New technique for producing vacuum concrete

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ABSTRACT

In this work a new technique is used to produce vacuum dewatered concrete. In this technique perforated PVC pipes incased in cotton cloth are used to dewater concrete from inside of concrete volume, rather than from the surface, as is the case in the conventional vacuum dewatering method. These pipes are laid in position inside concrete forms, and a vacuum pump is connected to the dewatering pipes, which is operated after casting of fresh concrete to remove the excessive water from internal portion. Properties of vacuum dewatered concrete using the new technique are investigated by a series of tests such as compressiveand flexural strength tests. Based on test results, the new technique improves concrete strength and other mechanical properties particularly at early ages. The new dewatering technique is a good alternative to the conventional vacuum dewatering technique and can have a wider range of practical applications than the conventional method.

Key words: vacuum concrete, dewatering process, compressive strength, bleeding water, water/cement ratio.

تقنية جديدة لانتاج الخرسانة المفرغة

الخلاصة

في هذا البحث تم استخدام تقنية جديدة لانتاج الخرسانة المسحوب منها الماء عن طريق التفريغ. في هذه التقنية استعملت انابيب من اللدائن البلاستيكية المغلفة بقماش قطني لسحب الماء من داخل الخرسانة بدلا من سحبه من السطح كما هو الحال في الطريقة التقليدية. يتم تثبيت هذه الانابيب في محلها في القوالب الخرسانية ويتم ربط جهاز التفريغ بهذه الانابيب ليتم تشغيل الجهاز بعد صب الخرسانة لسحب الماء الزائد منها. تم اجراء عدد من الاختبارات لدراسة و تقييم خواص الخرسانة المنتجة بهذه التقنية. وعلى ضوء نتائج هذه الاختبارات, فان التقنية الجديدة تزيد من مقاومة انضغاط الخرسانة و تحسن بقية الخواص الميكانيكية لها وخاصة في الاعمار المبكرة. تعتبر التقنية الجديدة بديل جيد للتقنية التقليدية لسحب الماء من الخرسانة ولها تطبيقات عملية اوسع من الطريقة التقليدية.

INTRODUCTION

Vacuum processed concrete which is extensively used in some countries, especially for slabs and floors [1] was first invented by Billner in the United States in 1935. In this technique (hereinafter termed the conventional technique), a filter pad is first applied on surface of freshly cast, vibrated and leveled concrete. Then, an airtight covering made of flexible mat is laid over the filter pads.

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The covering is connected to vacuum pump, and, since fresh concrete contains a continuous system of water-filled channels, the application of vacuum to the surface will result in a large amount of water being extracted from a certain depth of concrete[1]. Since the amount of water is generally is two to four times as much as the amount required for hydration of the cement, it is advantageous to remove water not needed for hydration. The removal of excess water from concrete causes compaction due to mobilization of atmospheric pressure on concrete surface. Therefore, what might be termed "water of workability" is removed when no longer needed [2]. The process is therefore reducing the final water/cement ratio of concrete before setting, which controls strength and other properties of concrete. Therefore, this technique produces concrete with higher strength and better other qualities like abrasion resistance, reduced shrinkage, lower permeability and greater durability than would otherwise be obtained. Tests showed that the required vacuum time is about 1min/5mm of concrete thickness and that only the upper 150mm of fresh concrete is affected by the dewatering process [2, 10]. Therefore, the effective duration of dewatering is about 20-30 min. The withdrawal of water produces settlement of the concrete to the extent of about 3 per cent of the depth over which the suction acts [1]. The vacuum cannot remove water needed for hydration because the capillary diameters in the cement paste decrease as the water-cement ratio decreases. This capillary constriction begins at the surface and then proceeds down-ward. Wherever the water- cement ratio decreases to about 0.30, capillary diameter becomes too small to permit passage of water under the magnitude of pressure the system induces. Thus there is no danger that the water-cement ratio will fall below 0.30, which is well above the minimum of 0.20 required for hydration of cement [3].

