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A STUDY OF MORTAR DURABILITY USING THE SCRATCH TEST

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Abstract

Masonry construction involves the positioning of masonry units in a bed of fresh plastic mortar to form a composite arrangement of units in a mortar matrix. Once hardened, the mortar must provide a barrier against wind and rain, impart structural integrity (flexural and compressive strengths) to the masonry and be durable. The Australian Masonry Code, AS3700, describes appropriate test methods for the evaluation of compressive and flexural strengths and specifies acceptance criteria. Until recently no such test method has been available for mortar durability with the exception of deemed-to-comply mortar composition requirements. Recent Australian research has led to the adoption of a mortar scratch test in the masonry code as a measure of the durability potential. The research work forming the basis of this paper involved a detailed investigation using the scratch test of a range of variables which influence mortar durability. The experimental program is outlined and preliminary results presented.

Key Words: Mortar Durability, Scratch Test, Cement Content.

1 Introduction

The durability of masonry mortar is an important factor in the life of a masonry structure. Durability can be described as resistance to any form of time – dependent mortar deterioration (Page 1993). Mortar durability is influenced by many factors, including: environmental conditions; properties of masonry units; properties of the mortar and its constituents; and the attention given to design and maintenance (Harrison 1986, Guirguis, Lawrence et al. 2003).

Most durability tests are laboratory based, usually involving the soaking of samples in sulphate solution or exposing samples to repeated freeze-thaw cycles. Freeze-thaw

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exposure is not a major issue in Australia as most Australian cities, being situated along the coast, are not subject to freeze-thaw cycles. Laboratory tests, while useful for comparative studies, don't give a direct indication of the in-situ performance of mortar (Page 1993). Until recently there have been no test methods for determining the durability of masonry mortar in-situ. The need for a simple test method capable of determining durability resistance in-situ led to the development of the Scratch Test (Lawrence & Samarasinghe, 1998). This test method has recently been incorporated into the Australian Masonry Code, AS 3700 (Samarasinghe & Lawrence, 2002a, 2002b).

Tests carried out during the development of the scratch test showed a strong correlation between durability and cement content. Since masonry is constructed from a diverse range of units, sands and cement types, and since mortar joints can be finished using various tooling techniques, there is also a need to thoroughly investigate the effect of these factors. These aspects are the focus of this investigation which involves a systematic study of 12 variables in two different environments over a two year period, covering a total of 21,600 individual scratch tests. The results are being analysed statistically using analysis of variance (ANOVA). The research is still in progress, but this paper gives an overview of the investigation and presents some preliminary results for the first 180 days of the study.

2 Scratch Test

The scratch test determines the durability potential of mortar and has been described previously (Lawrence & Samarasinghe 2000). The underlying theory behind the scratch test is that it is the surface hardness or strength of a mortar that determines its durability resistance. The scratch test is a systematic method of assessing this surface hardness. The apparatus consists of a spring-loaded probe with an abrasive end, enabling a mortar joint to be scratched under a given force. The probe is turned through a fixed number of turns and the penetration into the mortar surface is measured. The scratch index is calculated as the average of 5 separate measurements of penetration with the scratch tool. The lower the index the greater the durability potential. The maximum allowable scratch index quoted in AS 3700 varies according to mortar type, as can be seen in Table 1.

Table 1. Criteria for Mortar Durability (AS 3700)

Mortar Type, Volume Proportion	Scratch Index (mm)
M2 (1:2:9)	0.5
M3 (1:1:6, 1:0:5)	0.3
M4 (1:0.25:3)	0.1

The scratch tester used in the investigation was adapted from a commercially available device with some enhancements to improve the ergonomics of the apparatus in view of the large number of readings that had to be taken. The modified apparatus was checked for compliance with the standard specifications required by the masonry standard. The device is shown in Figure 1.

3 Factors Under Investigation

The variables listed in Table 2 were selected to provide as broad a range of factors as possible and to reflect the extremes that can exist in the materials and environment that are likely to exist on site.

