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ScienceDirect
Cement and Concrete Research 36 (2006) 1444 – 1452
Cement and Concrete Research

Automated air void analysis of hardened concrete — a Round Robin study

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Received 8 August 2005; accepted 5 March 2006

Abstract

The RapidAir is an automatic system for analysing the air void content of hardened concrete. The analysis requires polishing of the concrete surface as described in ASTM C 457 as well as a contrast enhancement of the surface. The system can automatically analyse the air void system according to the ASTM C 457 and EN 480-11 standards.

The sample preparation includes contrast enhancement steps ensuring white air voids in black concrete (aggregate and paste). For a well-lapped sample of good quality concrete the contrast enhancement procedure requires approximately 5–10 min to perform. The air content can be analysed in less than 15 min traversing 2413 mm (95 in.) — a significant improvement compared to several hours normally required to perform a manual linear traverse analysis.

This paper describes the method and technique required for automatic analysis using the RapidAir system as well as data from a Round Robin study. Three samples were circulated to 7 different laboratories for automatic air void analysis. Prior to the automatic analysis the samples were analysed manually using linear traverse and point counting methods. The results of the Round Robin study showed very good repeatability and reproducibility of the RapidAir system but large variations when using manually performed analysis.

Keywords: RapidAir; Concrete; Characterization; Image analysis; Pore size distribution

1. Introduction

A prototype RapidAir system was already developed in the early 1990s. This system, which was DOS software based, was at that time used at three laboratories. Technically much advancement has been made since the early 1990s and in 2002 a new and updated Windows software based RapidAir system was developed with new hardware. Today RapidAir systems are present at companies and universities across the world. Of these places 7 laboratories agreed to be part of the present Round Robin air void analysis study.

Three samples were lapped by one laboratory and send out for air void analysis following ASTM C 457 [1]. The first 2 laboratories did modify point count and linear traverse analysis directly on the lapped concrete surface. After finishing linear traverse at the second laboratory the samples were coloured black (ink) and white powder ($BaSO_4$) was filled into the voids. The samples were then analysed using the automatic system and shipped to the other laboratories participating in the test.

This test was initiated mainly to test the repeatability and reproducibility of automatic air void analysis using the automatic system as well as to compare these data to manually obtained results. Lately the manual test methods, modified point count and linear traverse according to ASTM C 457 have been the subject to many discussions. The manual methods are very time consuming and judgement calls are involved. There is a

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doi:10.1016/j.cemconres.2006.03.005

Table 1
Testing program followed by the participators

Lab	Time scale	Crinding and lapping	Manual point count	Manual line traverse	Black & white sample prep.	Automatic line traverse ASTMC 457
Lab 6	START	X				
Lab 1	↓		X	X		
Lab 2				X	X	X
Lab 3						X
Lab 4						X
Lab 5			X			X
Lab 6						X
Lab 7						X
Lab 1	END					X

need for new methods to perform these analyses and therefore the commercially available RapidAir system was chosen for this Round Robin study of automatic analysis.

The RapidAir system has already proven its accuracy in an earlier study by [2]. In that study, which was different from this study, samples already used in a finalized European study published by [3] was lent out in order to analyse them once by one laboratory using RapidAir. The study on the European samples showed that the repeatability expressed in terms of standard deviations of the measured total air contents, specific surfaces, and spacing factors of the RapidAir measured systems were at least as good as the repeatability values provided in ASTM C 457.

2. Sample preparation and analysis procedures

As described earlier several laboratories participated in the study. The tests performed by various laboratories are outlined above (Table 1).

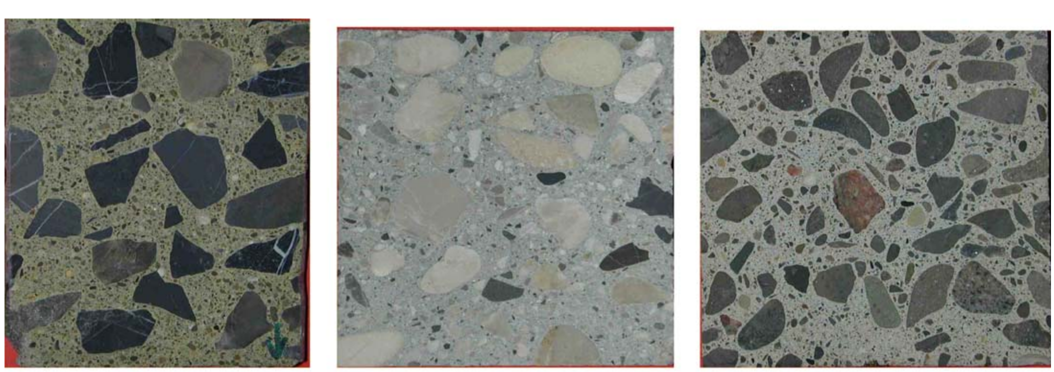
The samples analysed were selected in such a way that they visually represented different concrete composition (Fig. 1) and apparently different air content.

