AGGREGATE SHAPE AND ORIENTATION IN HISTORIC MORTARS

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Abstract

Fluorescence microscopy images were obtained and analysed using image analysis. The ratio between maximum and minimum Ferret diameter were used to obtain the aspect ratio (Ferret min/Ferret max) of the particles. Edge objects were excluded in the measurement. In the assessment of orientation objects with low aspect ratio were excluded. The aspect ratio can, presented as cumulative diagrams, be used as one tool to identify the source of the aggregate and to compare the aggregate in different samples. Other tools that can be used are mineralogical composition and aggregate size distribution. The aggregate orientation measured as the orientation of the longest axis of the particle can be used as a tool for assessment of surface treatment of the fresh mortar. A strong orientation of the aggregate particles near the surface implies a tooling of the surface. A lack of orientation implies a mortar of low workability or only little tooling of the fresh mortar. The analysed mortars range from pure lime mortars to hydraulic mortars with and without pozzolanic additives. The mortars come from buildings in southern and central Sweden and the age of the mortars date from the 16th to the 20th century.

Keywords: Mortars, image analysis, SEM, BSE, aggregate

Introduction

Microscopical analysis using the thin-section technique has been widely applied for the analysis of the properties of historical mortars during the last fifteen years (Elsen 2006). There is a continuous development of quantitative methods based on microscopy techniques that are suitable for the analysis of historical mortars (NT BUILD 370, Lindqvist & Sandström 2000, Mertens & Elsen 2006). The quantitative methods are based both on point counting and image analysis. The analysis of thin-sections can furthermore be used to determine the way the craftsman has worked with the mortar (Balksten 2005). The present paper introduces additional techniques that can be used to quantify aggregate shape and orientation, which can give information about the properties of the fresh mortar, the application technique and the source of the aggregate.

Orientation is an easily accessible aggregate parameter. If the mortar surface has been worked will the length axis of the aggregate will show a greater degree of orientation in parallel with the mortar surface. The orientation effect is also dependent on the properties of the fresh mortar. A stiff mortar will show less orientation effect then a more plastic mortar. The shape of the aggregate particles also affects the properties of the fresh mortar. Elongated particles give a stiffer mix than particles with spherical or cubic shape. Particle shape can also give useful information for the identification of the aggregate source. These methods can be complemented with quantitative mineralogy mainly using point counting.

Mortars

The investigation presented in this paper is a part of a study focussed on the use of hydraulic and pozzolanic mortars in Sweden from medieval times to the 20th century (Johansson 2006). Historical mortars from the 16th to the 20th century have been included in the present paper. The mortars are divided into four different groups based on type of binder and additives (Table 1). The first group includes lime mortars to hydraulic lime mortars. Several of these mortars are impure, subhydraulic, lime mortars. A second group includes natural cement and early cement mortars. It includes two groups of mortars with different types of pozzolanic additives including brick dust, hammer slag and burned alum shale. The investigation includes mortars for masonry and renders. Some of the natural cement mortars come from cast cement decoration.

Table 1. The type of mortars included in the study. O is outer, M middle and i inner layer.

Sample identity	Type of mortar	Age
SP20, 21, 22, 23, 24, 25, 38, 39i, 39O	Lime mortars to natural hydraulic mortars	1595 - 1950
SP26, 28i, 28M, 28O, 29, 30i, 30O, 31i, 31O, 33i	Natural cement and proto cement	1840 - 1880
SP34, 35i, 35O, 36, 37i	Brick dust mortars	1676 – 1688
SP37O, 39M, 40, 41	Alum shale mortars	1891 - 2002