Vacuum concrete stiffens very rapidly so that formwork can be removed within about 30 minutes of casting even on columns 4.5m high [2, 6] . This feature is of a considerable economic importance, particularly in precast plants, as the concrete forms can be used more frequently within the same time.

Another important characteristic of vacuum-processed concrete is its high bond strength to old concrete and can therefore, be used for applying concrete overly to road slabs and in other repair work.

Permeable and absorbing formworks are other recent means of reducing water/cement ratio of concrete after casting, which is in some ways similar in concept to vacuum-dewatering[4,5]. Permeable formwork has been used on hundreds of concrete structures around the world[4]. It was reported that properly designed permeable formwork will reduce the water/cement ratio in the concrete immediately behind the formwork after the concrete is placed and vibrated, and the change can affect concrete to a depth of 25 to 50 mm. [4]. Rubaratuka (2013)[5] investigated the influence of formwork materials on the quality of surface concrete; the concrete compressive strength obtained by testing the drilled concrete cores was greater for concrete of softwood formwork and lower for concrete of steel formwork.

New dewatering technique

In the present method (hereinafter termed the new technique), vacuum dewatering is processed from inside of the freshly placed concrete rather than the surface, through perforated PVC pipes encased in moslin (cotton cloth) to prevent the removal of cement and other fine particles with water. These pipes are embedded and fastened in place in forms via reinforcement bars or any other means, a steel bar or wire can be inserted inside the PVC pipes to give the required stiffness, keep alignment, facilitate bending and prevent pipes from clogging due to external pressure during vacuum process. The steel bar or wire shall be of a diameter smaller than the inside diameter of the perforated pipe to allow the extracted water to flow easily inside the pipe. Alternatively, a perforated pipe made of hard PVC or even metallic material can be used.

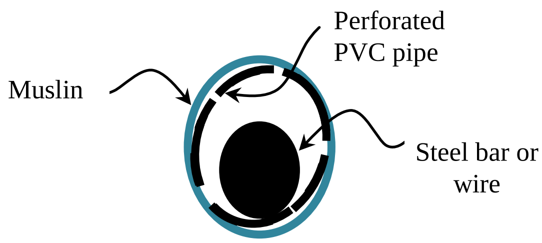

Figure (1) Cross-section of perforated dewatering pipe

The dewatering system can be multiple pipes connected directly to the vacuum pump or a net of interconnected pipes connected to the vacuum pump. A diagrammatic representation of the method is shown in Fig. 2. The present technique allows dewatering of concrete of high thickness and of almost any configuration. The vacuum dewatering process can be initiated as soon as the concrete is cast in the forms and can be done simultaneously with concrete

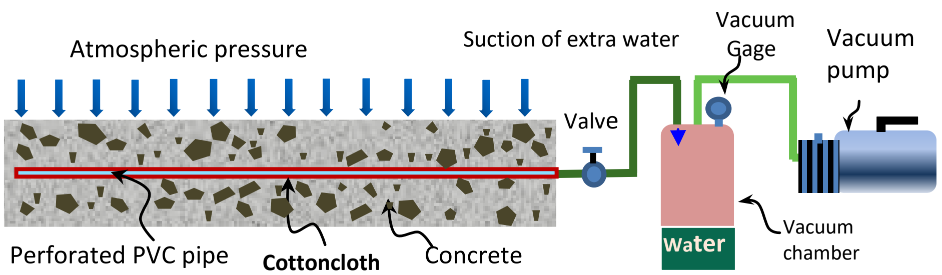

Figure (2)New vacuum dewatering technique

vibration and finishing, which is shown to yield better dewatering and compaction process. Therefore, in the new technique, most of the work is done during preparation for casting and minimum time is consumed during vacuum dewatering. The dewatering pipes are to be left in place in concrete, since they cannot be removed from rapidly stiffened concrete by vacuum process. However, these pipes are not costly, and the effect of dewatering pipes on the compressive strength is found to be negligible as the area of such pipes is small compared to the total area. In addition, the dewatering pipes can be grouted subsequently, if wanted, for very sensitive situations, i.e. water retaining structures.