The samples were first cut plane parallel in sizes of approximately 100 × 100 × 20 mm using a concrete saw having a smooth, continuous blade with a small diamond cutting edge. The resulting saw cut was smooth without major damaging of the concrete surface. The initial cutting is in fact the most important step in the sample preparation procedure. If the cut surface is smooth at a start it saves time at the later lapping stages. The samples were then ground using two different grain sizes of fixed diamonds (250 and 125 μm). Before each step of grinding a grid was drawn on the surface of the samples using a yellow wax pen. During grinding the grid slowly disappeared indicating that the surface was sufficiently even and the cut surface was removed. The quality of the concrete surface was checked under the stereomicroscope after every step. When the paste was smooth without any ripping or tearing and the air void edges sharp the grinding was stopped. After grinding the surface was lapped.

The lapping was performed on a cast iron plate using a slurry consisting of silicon carbide powder, a second generation superplasticizer and water. Three different grit sizes were used starting with grit 320, then 600 and finally 800. About 1 part of superplasticizer to 2 parts of water and one large tea-spoon of powder were used to make 100 ml solution. The finer the silicon carbide powder the less superplasticizer was used. The lapping time on each step was between 5 and 10 min. When the paste was smooth without any ripping or tearing and the void edges sharp the sample was ready for analysis. After lapping the samples appeared as seen in Fig. 1.

As mentioned the lapping procedure in this study was stopped at grid 800 because the surfaces at end of this step had a good quality. One may decide to continue to grid 1000 or even 1200 if necessary but it depends on the sample quality. Also if using a too fine grid the quartz grains often present in the sand fraction become highly polished and are difficult to coat with black ink later on. If not properly coated such grains may result in reflections. Reflection will appear white as if it was air voids, analysed as such and influence the results. Another step which may be used during sample preparation is to apply a thin solution of lacquer and acetone (1:5–10) to the sample surface before each step of grinding and lapping in order to strengthen the paste. Whether or not this step is used depends again on sample quality – it was not done in this study – but it would usually be a beneficial step to include. The lacquer is dissolved in acetone after the final lapping.

The sample preparation, cutting, grinding and lapping is crucial for good results in all types of air void analysis — if good, results are good independent of whether the analysis is performed manual or automatic; however, using an automatic system the influence of human decisions are eliminated.



Sample #2
Paste content: 29.1%

Sample #5
Paste content: 29.0%

Sample #7
Paste content 28.7%

Fig. 1. Appearance of the lapped surface of the samples. The manually determined paste content of the samples is noted below the images.

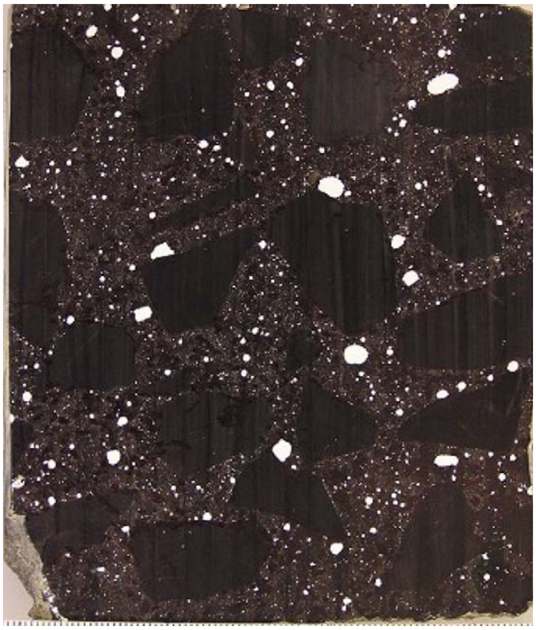


Fig. 2. Appearance of sample #2 after being coloured black and white $BaSO_4$ powder filled into the air voids.

After final lapping the samples were marked with an analysis starting point in one of the corners of the samples. All analyses were started in this corner but not in the exact same point. The samples were then analysed manually using modified point count and linear traverse methods according the ASTM C 457. During the point count the paste content of the samples was determined and this number was used during later automatic analysis.

