THE RAPIDAIR SYSTEM FOR AIR VOID ANALYSIS OF HARDENED CONCRETE – A ROUND ROBIN STUDY

U.H. Jakobsen, C. Pade[a], N. Thaulow[b], D. Brown[c], S. Sahu[d], O. Magnusson[e], S. De Buck, and G. De Schutter[f]

a. *Concrete Experts International, DK, uhj@concrete-experts.com*

b. *RJ Lee Group, PA, USA, nthaulow@aol.com*

c. W.R. Grace & Co., MA, USA, d.r.brown@grace.com

d. Degussa Admixtures, USA, sada.sahu@degussa.com

e. Cementa Research AB, SE, oskar.magnusson@ research.scancem.com

f. Magnel Laboratory for Concrete Research, Ghent University, BE, sandra.debuck@rug.ac.be

Abstract

The RapidAir is an automatic system for analyzing 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 ASTM C 457, procedure A, linear traverse method 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 minutes to perform. The air content can be analyzed in less than 15 minutes traversing 2413mm (95 inch) – 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 analyzed 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, Automatic air void analysis, Hardened concrete, Reproducibility, Repeatability

Introduction

A proto type RapidAir system was already developed in the early 1990th. This system, which was DOS software based, was used at three laboratories; namely RAMBOLL in Denmark, RJ Lee Group in Monroeville, PA, USA and Heidelberger Cement in Germany. 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 the old systems at RAMBOLL and RJ Lee Group have been updated and RapidAir systems are also present at companies and universities across the world. Of these places the following institutions agreed to be part of the present Round Robin air void analysis study: W.R. Grace & Co., USA. RJ Lee Group (RJLG), USA, Magnel, University of Gent, BE, Cementa Research, SE, Degussa Admixtures, USA, Concrete Experts International (CXI), DK, and RAMBOLL, DK.

Three samples were lapped by CXI and send out for air void analysis following ASTM C 457. The first 2 laboratories did modified 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 RapidAir 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 RapidAir system as well as to compare these data to manual 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 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 a study performed on samples used in a European Study (Pade et al., 2002). The data from the European study was published by Elsen et al., 2001. 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.

Sample Preparation and Analysis Procedures

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

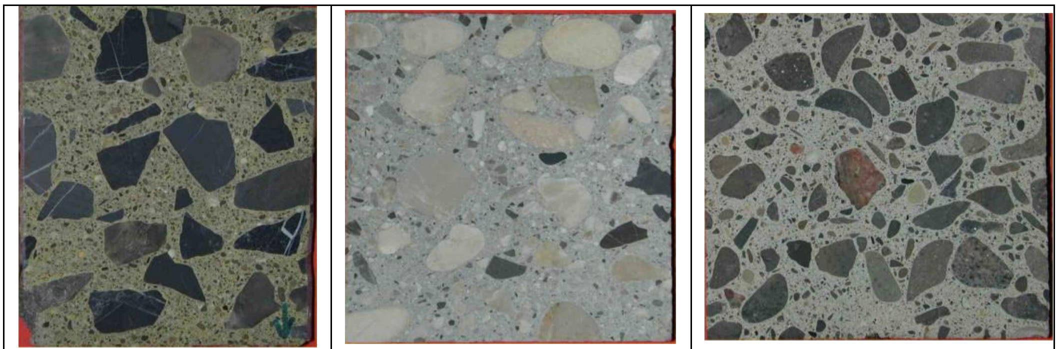
Table 1: Testing program followed by the participators.

Lab.	Time scale	Crinding and Lapping	Manual Point Count	Manual Line Traverse	Black & White sample prep.	Automatic line traverse ASTM C 457
CXI	START	X				
WR Grace	↓		X	X		
Cementa	↓			X	X	X
Magnel	↓					X
RJLG	↓					X
Degussa	↓					X
WR Grace	↓					X
CXI	↓					X
RAMBOLL	END					X

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

The samples were first cut plane parallel in sizes of approximately 100x100x20mm 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 microns). 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 minutes. 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 Figure 1.



