ELSEVIER

0958-9465(95)00042-9

Cement and Concrete Composites 18 (1996) 41-46

0958-9465/96/$15.00

Roller Compacted Sheets of Polymer Modified Mortar

B. P. Hughes & B. Lubis

School of Civil Engineering, University of Birmingham, Birmingham, UK

(Received 7 January 1994; accepted 20 September 1995)

Abstract

The strength development of a polymer modified mortar (PM mortar) compacted by rolling into sheets has been investigated and the test results include modulus of rupture, compressive strength and also bond strength when rolled onto a concrete surface at ages from 3 to 120 days. The mortar contained Ordinary Portland Cement (OPC), Pulverized Fuel Ash (PFA), fine sand, Polyvinyl Alcohol (PVA), and sometimes in addition Styrene Butadiene (SB) latex and silica fume slurry. As expected a mechanical roller provided the highest strengths with MOR values up to 26 MPa compared with up to almost 17 MPa for hand rolling.

The forms of failure for cube specimens tested either parallel to or perpendicular to the as-rolled direction were the same; thus the adhesion between the layers was very good. The bond strength development for the PM mortar to concrete correlated well with the cube strength development. The highest bond strength of about 12 MPa was obtained with 8% PVA by weight of cement. However, inclusion of between 5-10% PVA by weight of cement only had a small effect on the bond strength between PM mortar and steel. The average bond strength value from Pull Out tests for plain steel bars was of the order of 5 MPa.

The high bond strength to concrete as well as the high tensile strength shows that the PM mortar is especially suitable for enhancing the strength of concrete members in a repair situation, particularly in the form of ferrocement in which reinforcement is sandwiched between adjacent sheets of PM mortar.

Keywords: Concrete repair, ferrocement, polymer modified mortar, roller compaction, bond strength, tensile strength, polymer cement.

INTRODUCTION

The use of polymers in concrete continues to be widely investigated in many countries throughout the world and the developments can be broadly divided into three major categories: Polymer-Impregnated Concrete (PIC), Polymer-Concrete (PC) and Polymer-Cement Concrete (PCC).[1] A wide range of premix polymer modified cement concretes and mortars come within the general PCC category and in particular, includes the specific roller compacted polymer modified mortars investigated here.

If the properties of polymer modified concretes are compared with the best that can be obtained from conventional Portland Cement concretes it is clear that there is little advantage to be gained from polymer additions for either the compressive strength or stiffness, and considerable benefits for higher flexural and bond strengths, even though there may be some increase in brittleness.[2] Since the polymer can be considered to act as an adhesive and can also provide an internal lining to voids within the mortar, the tensile and bond strengths can be improved very effectively. The plasticity of the fresh mortar or concrete can also be improved by reducing the internal friction between the particles.[3] The strain at maximum compressive and tensile stress of polymer-modified mortar became steadily greater with the increasing polymer content.[11] The polymer modified concrete in another investigation showed a tensile splitting strength increase of 255% and a compressive strength increase of 277% in the respective strength of control cylinders.[12]

Improvements in compaction and reduced void contents should be possible with the use of better graded materials. For example, PFA can be used in concrete for all types of applications for both its pozzolanic properties and its rounded particle shape[4] and more recently it has become a most important ingredient of roller compacted concrete in the construction of dams and road pavements.[8] Similarly silica fume, which also has a rounded particle shape, but has a much finer particle size than the cement, can be used both as a very effective filler and as an effective pozzolan.

On-going research on high strength polymer modified mortars has proceeded at The University of Birmingham for some years.[3,5–7] The present paper presents further results for rolled sheets of polymer modified mortar which include modulus of rupture, compressive strength and also bond strengths when applied by rolling onto concrete surfaces.

PREPARATION OF MORTAR SHEETS

The materials used in this investigation included Ordinary Portland Cement (OPC), Pulverized Fuel Ash (PFA), 1·8 mm maximum size sand, Polyvinyl Alcohol (PVA), and sometimes in addition Styrene Butadiene (SB) latex and silica fume slurry. The uncrushed natural sand was supplied from Bodymore Heath, Sutton Coldfield and was composed almost entirely of quartz grains. This as-received sand was then screened to remove fractions coarser than 1·8 mm.

