AN INVESTIGATION OF FACTORS AFFECTING THE DURABILITY OF MASONRY MORTAR

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SUMMARY

Mortar durability in temperate climates is related to the surface hardness of the mortar joint. The Australian Masonry Structures standard AS 3700 contains a test method known as the scratch index test for measuring this hardness. The paper describes an investigation using the scratch test to explore the effect on durability of sand type, cement type, mortar composition and joint tooling.

The results at 90 days age indicate that joint finish, mix proportions and sand type are significant factors affecting durability. In addition, both cement type and joint finish interact with sand type. Ironing of joints and the presence of fines in the mortar, either from a proportion of clay in the sand or from the inclusion of lime, enhance the scratch index.

INTRODUCTION

In Australia and similar temperate climates, the durability of masonry mortar is a question of resistance to abrasion from wind action, wetting/drying cycles and crypto-efflorescence from air-borne or water-borne salts. In a review paper, Bowler (1993) refers briefly to fretting of mortar by forces caused by salt crystallisation but does not give it any emphasis. To date, the focus in all European studies of mortar durability has been on freeze-thaw and chemical attack by sulphates. The key factors in resistance to these mechanisms include sand grading, cement content, air content, brick properties, pore size distribution and workmanship (Harrison & Bowler, 1990). In temperate climates, on the other hand, freeze-thaw cycles do not occur and degradation does not involve a chemical reaction. The relevant mechanisms of attack are largely resisted by the surface hardness of the mortar and it is therefore logical to use surface hardness as a measure of mortar durability under these conditions. Test methods using rebound hammers (RILEM, 1997; Schmiedmayer 1997) have been directed at mortar compressive strength and pointing quality, and are not applicable to durability. All references to mortar durability in this paper are in the context of surface hardness and are not meant to relate to freeze-thaw or chemical attack by salts.

The Australian Masonry Structures Standard AS 3700 (Standards Australia, 2001) includes a scratch test for assessing the durability potential of masonry mortar, and includes deemed-to-satisfy criteria for various exposure conditions. Apart from its use in the standard as a control test, this test provides a means of assessing the relative effects of different factors on the mortar durability for a range of materials and construction techniques.

The scratch test employs a mechanical tool to measure the penetration of a standard probe under a given force and rotation into the mortar surface. The penetration depth is correlated with potential durability performance. A scratch index is derived as the average of five separate penetration measurements (in mm). The lower the index, the higher is the surface hardness and therefore durability. The technique determines the surface hardness of the mortar and can be used both on site to test in-situ walls and in the laboratory to evaluate new mortars. The test method was specifically developed as a means of predicting the durability potential of the mortar when it is exposed to the physical degradation mechanisms found in the Australian environment. The development of the test method has been reported elsewhere (Lawrence & Samarasinghe, 1998 and 2000; Lawrence et al, 2004).

The work leading to the development of the test methods identified joint tooling and mix composition as two important factors in determining durability, but did not systematically examine these or other possible factors. Sand grading has been examined as a factor in relation to freeze-thaw resistance, but has been shown to have little effect on resistance to sulphate attack (Harrison, 1986; Yool & Lees, 1995).

This paper describes an investigation, funded by Cement Concrete and Aggregates Australia, designed specifically to identify the factors affecting mortar durability in temperate climates and to measure their relative effects. The experiment was planned as a fully factorial design, so that the significance of the various factors could be examined by the analysis of variance (ANOVA).

OUTLINE OF TESTS

In designing the investigation, variables that were considered likely to influence mortar durability were chosen and a range of values was selected for each to provide as broad a range of factors as possible. The variables considered are clay brick type, sand grading, cement type (covering a range of general purpose and blended cements), mix proportions and joint finish. Specimens were exposed to two different environments – laboratory and marine exposure – and were tested over a period of three years from construction of the masonry. In total, 3024 measurements of scratch index were performed on 432 masonry prisms. As required by the test method, each measurement of scratch index was the average of five separate measurements with the test instrument.

The variables and factors are summarised in Table 1. Two masonry prisms were constructed for each combination of masonry unit, sand, cement, mortar mix, and joint finish. One of each pair of prisms was exposed to each of the environments from 7 days after laying. Measurements were taken on each prism at seven ages from seven days to three years. Building the stack-bonded prisms four courses high provided enough joint length in each prism to perform the tests for all ages. The three sand types were chosen to represent the range commonly used for clay brickwork in Australia.