Materials and methods

The materials used in this investigation were ordinary Portland cement (OPC) type 1, river sand of gradation F according to BS EN 882 and fineness modulus of 2.18, and river coarse aggregate of 20mm maximum size. Specific gravity of fine and coarse aggregates were 2.63 and 2.65 respectively. Clean tap water was used in all mixes. Electrical vacuum pump of 1.5 kW power producing vacuum pressure of 60mm of mercury was used in all tests. Concrete was cast in molds of various dimensions (150 x 150 x 750 mm, 200 x 200 x 750 mm and 250 x250 x 750 mm) using single dewatering pipes (see Fig. 1) laid along center of mold section. The molds were sealed at corners with silicon seal to simulate the condition of a continuous concrete volume around multiple dewatering pipes. Thus the cross sectional dimensions of molds represent horizontal and vertical spacing of dewatering pipes. Vacuum dewatering was started after casting the concrete. Concrete vibration was done simultaneously with vacuum dewatering process. Table vibrator was used for small (150x150x750 mm) molds and an internal vibrator (vibrating bar) was used for larger molds (200x200x750 mm and 250x250x750 mm). The volume of extracted water from fresh concrete was monitored and recorded frequently by putting the vacuum chamber on a digital weighing apparatus. Records were taken at small time intervals at the beginning of vacuum process and the time interval was increased later with a decrease in dewatering rate. For comparison purposes, control specimens were also cast and vibrated in a similar manner but without vacuum dewatering. The formwork for beams was stripped off after 24 hours and specimens were moist cured at room temperature. To measure compressive strength of concrete, core samples with 100 mm diameter and of a height / diameter ratio of 1.5 were taken and tested at different ages. The preparations and testing procedures to determine the compressive strength of the samples was in accordance with BS EN 12504-1:2000.

Experimental work

To access the proposed method and its validity and applicability, a series of experiments have been conducted. These experiments focused on the parameters affecting practical considerations and properties of concrete produced by the proposed method. The parameters studied were: Diameter of dewatering pipe and size and number of perforations per unit length of the pipe, water-cement ratio, specimen size (volume of concrete around dewatering pipe), and duration of vacuum process. Although other parameters such as vacuum pressure level, cement/aggregate ratio, grading of aggregates, finesse of cement, etc. influence properties of vacuum processed concrete, these parameters are considered of secondary importance and not studied here. Mix proportions of all mixes was (1 cement: 2.5 sand: 3.5 coarse aggregate) by weight.

To study the effect of dewatering pipe characteristics, pipes with three different outside diameters (6, 10 and 14 mm) and of 1.5 mm wall thickness were used. The number of perforations was 12, 16 and 20 holes per 100 mm of dewatering pipe in all pipe sizes. The holes were 2mm diameter and uniformly distributed on the pipe surfaces. The size of test specimens was 150x150 mm in cross section and 750 mm long. No appreciable difference in volume of extracted water was noted using three pipe sizes. Also, no further increase in volume of extracted water was recorded by increasing number of perforations by more than 12 holes per 100 mm of dewatering pipe length. Thus, for the pipe sizes used, the surface area of dewatering pipe has little effect on the volume of extracted water. However, for long dewatering pipes, which are intended to be used in practice, it is expected that the inside diameter of pipe will affect the dewatering rate, due to high discharge rate and consequent friction loses with small diameters of dewatering pipes. However, pipes with inside diameter of 7mm and outside diameter of 10 mm and with 12 holes per 100 mm of pipe length were considered as practical, and used in all subsequent tests.