Sample #2 Paste content: 29.1%	Sample #5 Paste content: 29.0%	Sample #7 Paste content 28.7%

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

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.

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^o 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 the surface. The method using white powder instead of zinc paste (Chatterji and Gudmundsson 1977 and Pade et al. 2002,) 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 2µm, 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 shinning 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 Figures 2, 3 and 4.

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

Comparing the pictures in Figure 1, the polished surfaces, with the pictures in Figures 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 compare 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.

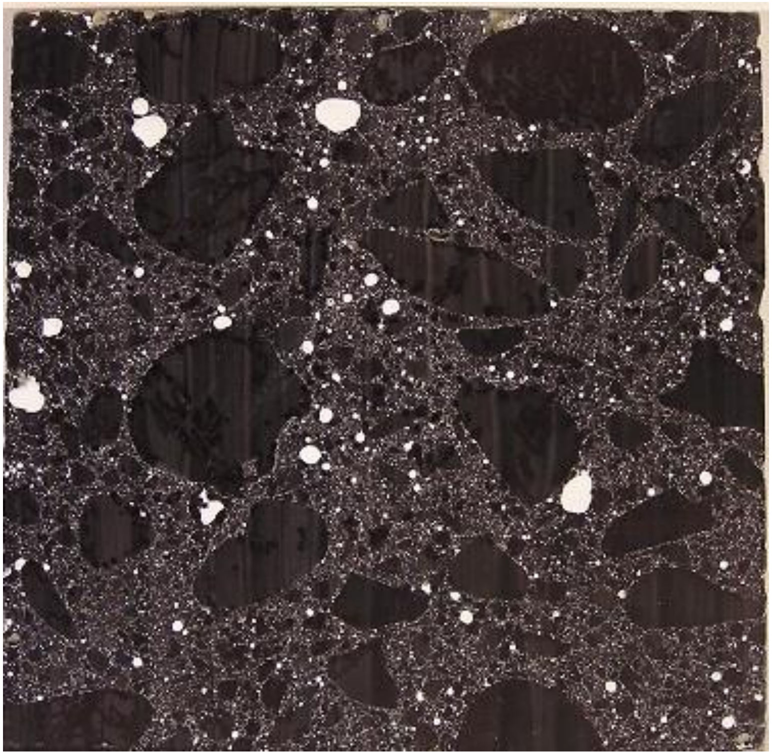


Figure 3: Appearance of sample #5 after being coloured black and white $BaSO_4$ powder filled into the air voids.

The three samples were all analysed by the 7 laboratories using 1 traverse line per frame (the RapidAir has the option to use more than one line simultaneously). 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^{o} 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 RapidAir 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 2413mm, the same threshold and the exact same starting point. In order to evaluate the use of different numbers of traverse lines an eleventh analysis was performed with 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.

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.