Methods

The analyses were performed using fluorescence microscopy on thin-sections of samples impregnated with epoxy containing fluorescent dye. The analysed thin-sections are cut perpendicular to the mortar surface. Two thin-sections cut at 90^{o} relative to each other make it possible to analyse orientation in 3D. In this project has only one direction has been analysed. The measurements were performed using the KS400 image analysis program. The images were taken in fluorescent light and the magnification was adapted to the aggregate particle size. In the mortars with brick dust and burned alum shale the brick and shale particles were included in the measurements. The parameter used to describe shape in this study is the aspect ratio which is the minimum length divided by the maximum length given as Ferret min/Ferret max (Fmin/Fmax). As the smallest objects in the images to a large extent are peripheral 2D slices through aggregate particles, these small objects are often nearly circular and independent of the 3D shape of the intersected aggregate particles. While larger objects in the image are slices cut near the centres of the aggregate particles, these larger 2D objects reflect to a high extent the 3D shape of the aggregate particles. For this reason half of the objects with the lowest Fmax has been excluded from the measurement. Generally these are the objects with an Fmax smaller than about 100 micron. This gave 124 to 1074 measured particles for the shape analysis in each mortar. Orientation is measured as the orientation of Fmax on elongated objects. Objects with Fmin /Fmax larger than 0.6 were excluded in the measurement of orientation. The reason for this was that an almost spherical or cubic particle could be expected to be randomly oriented. This gave a minimum of 44 objects and a median of 174 objects for each measured mortar for the measurement of orientation. Edge objects were excluded from the measurements of both shape and orientation. In addition the size distribution were determined using microscopy and thin-section technique according to NT BUILD 486 (1998).

Significance of the measured parameters

The orientation of the aggregate particles is dependent on the aggregate shape, the stiffness of the mortar and the application technique used by the craftsman. It is easier to obtain orientation with an elongated aggregate and a mortar that flows easily. A mortar with a more worked surface will have a higher degree of orientation in the aggregate particles.

The shape of the aggregate particles can, together with quantification of the mineralogical composition, be used as a fingerprint for the identification of the source of the aggregate. The mineralogy and the type of deposit e.g. rounded river sand or a more flaky particles in a till, gives the shape of the particles. The shape of the aggregate particles influences the plasticity and workability of the fresh mortar. A high abundance of elongated aggregate particles gives a less plastic and thus a stiffer mortar. Measurement of aggregate shape and orientation can thus, in combination with other observations, provide information about the source of the material, the properties of the fresh mortar and the technique used by the craftsman.

Results

The orientation was measured as the number of objects with specific length axis orientation, Fmax. These were divided into eight directions and the results given as percentages in the respective directions. An example from a natural cement sample with three different mortar layers is given in figure 1. These are fast setting natural cement samples and come from a cast facade decoration from about 1825. The middle layer lacks orientation of the aggregate while the other two layers have orientation at slightly different angles. An orientation ratio was calculated from these data as the sum of the dominating angle and its neighbouring angles divided by the sum of the angles at 90 degrees to the dominating angle. For the outer layer of SP28O in figure 1, the objects with Fmax oriented in the angles 112.5 + 135 + 90 divided by the objects in angles 22.5 + 45 + 180. This gives a ratio of 0.44. Samples 28i and 28O are rapid setting natural cements while 28M is early slow setting cement. A value close to 1 indicates lack of orientation while a low value indicates orientation of the aggregate. The orientation ratio for each sample is presented in table 2. Micro photos giving examples of oriented and unoriented samples are given in figure 8.