Figure 1. Modified Scratch Tester.

Table 2. Variables explored in the investigation

Variable	Number of Variables Investigated	Comments
Clay Unit	2	Low and High IRA.
Sand Grading	3	Two gradings (fine and coarse) and a third sand with high clay content.
Cement Blend	5	3 Commercial cements - GP, 2 GB blends (fly ash and slag) - and 2 laboratory blends derived from related bond study (Bosiljkov, Sugo et al. 2004)
Mortar Type	4	M2 (1:2:9), two M3 (1:0:5 and 1:1:6) and M4 (1:0.25:3). Volume proportion (C:L:S)
Joint Finish	3	Struck flush, ironed and raked
Environment	2	Laboratory internal and marine exposed
Exposure Time	6	Scratch tests to be carried out at 7, 28, 90, 180, 365 and 720 days. (Note 7 day scratch test would be the reference at zero time of exposure).
Total number of combinations	360	This is the total number of mortar/unit/joint finish combinations to be evaluated
Total number of piers to be constructed	720	Piers for all combinations will be exposed in each environment.
Total number of scratch tests	4320	Each scratch test result is the average of five separate indentations (giving a total of 21, 600 separate indentations).

4 Experimental Technique

4.1 Specimens

Masonry specimens used in the study consisted of four-unit stack-bonded piers constructed using fired clay masonry units. Piers were constructed four units high so that all the scratch indentations for all ages could be carried out on joints from the same pier. For each age a series of five scratch tests was carried out along one half of the length of a bed joint.

4.2 Material Properties

The materials used in the investigation were selected to represent the range of those typically used in masonry construction. Thus, two clay masonry units were selected for the investigation, one a high suction dry pressed unit (IRA = 5.24 kg/m^2/min) and the other a low suction extruded unit (IRA = 0.71 kg/m^2/min). Three sand types were used, a clean sharp dune sand known as Newcastle Beach Sand, a fatty bush sand with high clay content, and a sand with a coarser grading and moderate fines content. The grading for these sands is reported in Table 3.

Table 3. Particle Size Distribution of the three sands used.

Sieve Size	4.75mm	2.36mm	1.18mm	600μm	300μm	150μm	75μm	% Fines <75 μm
Fatty Bush	100.0	99.1	97.4	93.5	53.1	28.4	6.2	21.4
Bricklayer's White	100.0	97.7	90.9	67.1	24.9	5.9	1.4	8.4
Newcastle Beach	100.0	100.0	99.8	96.3	25.4	0.9	0.1	0

Note: The <75μm fines percentages given in the above table were determined by wet sieving.

Five cement types were selected; these were General Purpose Portland cement (GP), a commercial slag blend (referred to as GB1 in this paper), a commercial fly ash blend (referred to as GB2 in this paper), and two laboratory blends derived from a complementary masonry bond study (Bosiljkov, Sugo et al. 2004). (Note: Only results from the three commercial cements are reported in this paper). These cements cover a range of cementitious materials available for use in masonry construction. Each cement was used in four different mortar mixes (see Table 2) covering a range of cement and lime contents (and exposure ratings) as outlined in the Australian Masonry Code AS 3700. The lime used in the investigation was a commercially available hydrated lime. The amounts used in the various mortar mixes ranged from no lime to approximately 17% lime by volume. Hence the effects of cement content, lime content and cement type could be investigated.

4.3 Construction and Curing

Piers were constructed in sets of 12 according to mortar type (each mortar type consisted of 1 sand type and one cement type in specified proportions such as 1:2:9). Each set of 12 piers covered both unit types, and all three joint finishes for both exposure environments. Each set of piers was constructed using one batch of mortar to avoid any added influence of batch variations. Once construction was complete, piers were cured for 7 days under plastic to ensure the best possible curing was obtained before transporting the piers to their respective exposure sites. All piers were constructed by a professional bricklayer who judged the amount of water required for each mix.

4.4 Environments

The two exposure sites chosen for the investigation were:

- Internal, within the laboratory at the University of Newcastle where three large steel racks were constructed to support the 360 brick piers.