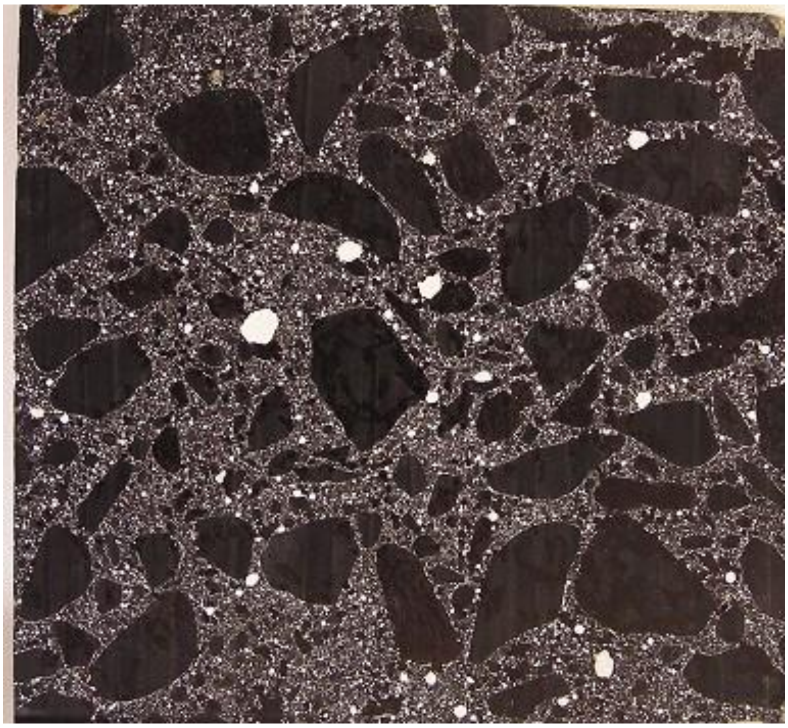


Figure 4: Appearance of sample #7 after being coloured black and $BaSO_4$ powder filled into the air voids.

The RapidAir system

The RapidAir system is an automated system for analysis of air content in hardened concrete and is specially designed to perform the linear traverse method accurate and fast. The system is capable of analysing the air void system either according to ASTM C 457 or EN 480.

Because it performs a 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.

During the line traverse analysis the area% of air per frame and the average of the measured frames are shown on the monitor. This enables the operator to compare the line traverse result with an area analyses performed simultaneous.

The RapidAir system consists of an X-Y table with a stepper motor which is equipped with a video camera, objective, and sample holder (Figure 5). User-friendly MS-Windows based software controls the movement of the system. Since a more detailed description of the RapidAir system is already presented in Pade et al. 2002 the following is a description of some of the special features, which are available in the RapidAir system and which have been used in this study.

Figure 5: The RapidAir system for automatic analysis of the air void system in hardened concrete

The resolution of the RapidAir systems varies between 2.1 μm and 2.9 μm – the size of 1 pixel. The actual pixel size depends on the age of the system with old systems having lower resolutions compared to the newest ones. RapidAir collects all white pixel arrays, in accordance with ASTM C 457, however, only arrays (chords) of 4 (8.4 μm – 11.6 μm) or more pixels in a row are included in the results.

The analysis may be performed using one traverse line per frame with an analysis time of about 15 minutes. 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 minutes. Another example of the possibilities, which lies in the RapidAir system because it is so fast, 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 2413mm results in an analysis time of 4 x 5 minutes and a statistical better result is obtained than only analysing the sample once.

The X-Y table is high precision ensuring accurate steps when moving and after the end of analysis the table returns to the exact starting point. This feature enables the user to analyse the repeatability of the system.

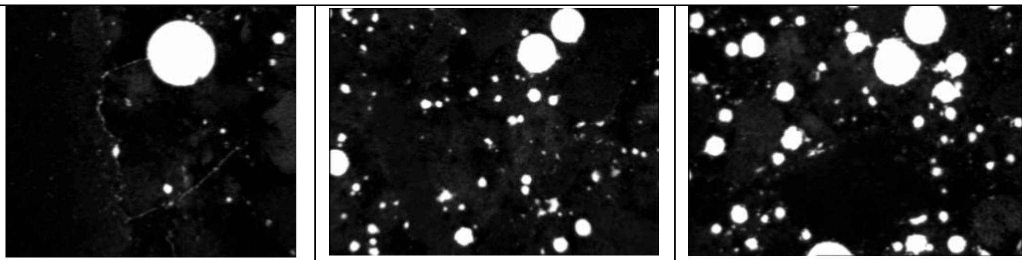
Another feature available in RapidAir is the possibility to save all raw images or threshold images of the analysis. The threshold images contain the traverse line(s) and can therefore be used for manual evaluation and measurement of the chords if required for quality control.

A special report feature is to include a photograph of the entire sample surface (e.g. like Figures 2, 3 and 4) at the front page of the MS Excel-based report. This picture may be used by the operator to compare the visual appearance of the air void structure to the calculated numbers of the analysis.

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. Figure 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.