Insignificant amount of cement and fine particles were extracted with water. Wet sieving of vacuum treated fresh concrete samples taken from upper, middle and bottom regions of demolded concrete showed that no replacement of cement, fine aggregate and coarse aggregate was taken place due to vacuum process. This is in agreement with the conventional method of vacuum dewatering [1]. To study the possibility of suction of atmospheric air through concrete above dewatering pipes, a mold of dimensions (150x150x750 mm) was cast with concrete having water/cement ratio of 0.5 and put in an airtight envelope made of polyethylene membrane through which, the dewatering pipe was emerged and sealed to it with an adhesive seal (see Fig. 3).No envelop contraction was noted after vacuum processing for 80 minutes, which means that no air had been sucked through concrete. This is consistent with the results obtained by the conventional method of vacuum dewatering in which, air bubbles are removed only from the surface since they do not form a continuous system [2]. Therefore, no mat or airtight covering is required to be put on fresh concrete surface during dewatering process. However both of the conventional and new dewatering techniques can be used simultaneously to remove water from surface and inside of concrete.

Figure (3) Airtight envelop around concrete specimen

To study the effect of spacing of dewatering pipes and water/cement ratio on efficiency of the process and properties of concrete produced, molds of different sizes were used. Molds were of dimensions: 150 x 150 mm, 200 x 200mm and 250 x250 mm in section and 750mm long. Concrete with same mix proportions and water/cement ratio of 0.55 were cast in each mold size. Fig. 4 shows typical curves for rate of withdrawal of water with time for different mold sizes.

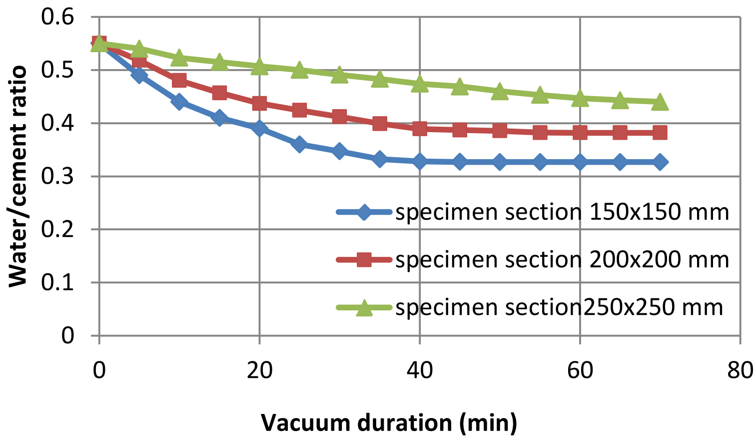

Figure (4) Relation between water/cement ratio and vacuum duration

The decrease in water content achieved by the new technique was up to 20 per cent in specimens of dimensions 250x250x750 mm. The reduction was increased to 41 per cent for 150x150x750 mm specimens. Whereas the conventional method reduces water content up to 20 per cent only, and it is usual to assume the suction in the conventional method to be fully effective over a depth of 100 to 150 mm only [2]. Therefore, the present technique gives solutions for the problem of vacuum dewatering of concrete of large dimensions.Figure 4 shows that the rate of withdraw of water falls off with time in a way similar to that of the conventional method. Little reduction in water content occurs after 40 minutes of dewatering and there is a limit for final water/cement ratio for each specimen size.The reduction in rate of water extraction is due to two reasons. Firstly,the capillary diameters in the cement paste decrease as the water-cement ratio decreasesin fresh concrete near dewatering pipes. Secondly, hydration and setting of cement paste at later times reduces capillary diameters as well. Thus, it is considered that vacuum processing during 40 minutes is practical and economical and is used in all subsequent tests.

Table 1 shows the effect of initial water/cement ratio on strength of vacuum processed concrete at different ages. Four mixes of same cement/aggregate ratio but with different water/cement ratios were cast in 150x150x750mm molds.