When manual analysis was performed the samples were coloured black by gently dragging a broad tipped marker pen over the surface in slightly overlapping lines. When dry (few seconds) the samples were turned 90° and the colouring repeated. The colouring was done making sure that the aggregate especially quartz was 100% covered and the voids not filled with black ink. Then dry white powder ($BaSO_4$) was sprinkled over

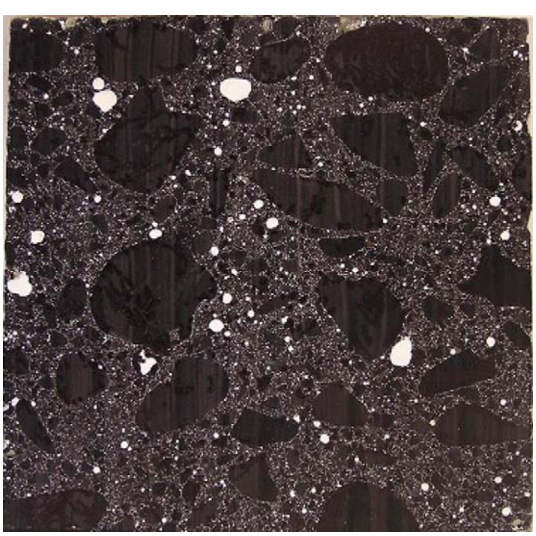


Fig. 3. Appearance of sample #5 after being coloured black and white $BaSO_4$ powder filled into the air voids.

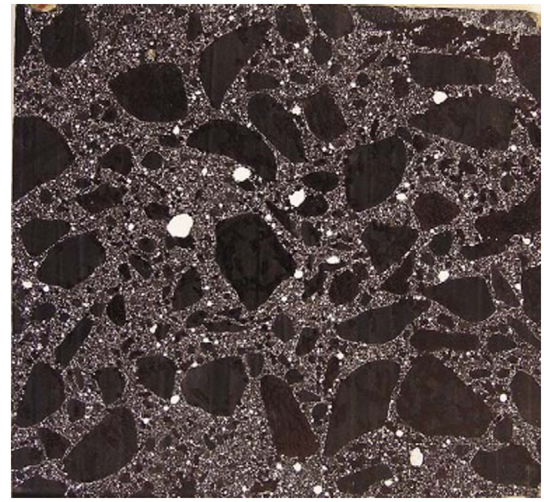


Fig. 4. Appearance of sample #7 after being coloured black and $BaSO_4$ powder filled into the air voids.

the surface. The method using white powder instead of zinc paste [4,2] was chosen because it is easier to work with, faster to perform and there is no shrinking of the paste involved. The non-shrinkage was important because the samples were to be sent around the world over a period of several months. The zinc paste often used starts shrinking very quickly and must be analysed shortly after preparation. The $BaSO_4$ powder, which has an average grain size of 2 μm, was filled into the air voids by tamping a hard rubber stopper over the surface of the sample. When all voids appeared filled the excess powder was removed by dragging, with some pressure, a smooth edged dense spatula one time over the surface. The surface was then cleaned by moving the palm of a hand in circular motion over the surface until the surface appeared shining without white dust. Holes present in aggregate were as a final step painted black with a fine tipped marker pen under the stereomicroscope. The final result of the surface enhancement is seen on Figs. 2, 3 and 4.

Comparing the pictures in Fig. 1, the polished surfaces, with the pictures in Figs. 2, 3 and 4, the black and white surfaces, it is obvious that the operator has a greater opportunity to evaluate the air void system before analysis and compares this to the results after analysis when using the black and white technique. The white air voids are very easy to observe as well as their size, amount and spacing. The samples were now ready for automatic analysis.

The three samples were all analysed by the 7 laboratories using 1 traverse line per frame[1]. Some of the laboratories performed only one analysis per sample; others did up to 4 analyses on the sample. When analysed 4 times the sample was turned 90° between the individual readings and an average of the four readings of the sample was reported. One of the 7 laboratories also performed a repeatability study of the automatic system on two of the samples. The two samples were analysed 10 times in a row using 3 traverse lines per frame, a traverse length of 2413 mm, the same threshold and the exact same starting point. In order to evaluate the use of different numbers of traverse lines an eleventh

[1] RapidAir has the option to use more than one line simultaneously.

Fig. 5. The RapidAir system for automatic analysis of the air void system in hardened concrete.

analysis was performed with the same settings but using only 1 traverse line per frame.

In order to distinguish between black and white a threshold value must be preset by the operator. Experience shows that the measurements are not very sensitive to some variations in the threshold setting. The actual threshold value depends on several factors such as the light/contrast setting of the system, the general room lighting and the type of black used for the colouring of the concrete surface. Because these factors may differ from laboratory to laboratory the threshold setting was not fixed during the Round Robin test. It was up to each laboratory to choose a proper threshold value for the tests based on experience.