Sample #2 Air: 3.20% SSA: 18.90mm^{-1} SpF: 0.328mm	Sample #5 Air: 5.71% SSA: 48.67mm^{-1} SpF: 0.096mm	Sample #7 Air: 7.63% SSA: 43.65mm^{-1} SpF: 0.085mm

Figure 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 & 4). Abbreviations: SSA: specific surface area, SpF: spacing factor

Figure 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 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 (Figure 6), indicating the smaller the voids and higher the air content the higher the uncertainty of manual performed analysis.

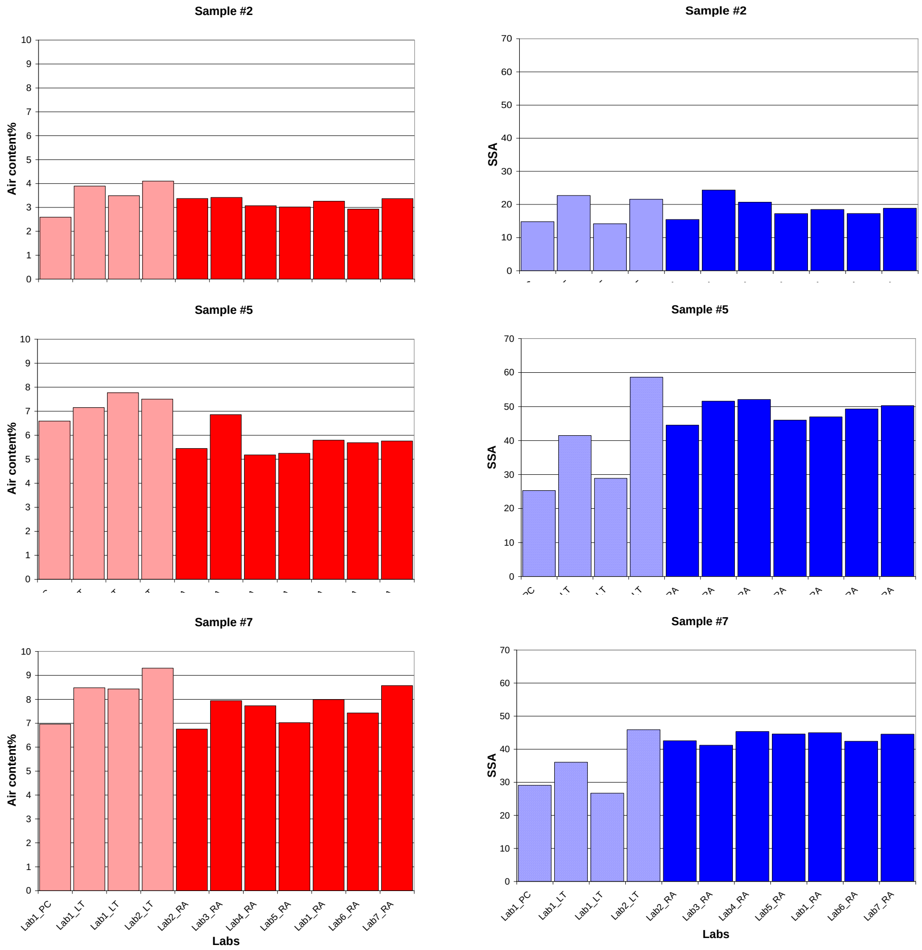


Figure 7: Graphical presentation of the air content and specific surface area (SSA) of the 3 samples analysed. Hatched: manual readings, solid: automatic analysis

Figures 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.

Table 2: Results of air void analysis of sample #2. Abbreviations: PC Point Count, LT linear traverse, MAN manual, RA RapidAir, SSA specific surface area mm^{-1}, SpF spacing factor mm.