No properties of the mortar (such as compressive strength) were measured, as the intention of the research was not to investigate secondary properties that might relate to durability performance, but to measure directly the surface hardness. As discussed in the Introduction, the scratch test has been demonstrated to be useful for this purpose.

Table 1. Variables Included in the Investigation

Variable	Levels	Details
Clay Brick	2	Low and high rates of absorption.
Sand	3	Two with low clay content (Dune and Coarse) and one with high clay content (Fatty).
Cement	3	General Purpose Portland (GP), Fly Ash Blend, and Slag Blend.
Mortar Composition	4	M2 (1:2:9), two M3 (1:0:5 and 1:1:6) and M4 (1:¼:3).
Joint Tooling	3	Struck flush, ironed and raked.
Exposure Environment	2	Laboratory (internal) and marine (exposed).
Age	7	Tests carried out at 7, 28, 90, 180, 365, 720 and 1095 days.

The particle size distributions of the sands are shown in Table 2. The values for sieve size < 0.075 were determined by washing and the other values by dry sieving. The amount of water added to the mortar mix was not monitored, as experience has shown that normal site practice is best simulated by allowing the bricklayer to mix the mortar to a suitable workability, using the amount of water appropriate to the sand type and mix composition.

Table 2. Sand Particle Size Distributions (% Passing Each Sieve).

Sieve (mm):	< 0.075	0.075	0.15	0.3	0.6	1.18	2.36	4.75
Dune	0	0.1	0.9	25.4	96.3	99.8	100.0	100.0
Fatty	24.1	4.2	9.0	28.4	72.7	86.5	95.7	100.0
Coarse	8.7	0.3	1.6	11.3	45.5	80.6	94.1	99.6

The test specimens stored in the laboratory environment are shown in Figure 1. Those in the exposed marine environment are shown in Figure 2. Figure 3 shows the scratch test instrument in use on a masonry wall.

Figure 1. Test Specimens in the Laboratory Environment

Figure 2. Test Specimens in the Exposed Environment

RESULTS AND ANALYSIS

For an experiment such as this, which involves several levels of several different factors, ANOVA is a powerful technique for identifying the significance of the factors and examining interactions between them. However, for this technique to be used, the data must satisfy certain requirements for normality and homogeneity of variance (Eisenhart, 1947). Initial examination of the data showed that these assumptions were not satisfied, but that a logarithmic transformation of the data would restore its normality and homogeneity of variance. A log-transform of the data was therefore used in performing the analysis of variance to identify significant factors and interactions.

Figure 3. A Scratch Test Performed on a Wall

The experiment produced a large data set, and a full analysis of performance over time for all factors will be presented elsewhere. For the purpose of the present paper, only the data at 90 days age are considered. This age has been chosen for a preliminary analysis of the factors because it allows for the hardening of the joints to take place, especially for the blended cements, where strength gain can be slower than for general purpose Portland cement. In addition, 90 days was expected to be insufficient for possible differences between the two exposure environments (laboratory and marine) to show up. Furthermore, to reduce the volume of data presented here, the two types of masonry units, pressed and extruded, have been pooled together, reflecting the impracticality of trying to distinguish between different types of clay bricks when designing for durability.

The experiment did not include any replication of tests for each combination of factors, with only a single measurement of scratch index available for each set of conditions. Initial ANOVA of the 90-day data therefore involved the pooling of all four-way and higher interactions between the factors into an error term, i.e. considering them as random effects. It is unlikely that such high-order interactions, for example between joint, mortar, cement and sand, would have any practical significance. This analysis confirmed that the site exposure effect was not significant at 90 days age and that all two-way interactions between factors, except cement-sand and joint-sand, were also not significant and could be treated as random. Pooling these non-significant interactions with the error term produced the ANOVA table shown in Table 3. This table shows the F-ratios in the column 6 and the applicable probability of the effect arising by chance in the column 7. The probabilities less than 0.05 (5%) are considered significant and are marked with *.