Table 2
Results of air void analysis of sample #2

Sample #2 Paste content: 29.1%									
No.	Type	Lab	Air %	SSA	SpF	Average of RA analyses			Vol.% by area
						Air%	SSA	SpF	
2 BD	PC, Man	Lab 1	2.59	14.80	0.452				
2 KT	LT, Man	Lab 1	3.89	22.70	0.240				
2 BD	LT, Man	Lab 1	3.49	14.17	0.410				
2 M	LT, Man	Lab 2	4.10	21.54	0.250				
2	RA	Lab 2	3.37	15.45	0.384	3.37	15.45	0.384	
2	RA	Lab 3	3.39	25.89	0.223	3.42	24.34	0.241	
2a	RA	Lab 3	3.59	23.23	0.248				
2b	RA	Lab 3	3.27	23.91	0.251				
2start	RA	Lab 4	3.27	21.10	0.285	3.07	20.69	0.301	
2_90	RA	Lab 4	2.60	22.63	0.295				
2_180	RA	Lab 4	3.10	20.02	0.308				
2_270	RA	Lab 4	3.31	19.00	0.315				
2	RA	Lab 5	3.02	17.23	0.362	3.02	17.23	0.362	
2start	RA	Lab 1	3.60	16.85	0.343				
2_90	RA	Lab 1	2.96	19.52	0.322				
2_180	RA	Lab 1	2.94	19.81	0.319				
2_270	RA	Lab 1	3.54	17.79	0.326	3.26	18.49	0.328	
2start	RA	Lab 6	3.22	17.85	0.340	2.93	17.28	0.367	3.1
2_90	RA	Lab 6	2.84	16.41	0.391				3.5
2_180	RA	Lab 6	2.98	17.17	0.365				
2_270	RA	Lab 6	2.66	17.69	0.373				
2start	RA	Lab 7	3.37	19.30	0.308	3.37	18.83	0.316	
2_90	RA	Lab 7	3.16	19.08	0.32				
2_180	RA	Lab 7	3.31	17.64	0.339				
2_270	RA	Lab 7	3.63	19.30	0.298				
Average			3.25	19.20	0.323	3.20	18.90	0.328	
Stdev			0.38	2.93	0.056	0.20	2.90	0.049	
Average manual			3.52	18.30	0.338				
Stdev manual			0.67	4.44	0.109				

Abbreviations: PC, Point Count; LT, linear traverse; MAN, manual; RA, automatic; SSA, specific surface area mm^{-1}; SpF, spacing factor mm.

Table 3
Results of air void analysis of sample #5

Sample #5 Paste content: 29%

Analysis	Type	Lab	Total			Average of RA analyses			Vol.% by area
			Air%	SSA	SpF	Air%	SSA	SpF	
5 BD	PC, Man	Lab 1	6.59	25.30	0.172				
5 KT	LT, Man	Lab 1	7.15	41.45	0.100				
5 BD	LT, Man	Lab 1	7.77	28.89	0.130				
5 M	LT, Man	Lab 2	7.50	58.63	0.070				
5	RA	Lab 2	5.45	44.54	0.107	5.45	44.54	0.107	
5	RA	Lab 3	6.34	53.37	0.083				
5a	RA	Lab 3	7.13	48.85	0.083				
5a3	RA	Lab 3	7.09	52.46	0.078				
5start	RA	Lab 4	5.04	54.03	0.091	5.18	52.09	0.094	
5_90	RA	Lab 4	5.23	53.19	0.091				
5_180	RA	Lab 4	5.30	52.18	0.093				
5_270	RA	Lab 4	5.16	48.94	0.100				
5	RA	Lab 5	5.25	46.00	0.105	5.25	46.00	0.105	
5	PC, Man	Lab 5	7.10	49.00	0.082				
5start	RA	Lab 1	6.13	45.00	0.100	5.80	46.97	0.100	
5_90	RA	Lab 1	5.88	49.21	0.094				
5_180	RA	Lab 1	5.27	52.14	0.093				
5_270	RA	Lab 1	5.90	41.52	0.111				
5start	RA	Lab 6	5.38	52.30	0.092	5.69	49.28	0.095	4.5
5_90	RA	Lab 6	5.69	50.34	0.093				6.1
5_180	RA	Lab 6	5.91	48.22	0.095				6.7
5_270	RA	Lab 6	5.76	46.25	0.101				5.9
5start	RA	Lab 7	5.81	52.44	0.088	5.76	50.27	0.093	
5_90	RA	Lab 7	5.89	45.81	0.100				
5_180	RA	Lab 7	5.41	52.84	0.091				
5_270	RA	Lab 7	5.92	49.98	0.092				
Average			6.04	47.80	0.098	5.52	48.19	0.099	
Stdev			0.80	7.30	0.019	0.26	2.84	0.006	
Average manual			7.22	40.65	0.111				
Stdev manual			0.45	13.85	0.041				

Abbreviations: PC, Point Count; LT, linear traverse; MAN, manual; RA, automatic; SSA, specific surface area mm^{-1}; SpF, spacing factor mm.

After the last analysis by one laboratory the samples were shipped to the next laboratory in line. The samples were not re-prepared; the white $BaSO_4$ powder was still in the voids after half a year of shipping and handling.