Sample #2		**Paste Content: 29.1 %**							
						Average of RA analyses			**vol%**
No.	**Type**	**Lab**	**Air%**	**SSA**	**SpF**	**Air%**	**SSA**	**SpF**	**by area**
2 BD	PC, Man	Lab1	*2.59*	*14.80*	*0.452*				
2 KT	LT, Man	Lab1	*3.89*	*22.70*	*0.240*				
2 BD	LT, Man	Lab1	*3.49*	*14.17*	*0.410*				
2 M	LT, Man	Lab2	*4.10*	*21.54*	*0.250*				
2	RA	Lab2	3.37	15.45	0.384	3.37	15.45	0.384	
2	RA	Lab3	3.39	25.89	0.223	3.42	24.34	0.241	
2a	RA	Lab3	3.59	23.23	0.248				
2b	RA	Lab3	3.27	23.91	0.251				
2start	RA	Lab4	3.27	21.10	0.285	3.07	20.69	0.301	
2_90	RA	Lab4	2.60	22.63	0.295				
2_180	RA	Lab4	3.10	20.02	0.308				
2_270	RA	Lab4	3.31	19.00	0.315				
2	RA	Lab5	3.02	17.23	0.362	3.02	17.23	0.362	
2start	RA	Lab1	3.60	16.85	0.343				
2_90	RA	Lab1	2.96	19.52	0.322				
2_180	RA	Lab1	2.94	19.81	0.319				
2_270	RA	Lab1	3.54	17.79	0.326	3.26	18.49	0.328	
2start	RA	Lab6	3.22	17.85	0.340	2.93	17.28	0.367	3.1
2_90	RA	Lab6	2.84	16.41	0.391				3.5
2_180	RA	Lab6	2.98	17.17	0.365				
2_270	RA	Lab6	2.66	17.69	0.373				
2start	RA	Lab7	3.37	19.30	0.308	3.37	18.83	0.316	
2_90	RA	Lab7	3.16	19.08	0.32				
2_180	RA	Lab7	3.31	17.64	0.339				
2_270	RA	Lab7	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*				

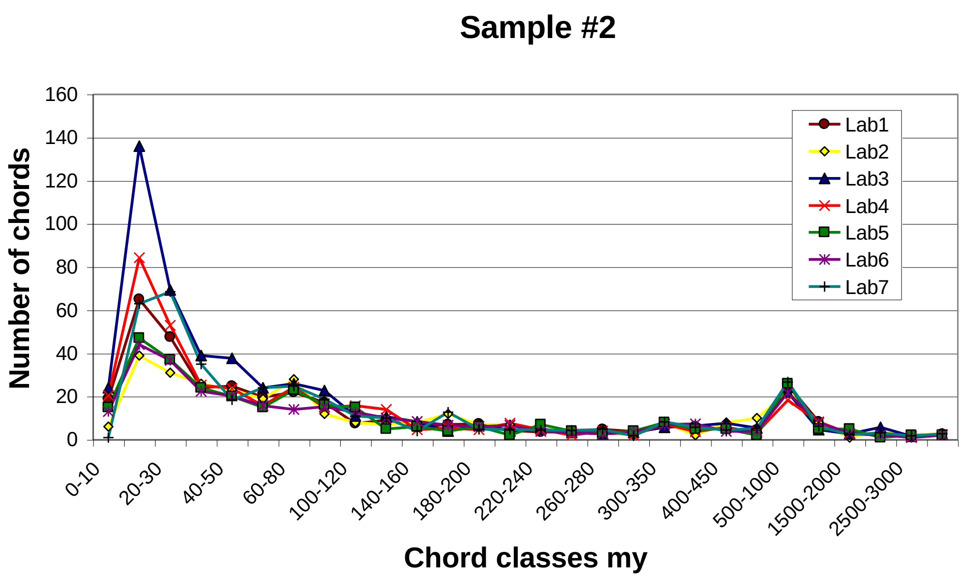


Figure 8: RapidAir chord length distribution determined by 7 laboratories.

Table 3: Results of air void analysis of sample #5. Abbreviations: PC Point Count, LT linear traverse, MAN manual, RA RapidAir, SSA specific surface area mm^{-1}, SpF spacing factor mm.