- Exposed in a marine environment about 150 metres from the breaking surf at Belmont Sewage Treatment Plant where two 18 metre long galvanised steel support racks were constructed to support the second set of 360 piers. The racks faced in a NE direction and were spaced 6 metres apart.

4.5 Testing

The testing regime involved performing scratch tests at 7, 28, 90, 180, 365 and 720 days on all piers. The mortar joints in the piers were divided such that half a bed joint was available for each test age, with tests starting from the left half of the top joint. Half of the piers were tested in reverse order, that is with tests starting from the right half of the bottom joint. Tests were reversed in an attempt to randomise any effect of test location. As indicated previously each scratch test involved taking the average of five separate indentations.

5 Results

5.1 Interaction Plots

Scratch test results at 7, 28, 90 and 180 days have been completed for 432 piers (covering all three sand types, three cement types and all four mortar types). Interaction plots were constructed and an analysis of variance (ANOVA) carried out using Minitab (Minitab Inc. 1997) on the results to date. The data is plotted in Figure 2 and analysed in Table 4 and is based on the mean scratch index for each factor/interaction.

Figure 2 shows a series of interaction plots constructed from the ANOVA using the results up to six months (180 days) exposure which have been completed to date. These plots aid in visualising any trends in the data. It is important to note that the scale on the plots is fairly small. Hence differences that seem large here may lose their significance when results at later ages are taken into account. Also, note that the durability potential decreases with a higher scratch index value. Each point on the plot represents the mean scratch index for a particular combination of factors. For example the first point (circle) on the line in the box at the intersection of the “site” row and the “age” column corresponds to the average scratch index for all Laboratory piers (216) tested at 7 days (with the right hand axis representing the Scratch Index). In Figure 2 each row represents a particular factor (e.g. site) and each column represents an interaction of a particular factor with the factors from the rows above it. For example, row 1 represents the factor “site”. Moving across row 1, each column represents the interaction of the factor “site” with another factor. Row 1 column 3 thus represents the interaction between “site” and “unit”, row 2 column 3 represents the interaction between “age” and “unit” and so on.

5.2 Analysis of Variance

To determine which factors are significant in Table 5, the F-value and P-value are used. The higher the F-value and the lower the P-value, the more significant is the effect. A 0.05 significance level for the P-values (that is, only accepting factors with P-values less than 0.05 as being significant) was used in determining significant factors and interactions. The factors and interactions which were deemed “significant” are noted accordingly in Table 5. It must be emphasized that these results are based on testing up to 180 days and the patterns might change as data from greater ages become available.