3. The automatic analysis system

The RapidAir system is an automated system for analysis of air content in hardened concrete. The system is capable of analysing the air void system either according to ASTM C 457 8 [1] or EN 480 [5].

Because it performs the linear traverse method on a black and white surface the paste content cannot directly be measured. The software, however, has recently been updated to include an application for semi-automatic point count, where the paste content can be determined and used directly in the linear traverse analysis. Moreover the latest software has an integrated module for performing the air void analysis according to ASTM C 457 modified point count Procedure B. Since neither of these new applications were available at the start of this study the paste content was determined manually by using ASTM C 457 modified point count Procedure B and the automatic air void analysis by using the linear ASTM C 457 procedure A.

The automatic system consists of an X–Y table with a stepper motor which is equipped with a video camera, objective, and sample holder (Fig. 5). MS-Windows based software controls the movement of the system[2]. A detailed description of the system is presented in [2].

The analysis may be performed using one traverse line per frame with an analysis time of about 15 min. It can, however, analyse up to 10 lines per frame. Using for example 3 traverse lines per frame (found by several laboratories to be a good number) and the same traverse length reduces the analysis time by a factor 3. On the other hand the traverse length may be tripled and a much better statistical result obtained, still in only 15 min. Another example of the possibilities, which lies in the automatic system, is to analyse the same sample 4 times with each analysis starting in a different corner of the sample. Using for example 3 lines per frame and a traverse length of 2413 mm results in an

[2] The resolution and magnification of the automatic system is 2.1 μm and 100×, respectively.

Table 4
Results of air void analysis of sample #7

Sample #7 Paste content: 28.7%								
No.	Type	Lab	Total			Average of RA analysis		
			Air%	SSA	SpF	Air%	SSA	SpF
7 BD	PC, Man	Lab 1	6.96	29.10	0.142			
7 KT	LT, Man	Lab 1	8.48	36.07	0.093			
7 BD	LT, Man	Lab 1	8.43	26.68	0.130			
7 M	LT, Man	Lab 2	9.30	45.89	0.070			
7	RA	Lab 2	6.75	42.56	0.101	6.75	42.56	0.101
7a	RA	Lab 3	7.94	41.19	0.088	7.94	41.19	0.088
7start	RA	Lab 4	7.27	47.32	0.083	7.73	45.33	0.082
7_90	RA	Lab 4	7.99	45.27	0.079			
7_180	RA	Lab 4	7.9	45.05	0.081			
7_270	RA	Lab 4	7.75	43.69	0.085			
7	RA	Lab 5	7.02	44.57	0.078	7.02	44.57	0.078
7start	RA	Lab 1	7.96	44.91	0.080	7.99	44.98	0.080
7_90	RA	Lab 1	7.98	47.25	0.076			
7_180	RA	Lab 1	8.25	46.46	0.075			
7_270	RA	Lab 1	7.75	41.29	0.090			
7start	RA	Lab 6	7.31	43.11	0.091	7.43	42.39	0.091
7_90	RA	Lab 6	7.44	43.67	0.088			
7_180	RA	Lab 6	7.32	42.83	0.092			
7_270	RA	Lab 6	7.63	39.96	0.094			
7start	RA	Lab 7	9.06	45.01	0.070	8.57	44.53	0.076
7_90	RA	Lab 7	8.57	43.22	0.078			
7_180	RA	Lab 7	8.10	45.42	0.078			
7_270	RA	Lab 7	8.54	44.47	0.076			
Average			7.90	42.39	0.088	7.63	43.65	0.085
Stdev			0.65	5.22	0.017	0.62	1.58	0.009
Average manual			8.29	34.44	0.109			
Stdev manual			0.97	8.61	0.033			

Abbreviations: PC, Point Count; LT, linear traverse; MAN, manual; RA, automatic; SSA, specific surface area mm^{-1}; SpF, spacing factor mm.

analysis time of 4 × 5 min and a statistical better result is obtained than only analysing the sample once.

4. Results and discussion

The results of the Round Robin test performed using the automatic system and manual line traverse and point count methods are presented in Tables 2, 3 and 4.

As seen from the results sample #2 has low air content and large voids whereas samples #5 and #7 have high air content and smaller voids. Fig. 6 shows a close-up of the air void system of the three samples. There is a very good correlation between the automatic average results and the actual visual appearance of the samples.