Sample #5		**Paste content: 29%**							
			Total			**Average of RA analyses**			**vol% by**
Analysis	**Type**	**Lab**	**Air%**	**SSA**	**SpF**	**Air%**	**SSA**	**SpF**	**area**
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 Stdev			0.45	13.85	0.041				

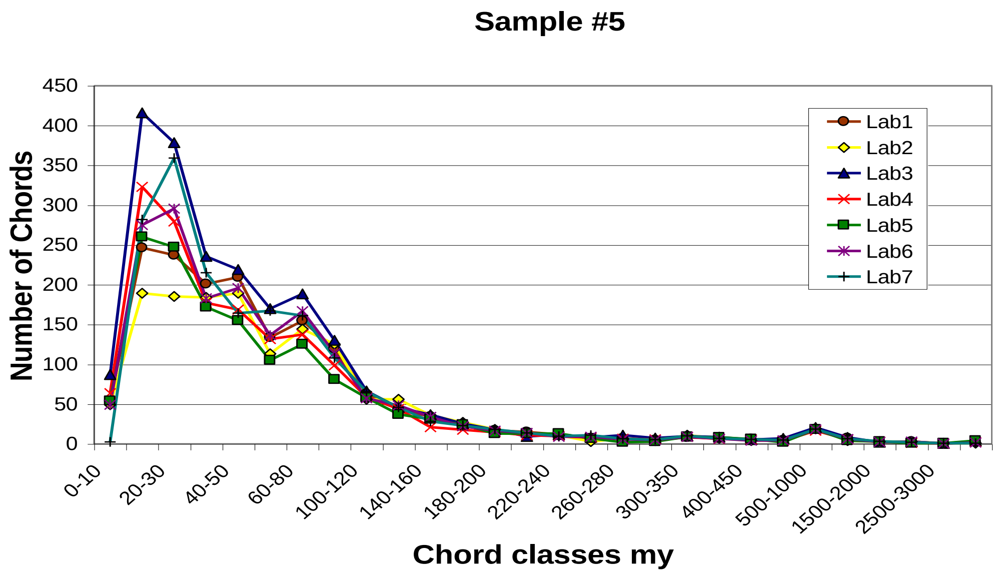


Figure 9: RapidAir chord length distribution determined by 7 laboratories.

Table 4: Results of air void analysis of sample #7. Abbreviations: PC Point Count, LT linear traverse, MAN manual, RA RapidAir, SSA specific surface area mm^{-1}, SpF apacing factor mm.

Sample #7		**Paste Content: 28.7%**						
			Total			**Average of RA analysis**		
No.	**Type**	**Lab**	**Air%**	**SSA**	**SpF**	**Air%**	**SSA**	**SpF**
7 BD	PC, Man	Lab1	*6.96*	*29.10*	*0.142*			
7 KT	LT, Man	Lab1	*8.48*	*36.07*	*0.093*			
7 BD	LT, Man	Lab1	*8.43*	*26.68*	*0.130*			
7 M	LT, Man	Lab2	*9.30*	*45.89*	*0.070*			
7	RA	Lab2	6.75	42.56	0.101	6.75	42.56	0.101
7a	RA	Lab3	7.94	41.19	0.088	7.94	41.19	0.088
7start	RA	Lab4	7.27	47.32	0.083	7.73	45.33	0.082
7_90	RA	Lab4	7.99	45.27	0.079			
7_180	RA	Lab4	7.9	45.05	0.081			
7_270	RA	Lab4	7.75	43.69	0.085			
7	RA	Lab5	7.02	44.57	0.078	7.02	44.57	0.078
7start	RA	Lab1	7.96	44.91	0.080	7.99	44.98	0.080
7_90	RA	Lab1	7.98	47.25	0.076			
7_180	RA	Lab1	8.25	46.46	0.075			
7_270	RA	Lab1	7.75	41.29	0.090			
7start	RA	Lab6	7.31	43.11	0.091	7.43	42.39	0.091
7_90	RA	Lab6	7.44	43.67	0.088			
7_180	RA	Lab6	7.32	42.83	0.092			
7_270	RA	Lab6	7.63	39.96	0.094			
7start	RA	Lab7	9.06	45.01	0.070	8.57	44.53	0.076
7_90	RA	Lab7	8.57	43.22	0.078			
7_180	RA	Lab7	8.10	45.42	0.078			
7_270	RA	Lab7	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*			
Average Stdev			*0.97*	*8.61*	*0.033*			