Two Test Series were carried out as follows:

Series 1. The materials used were OPC, PFA, fine sand, PVA and water in the proportions (by weight) of 1:0·33:2·13:0·0533:0·33.

Series 2. Silica fume slurry consisting of 50% solids and 50% water and SB latex with 44·5% solids and 55·5% water were also included. The proportions (by weight) of OPC:PFA:fine sand: silica fume slurry:SB latex:PVA:added water were 1:0·25:2:0·20:0·10:0·05:0·1915. This gave a total water/cement ratio of 0·347.

The dry ingredients (OPC, PFA, PVA and fine sand) for each batch were first mixed for 3–4 min to ensure good dispersal. The added water was mixed separately with the silica fume slurry and SB latex where appropriate before the liquid (water alone or slurry/latex/water mixture) was added to the dry ingredients. The 10 dm^3 bench mounted mixer was run at a medium speed when first mixing the 2–5 kg batches with water. The speed was then reduced to increase the torque for mixing as the plasticene-like material with very high cohesion was formed. The total time for mixing was 6–10 min before the material was ready for compaction. It was found that higher PVA or OPC contents resulted in a more cohesive material, which was more difficult to mix and to compact. Conversely more water, or PFA, or sand, was easier for mixing and compaction.

Compaction of the PM mortar was most conveniently achieved by rolling. The plasticene-like material was first rolled into a sheet of uniform thickness and the full thickness was then built up in several layers, depending upon the total thickness of sheet required. A suitable thickness for each layer for the hand roller to obtain good compaction was 5–8 mm. To obtain good bonding between layers the top face of the lower layer should be kept covered and water should be applied just before rolling on the next layer. The process of building up in layers readily lends itself to the inclusion of reinforcement by placing fabric between the layers.

The method of rolling and building up the full depth in layers was similar for the mechanical rollers. The mechanical rollers had the advantage that the gap between the roller and the base of the PM mortar could readily be adjusted and fixed to a constant distance and high pressures could also be applied. The minimum practical thickness that could be produced was about twice the maximum particle size of the mortar. For these tests, the minimum setting for the small spring-loaded mechanical roller was 3 mm and that for the larger mechanical twin-roller was 5 mm. The full section was built up by superimposing further layers cut from the primary rolled sheet and then, by resetting the roller gap to the required final thickness, a further rolling of the full section bonded the layers together.

SPECIMENS AND TESTING PROCEDURES

Hand rolling was completed in three layers to give a total thickness of 18 mm in a 400 × 280 × 18 mm mould to form the sheets from which the flexure test specimens were cut.

The average size of the hand rolled specimens for the flexure test was $320 \times 50 \times 18$ mm. The maximum thickness which could be rolled in the small roller was 22 mm using a mould measuring 320×100 mm in plan. The sheets were built up in seven layers and then rolled to 20 mm before cutting the $320 \times 50 \times 20$ mm flexure test specimens for the small roller. The sheets were built up in four layers in a mould 200×1000 mm in plan for the mechanical twin-roller and the 18 mm thick sheet was then cut to form the $320 \times 50 \times 18$ mm flexure test specimens. 5 specimens were prepared for each set of tests and covered with polypropylene sheet for 24 h. The flexural specimens for both Series 1 and 2 were tested using third point loading on a 300 mm span at the loading rate of 0·1 kN/min and the maximum load and failure section dimensions were recorded for each specimen (ASTM C78-75).

Compressive strength and the type of failure were determined by crushing 2" (50·8 mm) cubes at loading rates of 35 kN/min either perpendicular to or parallel to the as-rolled direction of PM mortar. In Series 1, 6 specimens were prepared for each set, 3 for each direction. In Series 2, 3 specimens were tested, all perpendicular to the as-rolled direction only. The material for the 2" cube specimens was rolled initially as for the flexure test specimens and then 3 layers were superimposed to form a 'thick' layer, which was then rolled to about 17 mm for the hand roller, or 8 mm for the small roller or 13 mm for the mechanical twin-roller. The 'thick' layers were cut into 50×50 mm square pieces and placed in the mould, and finally gently rolled to obtain good bond between the layers. In order to obtain a perfectly flat top surface to the cube, a flat steel plate was clamped to the top of the cube mould after placing the layers. Three 'thick' layers (i.e. 9 primary layers) were used for the hand roller, six 'thick' layers + one primary layer (i.e. 17 primary layers) for the small roller and four 'thick' layers (i.e. 12 primary layers) for the mechanical twin-roller. The specimens were covered with polypropylene sheet and demoulded after 24 h. It is anticipated that the 50·8 mm cubes would be about 8% stronger than a 150 mm cube which would normally be used for substrate concrete.[10]