Fig. 7 shows a graphical presentation of the air content and the specific surface area of the manual and automatic analyses. As seen, the results of the automatic analysis are very consistent for all samples and the reproducibility as expressed by the standard deviation is very good (Tables 2, 3 and 4). The standard deviation of the total air content of the automatic analysis ranges from 0.20 to 0.62. For comparison, the standard

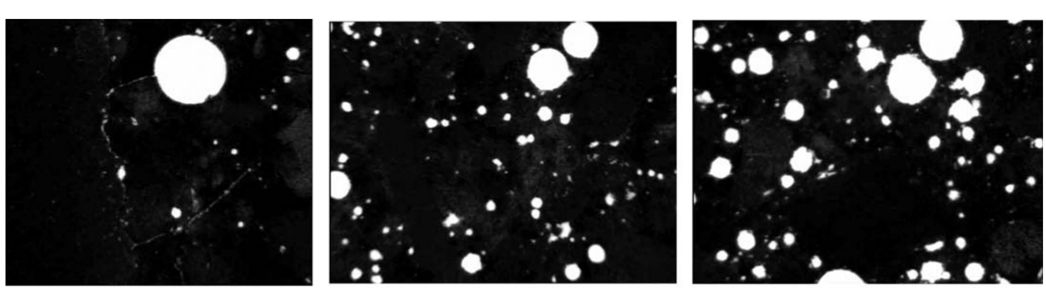


Fig. 6. Close-up of the air void structures of the samples analysed. The images were collected during analysis. The average results of the automatic analysis are provided below the images (from Tables 2, 3 and 4). Abbreviations: SSA: specific surface area, SpF: spacing factor.

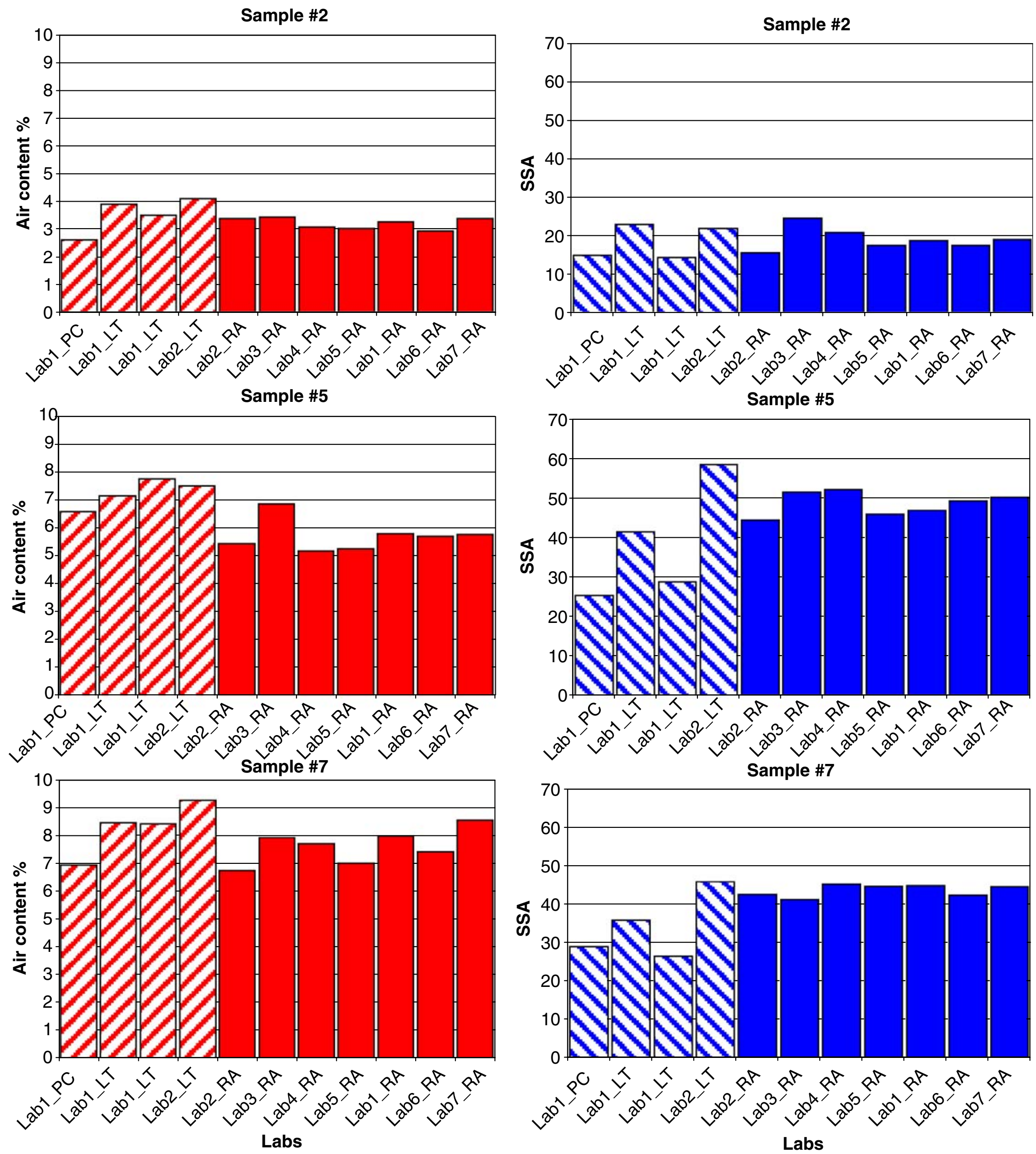


Fig. 7. Graphical presentation of the air content and specific surface area (SSA) of the 3 samples analysed. Hatched: manual readings, solid: automatic analysis.