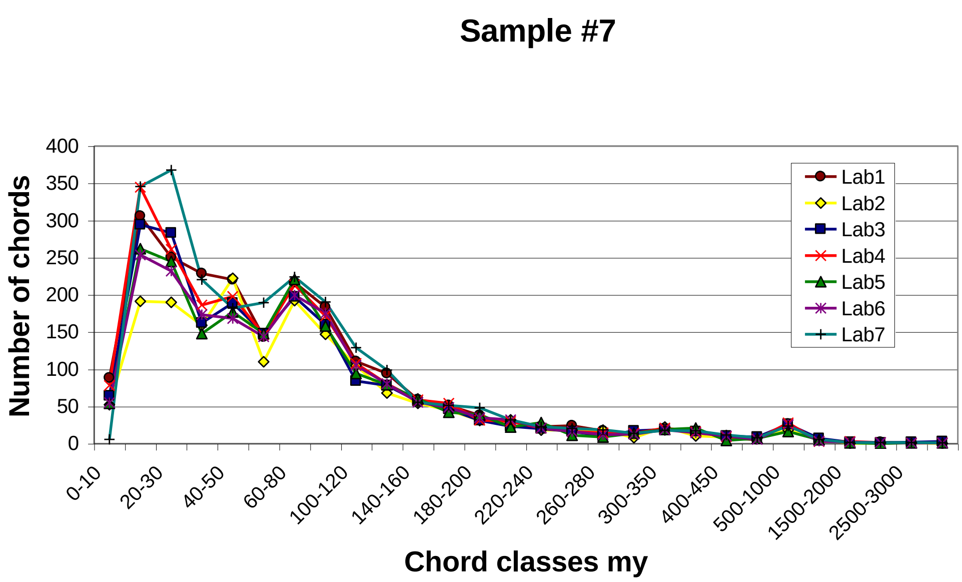


Figure 10: RapidAir chord length distribution determined by 7 laboratories.

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 also has the highest standard deviation.

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

The repeatability test performed by one laboratory on 2 of the samples gave a very good result as seen in Table 6. There are 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 minutes but having a better statistical background for calculation of the air void system.

Table 6: Repeatability study performed on samples #2 and #7. Each sample was analysed 10 times, using the same setup with 3 traverse lines. Data from an 11th analysis performed with only one traverse line and the average of the 4 analyses is also shown.

	Sample #2			Sample #7		
	Air	SSA	SpF	Air	SSA	SpF
Air% avg	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
Air% 1line	3.04	18.64	0.334	8.10	43.62	0.081
Air% of 4 analyses	3.07	20.69	0.301	7.73	45.33	0.082

The air content by area was noted by Laboratory 6 during the line traverse on samples #2 and #5 (Tables 2 & 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 ($49mm^{-1}$) and the spacing factor (0.082mm) were in the line of the automatic analysis which had an average specific surface of $48.67mm^{-1}$ and spacing factor of 0.096mm. 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 30μm's 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 minutes 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 precise because everything is user independent.

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 RapidAir 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 minutes or less to perform.

References

American Standard, ASTM C 457 – 98. Standard Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.

Chatterji, S. and Gudmundsson, H. (1977): Characterization of entrained air bubble systems in concrete by means of an image analyzing microscope, Cement and Concrete Research, 7: 423-428

European Standard, EN 480-11. Admixtures for concrete, mortar and grout – test methods – Part 11: Determination of air void characteristics in hardened concrete.

Elsen, J., (2001): Automated air void analysis on hardened concrete – Results of a European intercomparison testing program, Cement and Concrete Research, 31: 1027-1031

Pade, C., Jakobsen, U.H. and Elsen, J. (2002): A new automatic analysis system for analyzing the air void system in hardened concrete. Proceedings 24th ICMA: 204-213