Bond strengths between steel and PM mortar were obtained from the Pull Out test specimens, consisting of 100 mm cubes of PM mortar and 10 mm diameter plain steel bars. A central embedded bar was pulled at one end while the other was held by gripping two embedded bars. Each cube was built up from nine 10 mm and two 5 mm hand rolled layers and the steel bars were placed within the 3rd, 6th and 9th layers.

The concrete specimens for a slant shear test were basically based on the 'Arizona Slant Shear Test'.[9] It was also found that the most sensitive and least variable method of testing for bond strength and flexibility was the slant shear test.[13] The concrete prisms were cast in two parts with a separation plane at an angle of 30° in special prism moulds and they were demoulded after 24 h. The split prisms were stored in water for at least 28 days and then dry cured for 24 h before joining. The PM mortar strip was rolled on to each inclined surface and the two parts were pressed together under a standard pressure of 1·96 kN/m^2 (normal to the inclined surface) for 24 h.[6,7] $50 \times 50 \times 150$ mm and $100 \times 100 \times 300$ mm prisms were used for Series 1 and Series 2, respectively. The surface of some specimens in Series 2 were left smooth whereas others were either brushed to obtain a rough surface or painted with SB latex to act as a bonding aid just before rolling on the PM mortar. Bond strengths between PM mortar and hardened concrete were determined by compressing the jointed prisms. Three specimens for each group were tested at the rate of 35 kN/min for $50 \times 50 \times 150$ mm prisms, and 150 kN/min for the larger prisms ($100 \times 100 \times 300$ mm). These values were based on the load which should be applied on the cube, i.e. at a constant rate of stress equal to 15 MPa/min (BS 1881: Part 4: 1970 and ASTM Standards C 39-72).

All specimens in Series 1 were demoulded after 24 h, painted three times on the day of demoulding with a membrane curing compound Feb-Cure, and then dry cured until testing in the laboratory, in order to reduce both evaporation and absorption of water. Series 2 was similar to Series 1 except that the specimens were damp cured under hessian for 6 days before applying the Feb-Cure.

RESULTS AND DISCUSSION

The experimental results are shown in Table 1, Figs 1 and 2 for Series 1 and Figs 3–6 for Series 2. Strength development with age is seen to be

Table 1. Bond strengths at 28 days for Series 1 (hand rolling) with varying PVA proportions

Mix	*PVA/OPC (%)*	*Bond strengths (MPa)*	
		Pull out	*Slant shear*
D1	2·67	4·0	7·5
D2	5·33	5·3	11·7
D3	8·00	5·2	12·1
D4	10·67	5·1	10·0

affected by the method of rolling and, for cube strength, by the testing direction. The rolling technique is clearly important and could be further developed from the simple hand roller and mechanical rollers to a motorised vibratory roller for thicker layers.

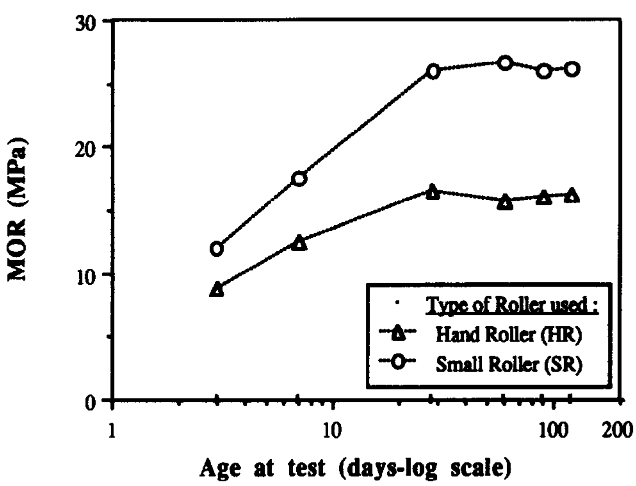

Fig. 1. Modulus of rupture vs age at test for Series 1.