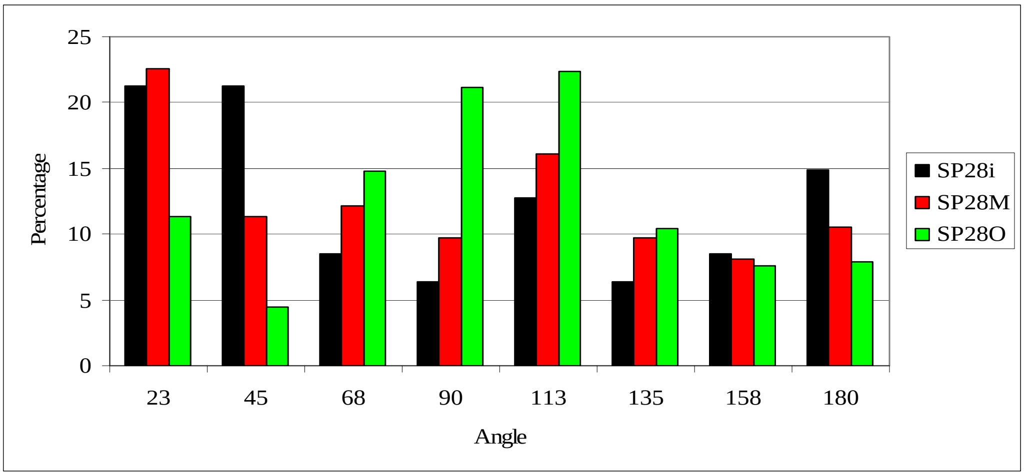


Figure 1: The sample 28i is the inner and 28O is the outer layer and 28M is a middle layer. The percentage is the objects with length axis in a specific direction given in degrees.

Table 2: Shows the ratio of orientation for the different mortar types (se text above).

Sample	Ratio	Lime	mortars	Sample	Ratio	Natural	cement
SP20	0.49	Max	1.02	SP26	0.33	Max	0.83
SP21	0.48	Min	0.24	SP28i	0.44	Min	0.33
SP22	0.71	Average	0.65	SP28M	0.80	Average	0.49
SP23	0.66			SP28O	0.44		
SP24	0.81			SP29	0.38		
SP25	1.02			SP30i	0.36		
SP38	0.42			SP30O	0.46		
SP39i	0.99			SP31i	0.83		
SP39O	0.24			SP31O	0.43		
				SP33i	0.41		
Sample	Ratio	Shale	mortars	Sample	Ratio	Brick	dust
SP37O	0.50	Max	0.55	SP34	0.64	Max	0.64
SP39M	0.55	Min	0.24	SP35i	0.43	Min	0.17
SP40	0.28	Average	0.39	SP35O	0.25	Average	0.36
SP41	0.24			SP36	0.30		
				SP37i	0.17		

Shape factors given as the Fmin/Fmax ratio divided in to shape classes and presented as accumulated percentages for the different mortars are shown in the figures 2 – 5. A high percentage of objects in the low shape classes indicates a flaky material. An example is the brick dust mortar SP36. The shape distribution curve for the aggregate in an individual mortar is very specific and gives much more information than an average value. The aggregates in the natural cement mortars are generally less elongated compared with the lime mortars. It should be noted that the additives, burned shale, brick dust and hammer slag are included in the measurement in these mortars and that the shape not only reflects the aggregate shape. An example is the brick dust mortar SP35O which contains flakes of hammer slag that explains the shape index for this mortar. These hammer slag particles are also strongly oriented. In order to get a value that can be used to assess of the amount of elongated particles, a shape index (Si) was calculated as 10 times the average Ferret ratio (Fr) multiplied with shape ratio that compares with the 10 percentage percentile (P) in the accumulated diagram, see table 3, as follows:

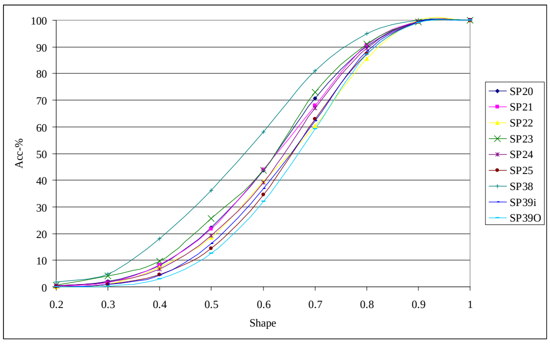
$$Si = 10*Fr*P$$

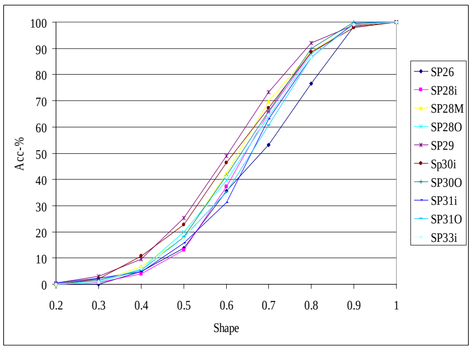
For the mortar SP36 the shape index is calculated accordingly as 1.73 = 10*0.308*0.561.