Core samples of 100mm diameter and 150mm height were taken from 150x150x750mm specimens. The specimens were vacuum processed for 40 minutes, and unprocessed specimens were also cast for comparison as control. To eliminate the need for capping, cores were drilled horizontally (perpendicular to height when cast). The in-situ estimated cube strength was calculated according toBS 1881: Part 120 using the following expression:

Estimated in-situ cube strength= $\frac{D}{1.5+\frac{1}{\lambda}}$xmeasured compressive strength of core.

Where

D is 2.5 for cores drilled horizontally (perpendicular to height when cast); or 2.3 for cores drilled vertically (parallel to height when cast); λ= length/diameter of core.

Table (1) Water/Cement ratio and of strength of vacuum processed concrete at different ages

W/C Ratio	Compressive strength (MPa) at age of:							
	3 days		7 days		14 days		28 days	
	Control	Vacuum Processed	Control	Vacuum Processed	Control	Vacuum Processed	Control	Vacuum Processed
0.45	8.5	25.7	17.8	29.2	21.8	39.9	25.7	43.2
0.5	8.1	21.5	14.5	24.6	18.5	32.8	21.5	37.6
0.55	7.7	13.9	12.7	21.3	14.4	32.0	18.4	37.3
0.6	7.2	16.1	9.9	16.5	12.6	33.9	16.3	35.3

The new dewatering technique increased strength by up to about 3 folds at early ages. The gain in strength is much higher than that obtained by the conventional method in which, the strength increase achieved in practical work was 25 to 40 percent [3]. The gain in strength at early ages is of considerable importance especially in precast concrete factories, where removal and reuse of formworks at frequent intervals is essential.

To investigate the early strength more exhaustively, and since core samples may be impaired by coring process at such ages, concrete specimens of dimensions 150x150x750 mm where cast with and without vacuum dewatering and tested for flexure and compression at ages of one and three days. Two points loading was used to determine modulus of rupture of specimens according to BS 1881: part 118:1993 specifications. The compressive strength of the same concrete for both vacuum processed and control specimens was determined using intact parts of beams tested in flexure. Because the beams are of square cross-section, an 'equivalent' or 'modified' cube is obtained by applying the load through square steel plates of the same size as the cross-section of the beam (150x150mm). The specimen is placed so that the as-cast top surface of the beam is not in contact with either plate. The test is prescribed by BS 1881-119: 1983. Table 2 shows flexural and compressive strength of vacuum processed and control specimens at early ages. Average values of equivalent cube strength for the two parts of each beam are shown in the table. It can be shown that the strength obtained by core samples (table 1) and equivalent cubes (table 2) at age of 3 days are consistent.

Table (2) Flexural and compressive strength of vacuum processed concrete at early ages

W/C Ratio	1 day				3 days			
	Flexural strength MPa		Compressive strength (equivalent cube) MPa		Flexural strength MPa		Compressive strength (equivalent cube) MPa	
	Control	Vacuum processed	Control	Vacuum processed	Control	Vacuum processed	Control	Vacuum processed
0.45	2.12	3.56	9.0	18.1	2.98	3.77	12.7	21.3
0.5	1.63	3.40	7.5	14.4	2.15	3.82	9.0	16.2
0.55	1.41	3.09	5.8	12.8	1.82	3.41	7.5	14.2
0.6	1.13	2.87	4.2	10.7	1.63	3.14	6.0	11.7

The effect of the process on compressive strength at early ages obtained by the new technique is consistent with those obtained by the conventional technique [8].

However, the increase in strength using the new technique is substantial and more pronounced.