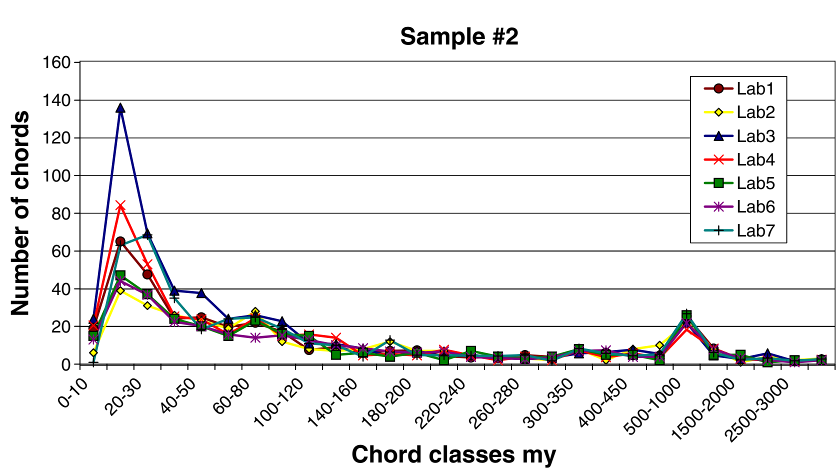


Fig. 8. Chord length distribution from 7 automatic analyses.

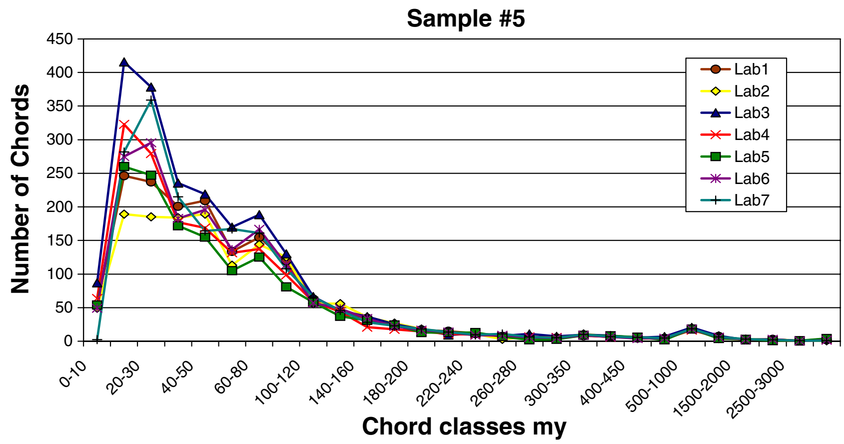


Fig. 9. Chord length distribution from 7 automatic analyses.

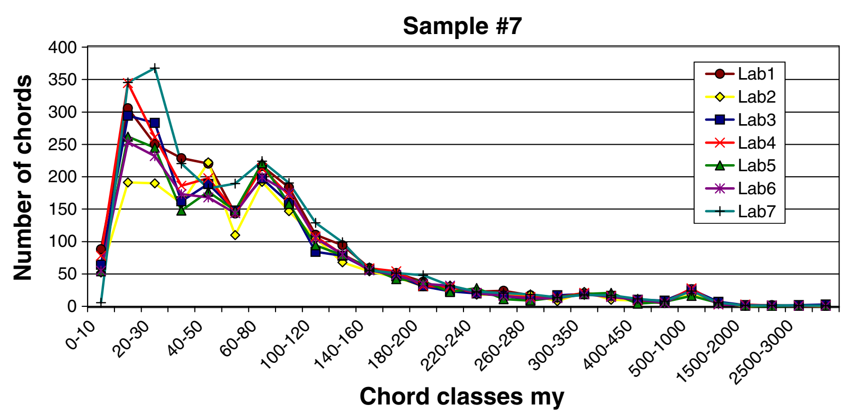


Fig. 10. Chord length distribution from 7 automatic analyses.

deviation of the manual readings ranges from 0.45 to 0.97. The standard deviation of the specific surface area (SSA) is for the automatic analysis from 1.58 to 2.90 mm^{-1}. In contrast the standard deviation of the manual readings ranges from 4.44 to 13.85 mm^{-1}, and it appears that the higher the SSA the higher the standard deviation. These samples are also the samples having the highest air content and the smallest air voids (Fig. 6), indicating the smaller the voids and higher the air content the higher the uncertainty of manual performed analysis.