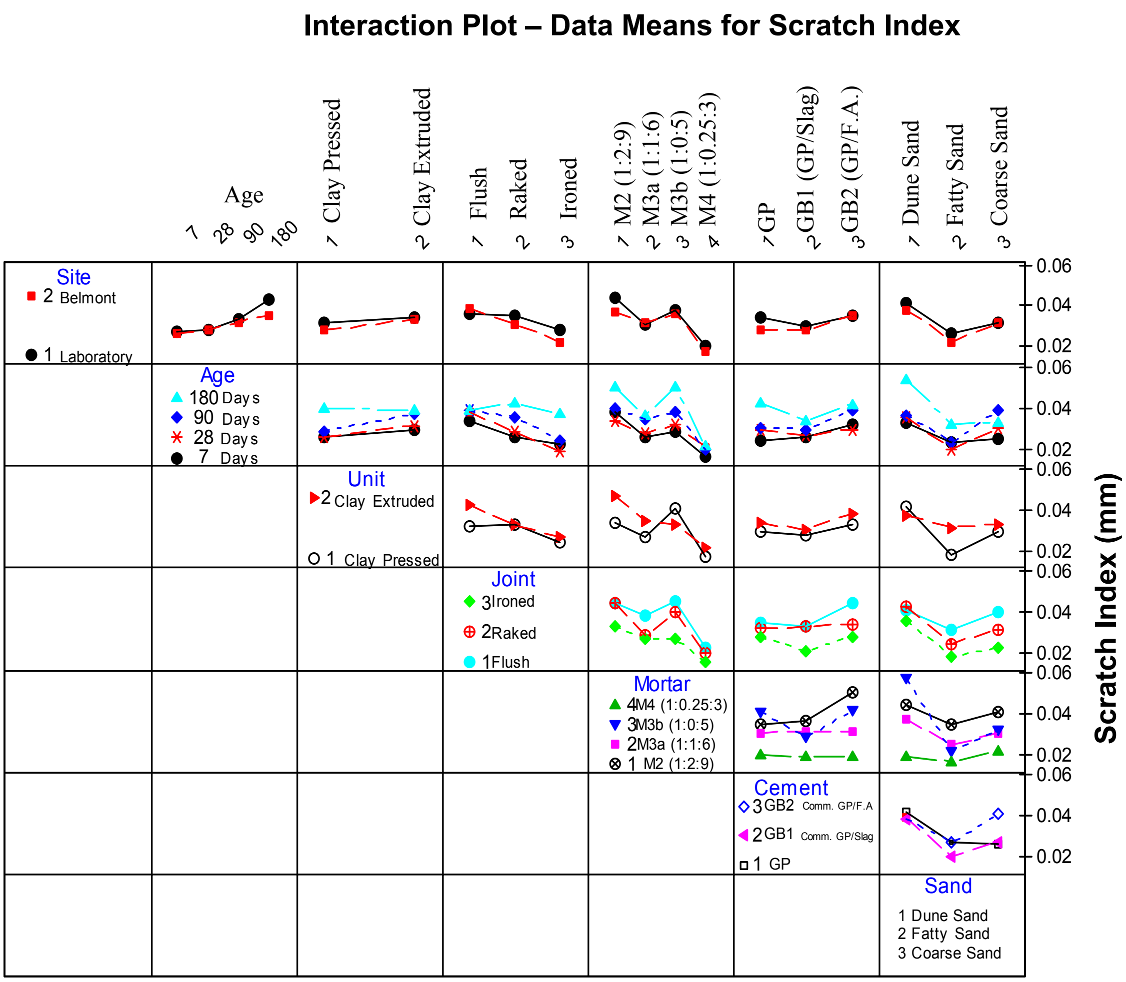

Figure 2. Interactions plot for 432 piers (7, 28, 90 and 180 day results

6 Observations and Discussion

A summary of the significant factors and interactions of the data presented in Figure 2 is presented in Table 4. The full analysis is given in Table 5 and discussed below. Note that the following discussion is in terms of scratch index, with a lower index implying a higher durability potential.

Table 4. Significant Factors and Interactions from ANOVA

Significant Factors	Significant Two-Way Interactions	Significant Three-Way Interactions
Age	Age*Joint	Site*Unit*Mortar
Unit Type	Unit*Joint	Age*Unit*Sand
Joint Type	Unit*Mortar	Age*Mortar*Sand
Mortar Type	Mortar*Cement	Age*Cement*Sand
Cement Type	Age*Sand	Unit*Joint*Mortar
Sand Type	Unit*Sand	Unit*Joint*Sand
	Mortar*Sand	Unit*Mortar*Sand
	Cement*Sand	Mortar*Cement*Sand