Table 3. Analysis of Variance Table (Data for 90 Days Age)

STAT. GENERAL MANOVA	Summary of all Effects; design: (anovadat.sta) 1-SITE, 2-JOINT, 3-MORTAR, 4-CEMENT, 5-SAND Customized Error Term					
Effect	df Effect	MS Effect	df Error	MS Error	F	p-level
Joint	2*	9.88206*	414*	.492920*	20.04799*	.000000*
Mortar	3*	6.02965*	414*	.492920*	12.23250*	.000000*
Cement	2	1.14183	414	.492920	2.31647	.099898
Sand	2*	10.98909*	414*	.492920*	22.29387*	.000000*
Joint-Sand	4*	2.02256*	414*	.492920*	4.10323*	.002844*
Cement-Sand	4*	4.69897*	414*	.492920*	9.53292*	.000000*

The cement-sand interaction is illustrated by the plot of mean scratch indices (averaged over all other factors) in Figure 4. Since a higher scratch index indicates a poorer performance, it can be seen that the fly ash blend cement performs worst in combination with the coarse sand. All cements perform better with the fatty sand than with other sands and all cements perform equally well with the dune sand. It is possible that the performance of the fly ash blend cement will improve over time, as it has been well established that mortars containing fly ash develop strength more slowly over the first year (Taha & Shrive, 2004).

All combinations of cement and sand are performing significantly better than the lowest criterion in Table 10.2 of AS 3700 (Standards Australia, 2001), namely 0.1 mm scratch index for an M4 mortar.

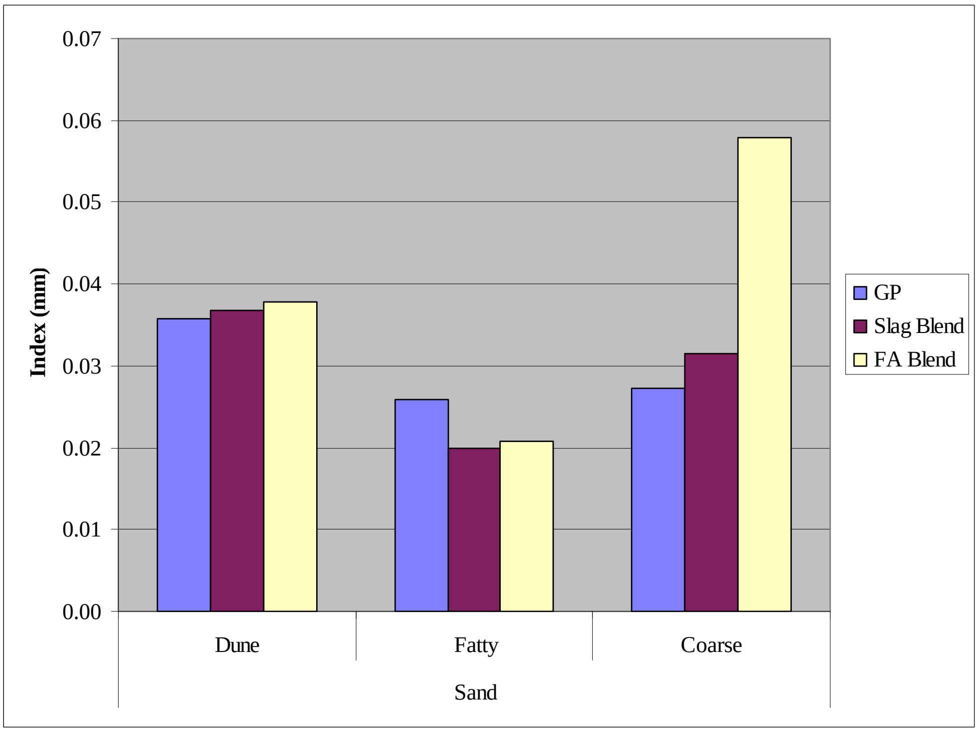

Figure 4. Means for Cement-Sand Interaction.

The joint-sand interaction is shown by the plot of mean scratch indices (averaged over all other factors) in Figure 5. The statistically significant interaction arises because the fatty sand/ironed joint combination performs exceptionally well, while the coarse sand/raked joint combination performs relatively poorly. In the case of the fatty sand used with an ironed joint finish, the clay fines in the sand enhance the compaction of the joint, resulting in a greater hardness and therefore scratch resistance. For the coarse sand used with a raked joint finish, the larger particles in the sand can be dislodged by the raking, resulting in an uneven surface, which gives a lower scratch resistance.

Apart from these two cases, the overall trends amongst the three sand types and amongst the three joint finishes are uniform and these are discussed under the main effects in the next section.