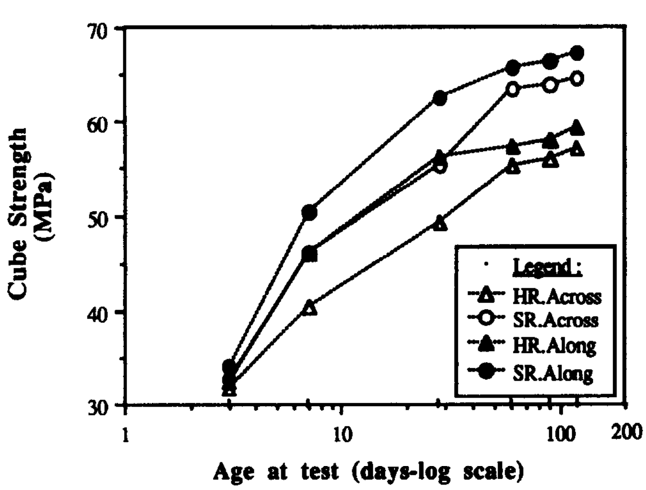

Fig. 2. Cube strength vs age at test for Series 1.

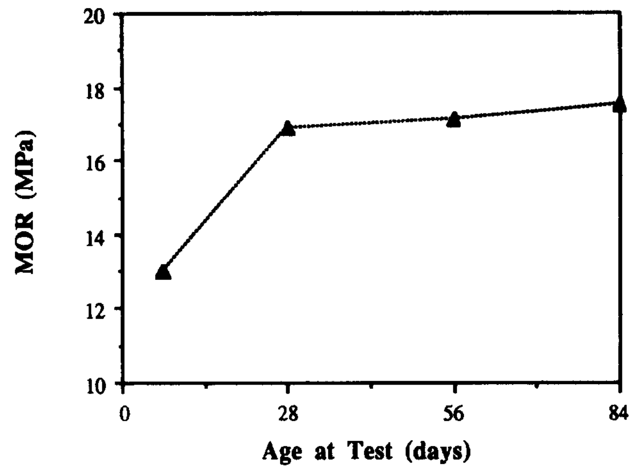

Fig. 3. Modulus of rupture vs age at test for Series 2.

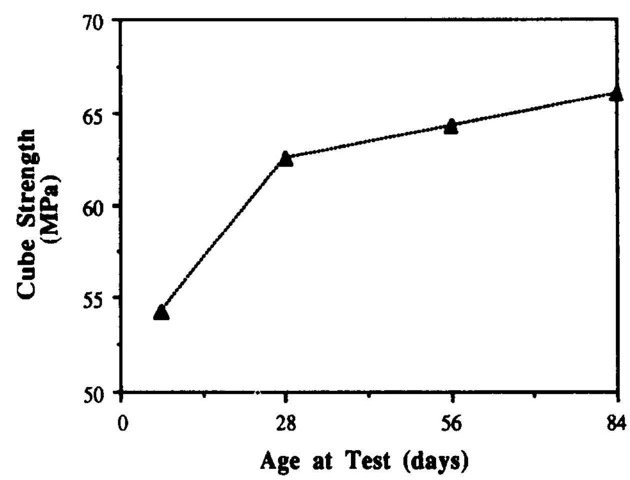

Fig. 4. Cube strength vs age at test for Series 2.

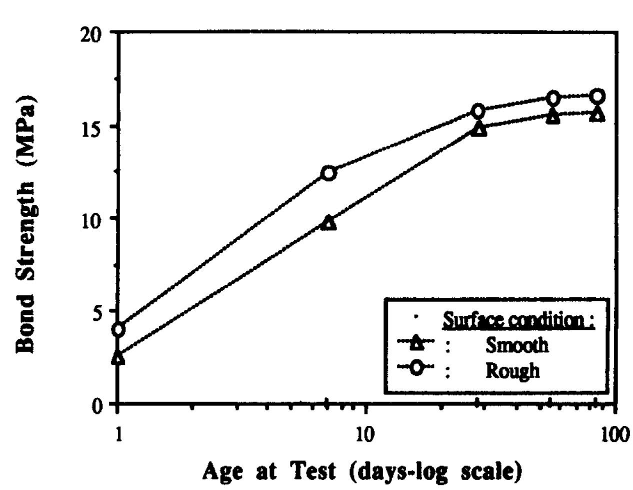

Fig. 5. Bond strength vs age at test for Series 2 for alternative surface conditions.