Table 5. Minitab ANOVA analysis

General Linear Model 7-180 Day Commercial Cements (Using Significant factors and interactions from above)								
Factor	Type	Levels	Values	Factor Level Mean Scratch Indexes				
Site	fixed	2	1 2	0.03319 0.03702				
Age	fixed	4	7 28 90 180	0.02720 0.02838 0.03282 0.03942				
Unit	fixed	2	1 2	0.02987 0.03404				
Joint	fixed	3	1 2 3	0.03740 0.03293 0.02554				
Mortar	fixed	4	1 2 3 4	0.04037 0.03106 0.03708 0.01931				
Cement	fixed	3	1 2 3	0.03156 0.02884 0.03547				
Sand	fixed	3	1 2 3	0.03970 0.02467 0.03149				
Analysis of Variance for Scratch Index								
Source	DF	SS	MS	F	P			
Site	1	0.0026502	0.0026502	2.75	0.097			
Age	3	0.0397021	0.0132340	13.73	0.000	Significant		
Unit	1	0.0075000	0.0075000	7.78	0.005	Significant		
Joint	2	0.0413203	0.0206601	21.44	0.000	Significant		
Mortar	3	0.1114211	0.0371404	38.54	0.000	Significant		
Cement	2	0.0128008	0.0064004	6.64	0.001	Significant		
Sand	2	0.0652855	0.0326428	33.88	0.000	Significant		
Site*Joint	2	0.0057515	0.0028758	2.98	0.051			
Age*Joint	6	0.0137247	0.0022874	2.37	0.028	Significant		
Age*Sand	6	0.0243344	0.0040557	4.21	0.000	Significant		
Unit*Joint	2	0.0099073	0.0049536	5.14	0.006	Significant		
Unit*Mortar	3	0.0241944	0.0080648	8.37	0.000	Significant		
Unit*Sand	2	0.0233962	0.0116981	12.14	0.000	Significant		
Joint*Sand	4	0.0091454	0.0022863	2.37	0.050			
Mortar*Cement	6	0.0234543	0.0039090	4.06	0.000	Significant		
Mortar*Sand	6	0.0505098	0.0084183	8.74	0.000	Significant		
Cement*Sand	4	0.0198940	0.0049735	5.16	0.000	Significant		
Site*Unit	1	0.0010704	0.0010704	1.11	0.292			
Site*Mortar	3	0.0032488	0.0010829	1.12	0.338			
Site*Unit*Mortar	3	0.0099537	0.0033179	3.44	0.016	Significant		
Age*Unit	3	0.0059986	0.0019995	2.08	0.102			
Age*Unit*Sand	6	0.0187663	0.0031277	3.25	0.004	Significant		
Age*Mortar	9	0.0152118	0.0016902	1.75	0.072			
Age*Mortar*Sand	18	0.0580184	0.0032232	3.35	0.000	Significant		
Age*Cement	6	0.0064094	0.0010682	1.11	0.355			
Age*Cement*Sand	12	0.0231583	0.0019299	2.00	0.021	Significant		
Joint*Mortar	6	0.0107084	0.0017847	1.85	0.086			
Unit*Joint*Mortar	6	0.0185038	0.0030840	3.20	0.004	Significant		
Unit*Joint*Sand	4	0.0126528	0.0031632	3.28	0.011	Significant		
Unit*Mortar*Sand	6	0.0173788	0.0028965	3.01	0.006	Significant		
Mortar*Cement*Sand	12	0.0263648	0.0021971	2.28	0.007	Significant		
Error	1577	1.5195523	0.0009636					
Total	1727							

Note in Table 5. The abbreviations are as follows:

SS = sum of squares = variation among groups   SS Error = variation within groups
MS = Mean Square = SS/DF = Variance   MS Error = Variance within groups
F = F-Test = MS/MS Error

6.1 Significant Factors – All Data Pooled

Column 1 in Table 4 lists all the factors that were deemed statistically significant, this includes all the variables under investigation with the exception of exposure site. This may change as data from later ages is added to the database.

- *'Age'* was significant due to 180 day results showing the highest values and the 7 day results showing the lowest values.

- *'Unit Type'* was significant due to the extruded brick specimens showing a higher average scratch index than the dry-pressed brick specimens. This is likely due to the different suction characteristics of the units.

- *'Joint Type'* was significant due to flush joint specimens showing a higher average scratch index followed by raked joint specimens, with the ironed joint specimens having the lowest scratch index of the three.