Figs. 8, 9 and 10 show the chord length distribution of the various analyses performed by the 7 laboratories. As seen, the chord length distribution is very similar. The reason for the few chords below 12 μm observed by lab-7 is due to a pixel resolution of their old system of 2.9 μm, which results in a lower cut off at about 12 μm. One laboratory is somewhat higher for the small chords, which may have been caused by reflections from overhead light being measured as voids.

Taking 4 measurements from the same sample by turning 90° between measurements appears to give a very accurate determination of the air void structure. As seen in Table 5 the standard deviation of the analysis performed 4 times are low for all measured parameters. However, it also shows sample #5 having the highest SSA and has the highest standard deviation.

The repeatability test performed by one laboratory on 2 of the samples gave a very good result as seen in Table 6. There are

Table 5
Standard deviation of 4 analyses performed on the 3 samples

Lab	Sample #2			Sample #5			Sample #7		
	Air	SSA	SpF	Air	SSA	SpF	Air	SSA	SpF
4	0.33	1.55	0.013	0.11	2.33	0.004	0.32	1.50	0.003
1	0.36	1.41	0.011	0.37	4.67	0.008	0.21	2.64	0.007
6	0.24	0.65	0.021	0.22	2.62	0.005	0.15	1.66	0.002
7	0.20	0.80	0.018	0.24	3.23	0.005	0.39	0.96	0.004

Table 6
Repeatability study performed on samples #2 and #7

Tests	Sample #2			Sample #7		
	Air	SSA	SpF	Air	SSA	SpF
Avg. of 10 (same start)	2.95	18.45	0.342	7.44	44.81	0.086
Stdev	0.012	0.29	0.006	0.02	0.33	0.001
One analysis line	3.04	18.64	0.334	8.10	43.62	0.081
Avg. of 4 (different start)	3.07	20.69	0.301	7.73	45.33	0.082

Each sample was analysed 10 times with same starting point and 3 analysis lines. Data from an 11th analysis performed with only one traverse line (and same starting point as the 10) and the average of 4 analyses performed with starting points in the 4 corners of the samples is also shown.

almost no differences between the 10 results. The standard deviations are resultantly very low. The low values of standard deviation show that the automatic analysis is very precise. Comparing the results of the analysis performed using 3 lines per frame to the 11th analysis using only 1 line per frame shows that there is almost no difference. In order to save time the operator may then select to use 3 lines instead of one without having doubts about the results. On the other hand the operator may select the 3 lines and then triple the traverse line, still analysing the sample in 15 min but having a better statistical background for calculation of the air void system.

The air content by area was noted by Laboratory 6 during the line traverse on samples #2 and #5 (Tables 2 and 3). The air content by area was very close to the air content measured by the line traverse (chords traversed). This suggests that the use of the line traverse method is an accurate method for determining the air content of concrete.

The samples were, except for one analysis of sample 5 (Table 3), not manually analysed after the contrast enhancement. Lab 5 did, however, after the automatic analysis perform a manual point count. The result of this point count showed that both the specific surface (49 mm^{-1}) and the spacing factor (0.082 mm) were in the line of the automatic analysis which had an average specific surface of 48.67 mm^{-1} and spacing factor of 0.096 mm. Earlier studies, not published, support this result and by studying the raw data it is obvious that the manual operator suddenly sees air voids less than about 30 μm in size which is rarely the case when performing air void analysis manually without the surface enhancement. The measurement of more small voids affects the specific surface and spacing factor in a positive direction.

Not tested in this study is the influence of the sample preparation on the results. As the results shown in this study indicate that the automatic system measures very precisely what it sees and that may be more or less correct depending upon sample preparation quality. This is, however, not different from any other available method. If the sample preparation is poor all methods give poor results. On the other hand if sample preparation is good the automatic system gives very precise results in contrast to manual readings, and it gives results in less than 15 min as opposed to hours. So sample preparation is crucial; not the black and white part of the sample preparation because it will be good if the sample surface is well prepared, but the ordinary procedure with cutting, grinding and lapping. The sample surface has to be without scratches, the paste must be smooth and the air voids must have sharp edges. A way of achieving this is to use the procedures described in this paper. Even if a good sample preparation is achieved different manual operators often get very different results probably due to many hours of analysis time, the angle of light, experience, etc., whereas the automatic system measures very precisely because everything is user independent.

5. Conclusion

The RapidAir system has been validated in an international Round Robin study. Seven laboratories used their RapidAir system for automatic analysis of the air void system in hardened concrete according to ASTM C 457 on the same samples. Prior to the automatic analysis the samples were analysed manually by two of the laboratories.

The results showed a very good reproducibility and repeatability of the automatic system. Even though not many manually performed analyses were performed during this test it is clear that the data shows a much higher variation than when compared to the automatic analysis performed using the RapidAir system. The automatic analysis is much faster than the manual analysis and takes 15 min or less to perform.

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