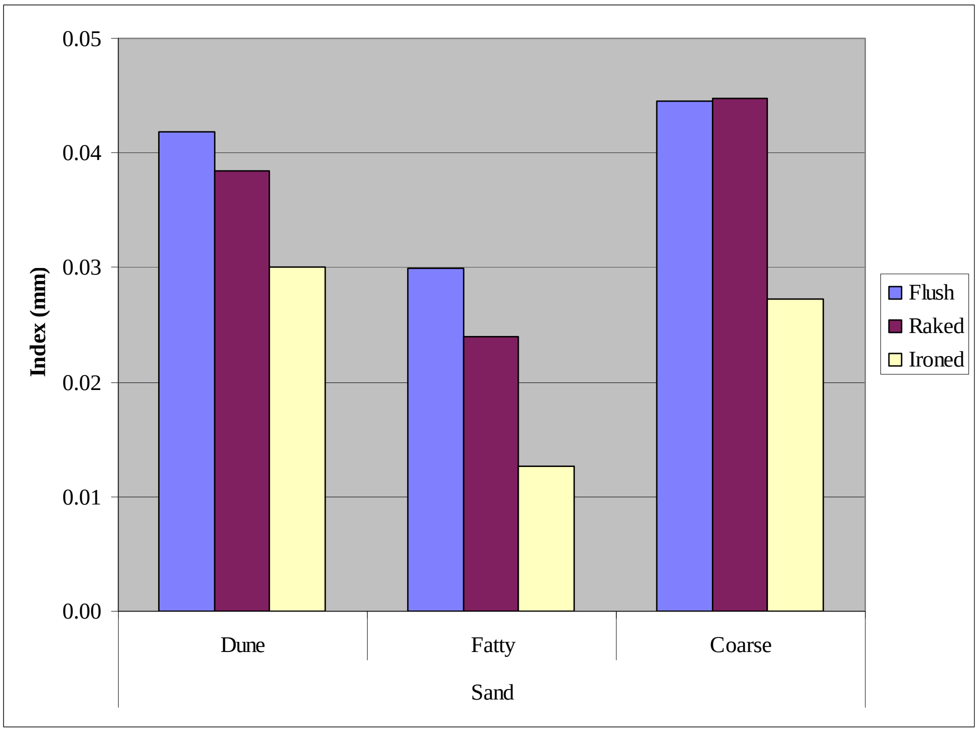

Figure 5. Means for Joint-Sand Interaction

SIGNIFICANT FACTORS

The overall effect of joint finish, averaged over other factors, is shown in Figure 6. It can be seen that the ironed joint finish performs the best, and this is attributed to the compacting effect of the ironing, which produces a denser surface layer on the joint, thus imparting higher resistance to the scratch test and an expected greater durability in exposure to a harsh environment. This effect was noted in the initial trials for development of the scratch test (Lawrence & Samarasinghe, 1998).