The shape index and the shape distribution can be used to identify the source of the aggregate. An example of this is from renders and masonry mortars from a 17th century building in the Old Town in Stockholm, as given in figures 6 and 7. The sample SP21 is a weakly hydraulic mortar from 1595 – 1603, which makes it the oldest known hydraulic mortar in Sweden. The other samples SP22 and 23 are subhydraulic mortars from 1676-1680 (Lindqvist & Johansson 2004).

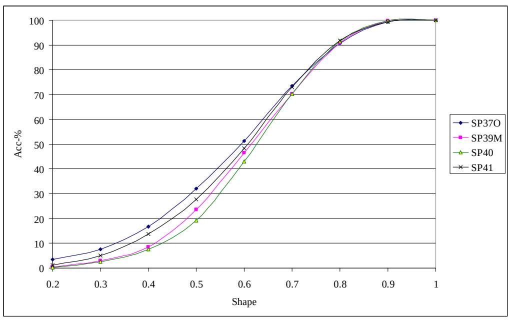
Table 3: Shape index for the different mortars and mortar groups.

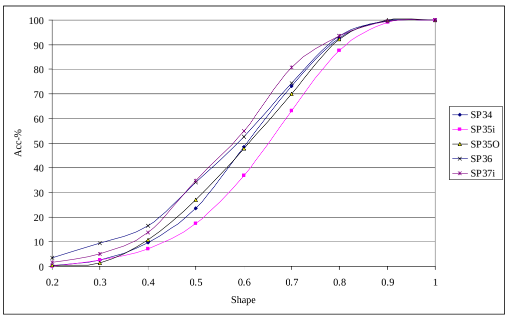
Sample	Shape	Lime	mortars	Sample	Ratio	Natural	cement
SP20	2.53	Max	3.1	SP26	3.07	Max	3.07
SP21	2.54	Min	1.88	SP28i	3.00	Min	2.40
SP22	2.71	Average	2.62	SP28M	2.68	Average	2.73
SP23	2.42	Std dev	0.35	SP28O	2.72	Std dev	0.20
SP24	2.67			SP29	2.48		
SP25	2.91			SP30i	2.40		
SP38	1.88			SP30O	2.72		
SP39i	2.86			SP31i	2.77		
SP39O	3.10			SP31O	2.69		
				SP33i	2.76		
Sample	Ratio	Shale	mortars	Sample	Ratio	Brick	dust
SP37O	1.87	Max	2.6	SP34	2.42	Max	2.72
SP39M	2.49	Min	1.87	SP35i	2.72	Min	1.73
SP40	2.60	Average	2.27	SP35O	2.36	Average	2.25
SP41	2.12	Std dev	0.34	SP36	1.73	Std dev	0.38
				SP37i	2.03		





Figures 2 and 3: Cumulative shape factors for the aggregate in lime and natural hydraulic lime mortars to the left and natural cement mortars to the right.





Figures 4 and 5: Accumulated shape factors for the aggregate in mortars with burned alum shale to the left and brick dust to the right.

The size distribution was also determined using fluorescence microscopy on the lime to natural hydraulic lime mortars and on the natural cement and early cement mortars. This revealed that the aggregates used in the cement based mortars were generally finer than the aggregates in the lime based mortars (Figure 9).

This is in agreement with the indication from the shape measurement that different types of aggregate were used for these two mortar groups.

