9.2
UW, kg/m³	1708.6	49.7	1759.2	154.4	1813.9	20.2	1895.0	39.4	1818.5	157.6

Considering the laboratory specimens, the 28-day compressive strength increases with increasing casting height which is due to the average void content of the specimens decreasing, as also discussed in Section 3.2. This is also expressed through the hardened UW, which increases with decreasing void content.

For the cylinder specimens cast in connection with the full-scale casting of the soakaway ring, Table 4 shows that mix design F-1 and F-2 have similar void contents (considering the standard deviations on the results); however, the 28-day compressive strength of mix design F-2 is less than that of mix design F-1. This is believed to be caused by the reduced thickness of the layer of cement paste around the aggregates in mix design F-2 which is due to the increased SP dosage of that mix design, see Section 3.1. This makes the concrete less dense and also weaker. Thus, future recommendation is to use mix design F-1 for the SCCPC soakaway rings.

The void content and strength results of mix design F-1 and F-2 are determined on cylinders cast with a casting height of 0 cm like specimens L0; however, Table 4 shows that the void content of specimens F is considerably lower than that of specimens L0, which indicates that mix designs F are more workable and pack better than mix design L. Nevertheless, it is expected that the cylinder specimens of mix design F-1 and

F-2 show the same variation as specimens L0 in the distribution of voids throughout the height of the specimen and that an increased casting height reduces the void content and improves the homogeneity of the specimens. Thus, when using mix design F-1 in a full-scale casting of SCCPC soakaway rings it must be expected that the average void content is slightly less than the value given in Table 4.

FULL-SCALE SCCPC SOAKAWAY RING

Fig. 7 shows the appearance of the full-scale SCCPC soakaway ring immediately after it was removed from the mold two days after casting it. The interface between the layers appears as dark circles around the soakaway ring; however, no visual difference in the void content throughout the height of the soakaway ring was observed and neither was any paste runoff. There was no difference in the visual appearance between the different layers; thus visually, it made no difference whether mix design F-1 or F-2 was used. However, as seen in Section 3.3, it is most reasonable to apply mix design F-1 for future full-scale casting of SCCPC soakaway rings.

Fig. 7. Full-scale 2.25 m high SCCPC soakaway ring with a diameter of 1.25 m.

Casting of the 2.25 m high SCCPC soakaway ring was successful in many perspectives. Firstly, the visual appearance of the soakaway ring revealed a homogenous SCCPC surface with all aggregates covered by a uniform paste. This indicates the use of a well-balanced mix design. Secondly, the improved workability of the mix design compared to conventional PCPC made it possible to avoid the use of a handheld compactor to compact the PCPC mix. Hereby the soakaway rings appear more uniform because their void distribution is controlled by the mix design rather than the personnel placing them. Finally, with the used mix design, a void content of approximately 23% or slightly less is expected (see Section 3.3), which, from other literature, is well-known to provide the soakaway rings with a high permeability, which is sufficient enough to drain a rain event with a 100-year return period (see Section 1).

Conclusions

In the present study, a self-compacting pervious concrete mix design was developed to use for permeable soakaway rings. The study was divided between laboratory testing of small cylinder specimens and full-scale casting of a 225 cm high permeable soakaway ring. The main conclusions from the study can be summarized as follows:

1) A successful self-compacting pervious concrete mix design was designed by carefully balancing the use of superplasticizer and stabilizer. For the fresh concrete, the paste appeared wet and uniform and covered the aggregates completely without draining off. Too large a dosage of superplasticizer and too small a dosage of stabilizer caused paste runoff, which is undesired.

2) For the 300 mm-high laboratory cylinder specimens, three different casting heights of 0 cm, 80 cm, and 150 cm were tested to determine the influence on the distribution of voids. For a casting height of 0 cm, the variation in void content throughout the specimens was large causing large differences in the properties of the specimen; however, for specimens placed with a casting height of either 80 cm or 150 cm, the specimens appeared much more homogeneous. Thus, the main part of the permeable soakaway rings is expected to be homogenous since the rings have a height of 225 cm.

3) A successful full-scale casting of a 2.25 m high self-compacting pervious concrete soakaway ring was carried out. The use of a self-compacting mix design made it possible to avoid the use of a handheld compactor which is normally used to place pervious concrete soakaway rings. The result is a reduced risk for operational deviations during placement and thereby, a more uniform void distribution throughout the soakaway rings.

4) The recommended mix design for permeable soakaway rings had a void content of 23% with a casting height of 0 cm and a 28-day compressive strength of 20 MPa, all without the use of vibration compaction.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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