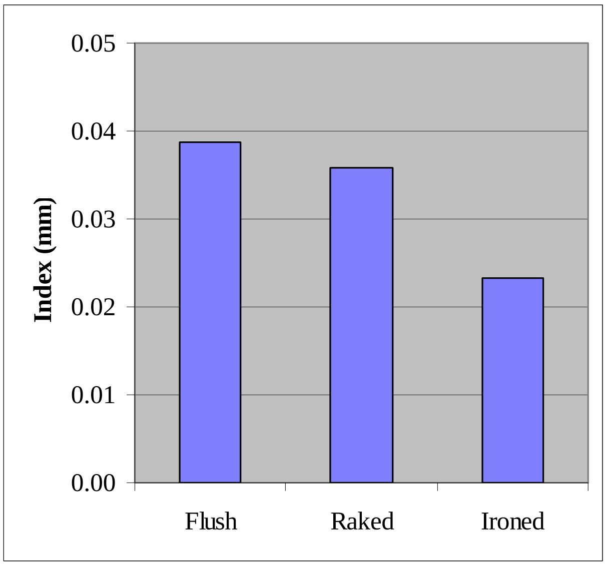

Figure 6. Joint Effect

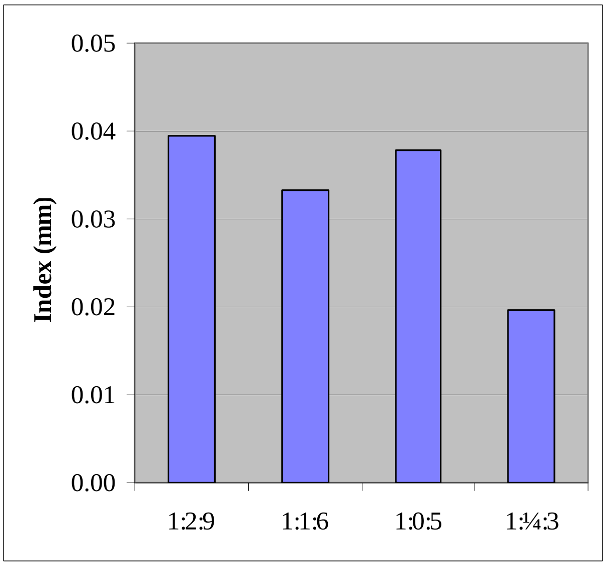

Figure 7. Mortar Effect

The effect of mortar, averaged over other factors is shown in Figure 7. The performance can be ranked in order of improvement from the M2 mortar (1:2:9) to the M4 mortar (1:¼:3). One of the M3 mortars (1:1:6) performs somewhat better than the other M3 mortar (1:0:5), despite the higher cement content of the latter. This is attributed to the presence of lime in the 1:1:6. The 1:0:5 mortar is only marginally better than the 1:2:9, despite having a significantly higher cement content, and this is also attributed to the presence of lime in the latter, which helps to impart a dense compacted surface, especially with the ironed joint finish and to a lesser extent with the raked joint finish. The correlation of scratch penetration with cement content of the mortar was noted during development of the scratch test (Lawrence & Samarasinghe, 1998) and is confirmed by these results with a wider range of materials and joint finishes.

The cement effect, averaged over other factors, is shown in Figure 8. While the performance of the Portland (GP) cement and the slag blend cement are similar, the fly ash blend cement shows a worse performance overall. However, its performance might improve over time, with further strength development, and this will be examined in a future analysis of the whole data set. In the meantime, it should be noted that all the cements have given overall results significantly better than the lowest criterion of 0.1 mm scratch index in AS 3700 (Standards Australia, 2001).

The effect of sand type, averaged over other factors, is shown in Figure 9. The fatty sand is the best performer and, as discussed earlier, this is primarily attributed to the clay content producing a better compaction of the joint and a greater scratch resistance. However, the fact that the fatty sand performs best for all three joint finishes (see Figure 5) might indicate that there is a pozzolanic effect from the clay material in the fatty sand. The coarse sand gives marginally worse results than the dune sand.