Table3 shows the effect of spacing of dewatering pipes on compressive strength of core samples taken from vacuum processed and unprocessed (control) concretes at 28 days of age. Four mixes of same cement/aggregate ratio but with different water/cement ratios were cast in molds of 150x150mm, 200 x 200mm and 250 x250 mm in cross section and 750mm long, using single dewatering pipe laid along center of each mold section. Specimen sectional dimensions, as discussed earlier, represent spacing of dewatering pipes in larger concrete sections to be used in practice. Since the vacuum pressure is constant along horizontal dewatering pipes, the length of specimens does not have an effect on processed concrete properties. However, for very long and small size pipes, friction losses of extracted water may have small effect on dewatering rate along pipes at initial stages. At subsequent stages, where the dewatering rate is reduced, it is expected that the final water/cement ratio will not differ a lot along dewatering pipes. For vertical pipes, where the external pressure is increased with depth of fresh concrete, it is expected that water/cement ratio after dewatering will be lower at lower concrete sections and higher at upper concrete sections due to variation in pressure and bleeding of concrete[9].

Table (3) Water/cement ratio and strength of vacuum processed concrete for different specimen cross sections.

Before processing		**After processing**					
W/C ratio	**specimen size 150x150x750mm**	**specimen size 150x150x750mm**		**specimen size 200x200x750mm**		**specimen size 250x250x750mm**	
	Compressive strength MPa	W/C ratio	Compressive strength MPa	W/C ratio	Compressive strength MPa	W/C ratio	Compressive strength MPa
0.45	25.7	0.308	43.3	0.373	42.4	0.386	34.0
0.5	21.5	0.316	37.7	0.389	34.1	0.432	30.5
0.55	18.4	0.328	37.3	0.389	33.5	0.476	35.5
0.6	16.3	0.337	35.3	0.456	27.1	0.464	35.1

Although the water/ cement ratio is reduced remarkably in all tests, the relation between strength of vacuum processed concrete and water/cement ratio was however not consistent. This can be explained by the fact that some of the water extracted leaves behind voids, so that the full theoretical advantage of water removal may not be achieved in practice [2]. Malinowskiand Wenader(1973)[1] confirmed in tests using conventional dewatering process, that the volume of removed water is larger than the volume reduction of concrete. Nevertheless, the strength of vacuum processed concrete almost follows the usual dependence of the final water/cement ratio. The withdrawal of water produced settlement of the concrete to about 3.5 per cent of the depth of concrete for specimens of 250 mm high, and about 4 per cent for specimens of 150 mm high. In the conventional method, the ratio of settlement is about 3 per cent of the depth over which the suction acts [2].

In fact, the increase in strength on vacuum treatment is proportional to the amount of water removed up to a critical value beyond which there is no significant increase, so that prolonged vacuum treatment is not useful [2,10]. In the conventional method, the critical value depends on the thickness of concrete and on the mix proportions [3], whereas in the present technique, the critical value depends on spacing of dewatering pipes, and also on mix proportions. However, prolonged vacuum accelerates concrete setting and can be useful in precast concrete plants and other situation were rapid setting is beneficial.

CONCLUSIONS

In this study a new vacuum dewatering technique is used to extract excess water from inside of concrete volume rather than the surface. Based on tests conducted to study the parameters affecting practical considerations and properties of concrete produced by the proposed method, the following conclusions were made:

1. The new technique is a good alternative to the conventional vacuum dewatering technique, and is suitable and more convenient for concrete of high thickness and large dimensions.
2. Perforated PVC pipes of 10mm outside diameter enclosed in cotton cloth can be used as practical artificial drains to consolidate concrete and improve concrete properties by vacuum process.
3. The most suitable and practical spacing of dewatering pipes for concrete of large dimensions is 200-250 mm.
4. Vacuum duration depends on spacing of dewatering pipes and cement/aggregate ratio, for spacing of 200-250mm, vacuum processing during 40 minutes is convenient.
5. The new vacuum dewatering technique stiffen concrete very rapidly and increase early strength of concrete by 2 to 3 folds, which is of considerable economic value, particularly in a precast concrete factories.
6. The new technique can be used simultaneously with the conventional dewatering technique to extract excess water from inside and surface of concrete, using one vacuum pump for both processes.
7. The new dewatering technique increases preliminary work before concrete casting, but save work and time during concrete casting in comparison with the conventional method.

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