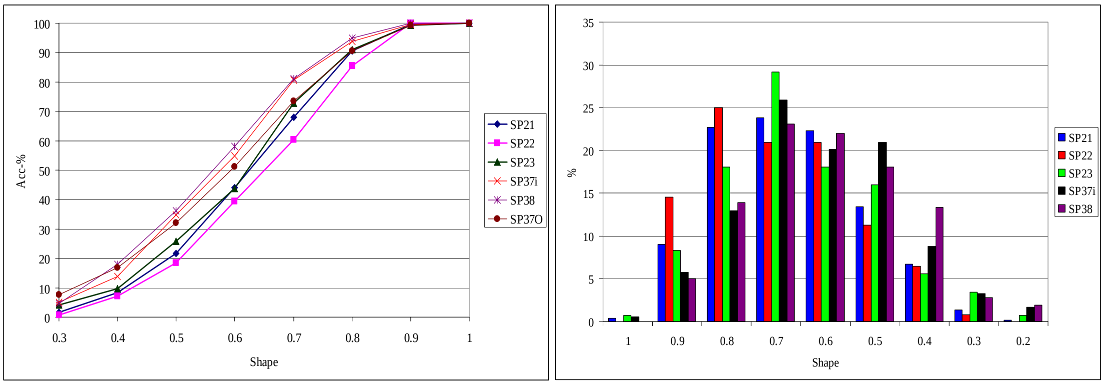


Figure 6 and 7: Shows the shape of the aggregate in three different masonry mortars and two renderings from the Southern Banco House in Stockholm.

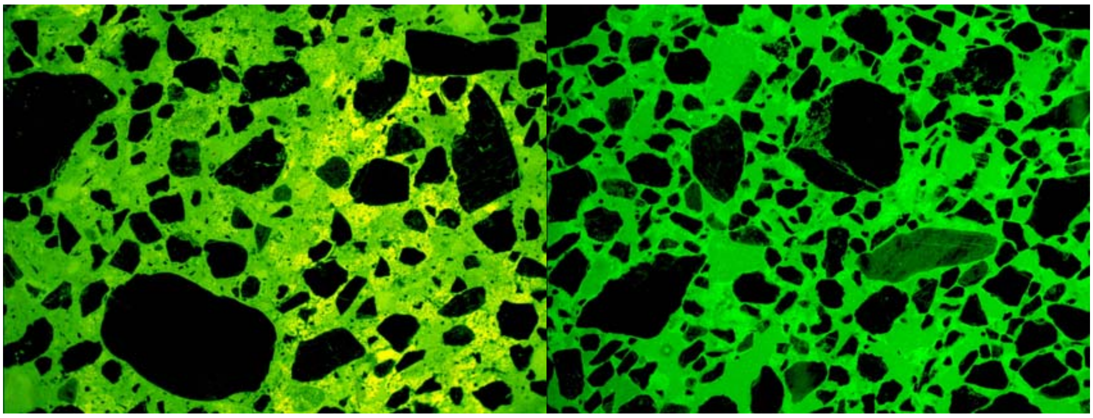


Figure 8: Fluorescence images that give an example of unoriented aggregate to the left (SP25) and oriented to the right (SP40). The orientation ratio is 1.0 in the left hand image and 0.28 in the right hand image. The shape index is 2.91 in the left and 2.60 in the right hand image. The imaged area in the photo to the left is 8.7*6.5 mm^2 to the right 5.5*4.2 mm^2.