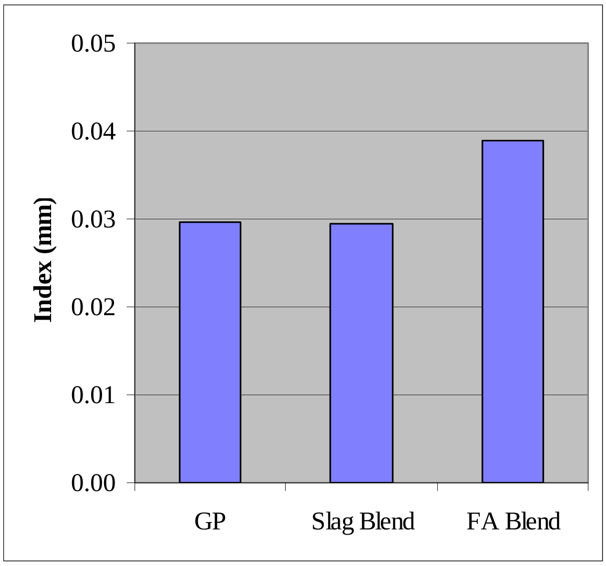

Figure 8. Cement Effect

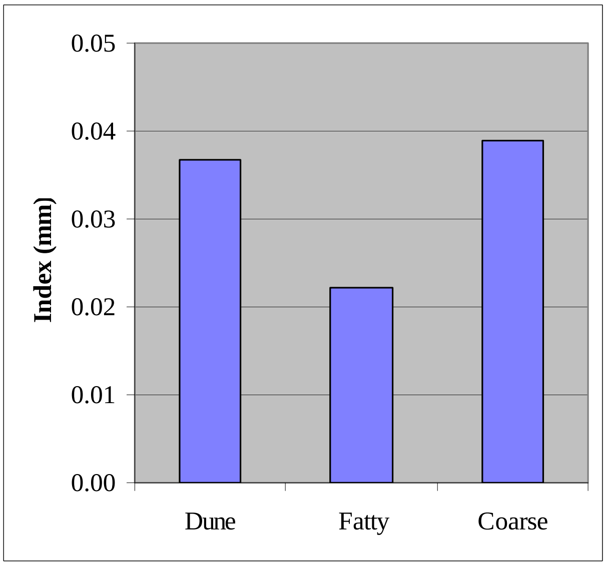

Figure 9. Sand Effect

RELEVANCE FOR STANDARDS

The results of the investigation, for the scratch index resistance at 90 days age, support the current provisions of AS 3700 concerning the relative performance of M2, M3 and M4 mortars. The investigation was not designed to examine the acceptance criteria of AS 3700, although future analysis of the data might allow some comment to be made concerning the relative performance under exposure to a marine environment.

The results confirm that joint finish is an important factor in affecting hardness of the joint, and that this is measured by the scratch test. They also indicate that sand type can be a factor, and that this can interact with joint finish in determining the final hardness of the joint. However, it is possible that high clay content in the mortar might have a longer-term effect in allowing the surface of the joint to break down under repeated wetting and drying cycles, with or without the presence of salts. This would have obvious implications for durability of the joints and will be examined further using the full data set from this investigation.

CONCLUSIONS

The scratch test is useful for assessing the relative effects of various factors influencing mortar hardness and hence durability in the Australian and other temperate environments. The significant factors affecting performance are:

1. Joint finish, with ironed joints performing the best.
2. Mortar composition, with high cement content and the presence of lime enhancing performance.
3. Sand type, with the presence of clay enhancing performance at 90 days age and the presence of coarse particles detracting from performance.

Joint finish and sand type can interact, in that an ironed joint combined with sand that contains a proportion of clay fines will produce a significantly enhanced performance.

Further analysis of the data will be used to examine the effect of blended cements, compared with GP Portland cement, to examine the age and exposure effects, and to assess the main factors over the full age range up to three years.

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REFERENCES

Bowler, G.K., 1993, “Deterioration of Mortar by Chemical and Physical Action”, *Masonry International*, Vol.6, No.3, pp.78-82.

Eisenhart, C., 1947, “The Assumptions Underlying the Analysis of Variance”, *Biometrics*, Vol.3, No.1, pp.1-21.

Harrison W.H., 1986, “Durability Tests on Building Mortars – Effect of Sand Grading”, *Magazine of Concrete Research*, Vol.38, No.135, pp.95-107.

Harrison, W.H. & Bowler, G.K., 1990, “Aspects of Mortar Durability”, *British Ceramic Society Transactions and Journal*, Vol.89, No.13, pp.93-101

Lawrence, S.J. & Samarasinghe, W., 1998, “A New Method for Assessing the Service Life of Masonry Mortars”, *Rehabilitation of Structures: Proceedings of the 2nd International RILEM/CSIRO/ACRA Conference*, Melbourne, pp.481-488.

Lawrence, S. & Samarasinghe, W., 2000, “Assessing the Durability of Masonry Mortars”, *Proceedings of the 12th International Brick/Block Masonry Conference*, Madrid, pp.1053-62.

Lawrence, S.J.; Samarasinghe, W. & Guirguis S., 2004, “Mortar Durability – Development and Standardization of Test Methods”, *Proceedings of the 13th International Brick/Block Masonry Conference*, Eindhoven University of Technology.

RILEM, 1997, “MS-D.7: Determination of Pointing Hardness by Pendulum Hammer”, *Materials and Structures*, Vol.30, pp.323-324.

Schmiedmayer R., 1997, “Non-destructive In Situ Determination of Mortar Load Capacity Using a Modified Schmidt Rebound Hammer”. *Proceedings of the 11th International Brick/Block Masonry Conference*, Shanghai, China, pp.367-375.

Taha, M.M.R. & Shrive, N.G., 2004, “Flexural Bond Strength of Normal and Fly ash Modified Mortars”. *Proceedings of the 7th Australasian Masonry Conference*, Newcastle, NSW, pp.161-170.

Standards Australia, 2001, *AS3700 Masonry Structures*, Sydney.

Yool A.I.G. & Lees T.P., 1995, “The Effect of Clay Fines in Sand on the Durability of Mortar”, *Proceedings of the British Masonry Society*, Vol.7, No.1, pp.13-18.