- *'Mortar Type'* was significant due to the average scratch index decreasing with increasing cement content, that is the average scratch index of M2 (1:2:9) mortar being the highest of the four mortar types and the average scratch index of M4 (1:0.25:3) being the lowest scratch index of the four. The M3b (1:0:5) mortar doesn't seem to perform as well as expected (with the second highest scratch index and the second highest cement content). Being the only mortar without any lime could suggest that lime addition may be beneficial.

- *'Cement Type'* was significant due to samples constructed from GB2 cement exhibiting the highest average scratch index of the three cement types followed by the GP cement with the GB1 cement exhibiting the lowest scratch index value.

- *'Sand Type"* was significant due to the average scratch index decreasing with increasing fines (<75μm) content. That is the average scratch index for dune sand > coarse sand > fatty sand.

6.2 Two-way Interactions

Column 2 in Table 4 lists all the two-way interactions that were deemed significant. This may change as data from later ages is added to the database.

- *Age*Joint Interaction:*
  - 7 to 90 days: flush joints > raked joints> ironed joints.
  - 180 days raked joints> flush joints > ironed joints, with ironed joints being only slightly lower than flush joints.

- *Unit*Joint Interaction:* Dry-pressed unit specimens show lower values than extruded unit specimens for flush joint. Both specimen types are equal for raked joints and there is only a minor difference between units for ironed joints. Generally flush joints show the highest average scratch index followed by raked joints then ironed joints for both units.

- *Unit*Mortar Interaction:* As cement content increases, the scratch index decreases. The M3b (1:0:5) mortar with pressed units seems to be the exception, possibly be due to lack of lime in the mortar mix combined with the high suction of the pressed units.

- *Mortar*Cement Interaction:*
    - M2 Mortar: GP cement > GB1 cement > GB2 cement in terms of scratch index.
    - For M3a and M4 mortar all cement types are equal.
    - For M3b mortar average scratch index for GB1 cement < GP cement = GB2 cement.

- *Age*Sand Interaction:*
    - 7 and 28 days: the scratch index for dune sand > coarse sand > fatty sand.
    - At 90 days coarse sand > dune sand > fatty sand.
    - At 180 days dune sand > fatty sand = coarse sand.

- *Unit*Sand Interaction:*
    - With pressed units: dune sand > coarse sand > fatty sand.
    - With extruded units: dune sand > coarse sand > fatty sand though the differences between sand types are far smaller.

- *Mortar*Sand Interaction:*
    - Fatty sand: follows cement content, i.e., M2 mortar > M3a mortar > M3b mortar > M4 mortar.
    - Dune sand: M3b mortar > M2 mortar > M3a mortar > M4 mortar.
    - Coarse sand M2 mortar > M3b mortar = M3a mortar > M4 mortar.

- *Cement*Sand Interaction:*
    - GP cement: dune sand > fatty sand = coarse sand.
    - GB1 Cement follows fines content, with dune > coarse sand > fatty sand.
    - GB2 Cement: coarse sand > dune sand > fatty sand.

Note: Not all trends observed in the two-way interactions discussed above are included due to space restrictions (as there are both trends along and between lines in the interaction plots). Also note that three-way interactions are not discussed due to space restrictions.

7 Summary and Conclusions

The study described in this paper is investigating systematically the factors affecting mortar durability. Preliminary results to date reveal the strong influence of joint finish, mortar type and sand type. Any form of joint tooling seems to enhance the durability performance of the mortar, with joint ironing being the most beneficial. The preliminary results reveal a strong correlation between scratch index and cement content with scratch index decreasing with increasing cement content. This is consistent with the earlier studies carried out during the development of the test method (Lawrence & Samarasinghe, 1998).

An interesting observation from the results relating to cement and lime content was the unusual behaviour of the M3b (1:0:5) mortar (containing the second highest cement content and no lime). This mix did not perform as well as the M3a (1:1:6) mortar despite having a higher cement content, suggesting that there may be added benefits of incorporating lime into the mortar mix. The effects of age appear to potentially influence the durability performance.
While the preliminary results show some trends it is important to stress that only tests at early ages have been completed. Hence differences that are significant at this stage may lose their significance when results at later ages are taken into account.

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