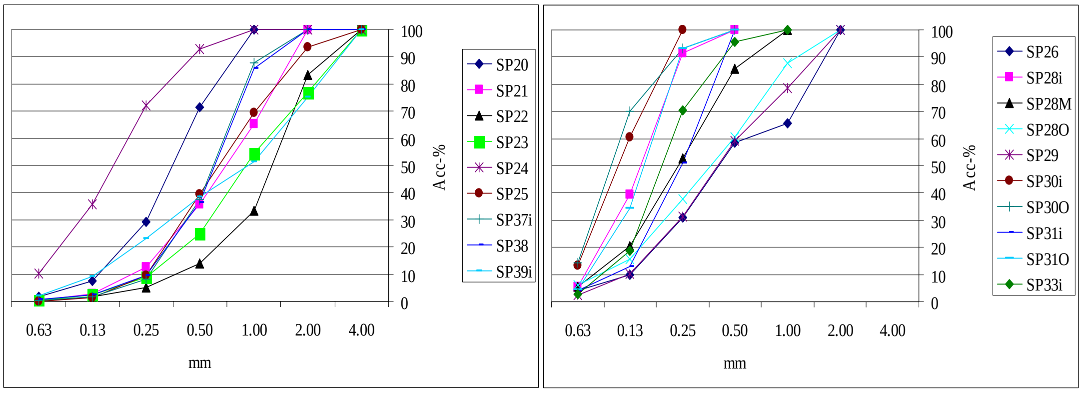


Figure 9: Size distribution of the aggregate in the lime to natural hydraulic lime mortars to the left and the natural cement and early cement mortars to the right.

Discussion

Although the variation of the individual mortars is more conspicuous than the variation between the different groups of mortars it is still possible to identify some general trends related to the type of mortar both regarding orientation and shape. The number of mortars is not sufficient to distinguish the type of application, such as masonry mortar or render. It can, however, be noted that the lime mortars have a low degree of orientation indicating that these mortars were rather stiff when fresh. There is no systematic relation between the degree of orientation and age within this mortar group. The cement based mortars have a slightly more oriented aggregate. This implies that these mortars did flow rather easily. The spread within this group is less than in the lime mortar group. This also holds true for the shape factor and the size distribution of the aggregate. Probably this reflects the more industrialised building process in the 19th century, which led to more uniform mortars. The number of alum shale mortars is too small for a systematic analysis. The two highly oriented samples are from approximately 1920 which is very late for this mortar type and their properties may differ systematically compared with older mortars of this type. Also the brick dust mortars are too few to permit a systematic analysis. The inclusion of the additives in the measurement of the two latter groups of mortars probably results in a higher degree of orientation. An example is SP35O contains highly oriented hammer slag flakes.

The measurement of shape shows that the aggregate particles in the cement based mortars are generally more rounded and show less variation in shape. The variation in the brick dust and alum shale mortars reflects to a large extent the amount and character of the additives and the number of samples is too low to allow a systematic analysis. Of special interest are the samples SP21 22 23, which are masonry mortars from the Southern Banco Building in the Old Town in Stockholm, and the samples SP37 and SP38, which are, renders from the same building and the same period. In this case a more flaky, sharper, aggregate has been used for the renderings while a rounder, softer, aggregate has been used for the masonry mortars. The Old Town in Stockholm is situated on an island that is a part of a subaquatic esker. The three sands used as aggregate in the masonry mortars were probably quarried locally in the esker. The aggregate in the renders have more elongated aggregate and are probably from a till. As can be seen in figures 6 and 7 the aggregates in the renders are almost identical and are probably from the same source. The aggregates in the masonry mortars show slight differences and are at least not from the same stratum in the same quarry.

Conclusions

There is a considerable variation in the degree of shape and orientation between the aggregate particles in the individual mortars. It is to some extent also possible to identify trends of the different groups of mortars. An example is that the cement based mortars that show less variation in the aggregate properties than the other mortar groups.

The majority of the investigated mortars show a significant degree of orientation of the aggregate particles. Measurement of the orientation of the aggregate particles can provide information on the properties of the fresh mortar. In a mortar that flows easily the length axis of the aggregate particles will be oriented in the direction of flow. Most of the cement based mortars come from cast decorations. A mortar with a good flow has probably been used for this application and the aggregate in these mortars shows a high degree of orientation. The pure lime and natural hydraulic mortars show a lower degree of orientation implying a rather stiff consistency of the mortars.

Measurement of orientation can also be used in order to get information about the application technique. For example the decorations above but it can also be measurement of the increase of aggregate particle orientation towards a tooled mortar surface although this type of investigation was not included in this project.

The shape of the aggregate particles is a useful tool for the identification of the source of the aggregate. This is especially true if combined with a quantification of the mineralogical composition. This can also be used as a tool for the identification of different mortars on a building. This could be used for determination of the mortar stratigraphy on a rendered building or as a tool in combination with other methods for identification of different building stages. The work to formalise the techniques presented in this paper into testmethods remains however to be done.

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