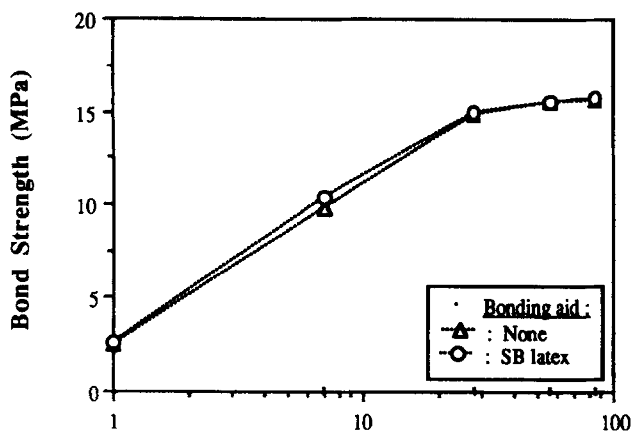

Fig. 6. Bond strength vs age at test for Series 2 with and without bonding aid.

Figure 1 shows that there was a marked increase in strength for the specimens compacted with the small roller compared with those compacted with the hand roller, especially for the MOR. At the age of 3 days the strength for the small roller was 38% higher than that for hand rolling. This value increased further with age to 42% at 7 days and 57% at 28 days. The MOR values then remained essentially constant with age at about 16 MPa and 26 MPa for hand rolling and for mechanical rolling with the small roller, respectively.

The cube strength continued to increase up to 60 days or more as shown in Fig. 2. The cube strengths for hand rolled specimens were about 15% lower than those obtained for the small roller but both had similar strength development trends from age 3 days. These results confirmed that the small roller with high pressure could provide better compaction and more uniform thickness of the composite sheets. Nevertheless, as was also concluded by Jada,[3] the advantages of hand rolling are simplicity and low cost.

Figure 2 shows that the strengths of the cube specimens tested parallel to the as-rolled direction were generally higher than for the perpendicular direction. No splitting occurred between layers hence the adhesion between the layers was good: so good in fact that the cubes were more prone to fail across the layers than between the layers.

The inclusion of SB latex and silica fume slurry in the mixes in Series 2 was expected to offset the lower pressure obtainable with the wider mechanical twin-roller. Surprisingly, Fig. 3 shows that the flexural strengths were only slightly higher than for hand rolling in Series 1. However, there was a marked increase in compressive strength at earlier ages compared with hand rolling with the inclusion of SB latex and silica fume slurry as shown in Fig. 4. This is assumed to be due to the silica fume which is finer than the cement, has a rapid pozzolanic action and should also improve the overall grading, and hence also the compressive strength and long term durability of the polymer modified mortar.

Figure 5 shows that a bond strength of 15 MPa was achieved for smooth surface specimens at 10% polymer–cement ratio. In previous investigations, it was found that the value was between 10–11 MPa for 5–10% polymer–cement ratio,[14] while by using PVAc (Polyvinyl Acetate) as a bonding agent for joining the substrate concretes,[13] the bond strength achieved was about 4·5 MPa. Figure 5 also shows that the rough concrete surface specimens provided better bond strengths between concrete and the PM mortar strip than the smooth specimens especially at the earlier age of joining. At the age of 7 days the bond strength for the rough surface was 27% higher and from 28 to 84 days, about 6·5% higher. It was thought previously that applying the bonding aid to the concrete surface before rolling on the PM mortar sheet would increase the bond strength. However, the effect of applying SB latex onto the smooth concrete surface specimens was negligible. Even at the very early age of one day (see Fig. 6), it gave little improvement in bond strength.

Comparison between Series 1 (see Table 1) and Series 2 (Figs 5 and 6) shows that inclusion of SB latex in the mix proportions (about 10% by weight of cement) gave a significant increase in bond strength. The reduction in thickness achieved to form the initial 3 mm thick mechanically rolled sheet was about 25%. A similar reduction could perhaps be achieved more conveniently by successive rolling of a single initially thick layer rather than recombining thin layers to achieve the final thickness.

CONCLUSIONS

A polymer modified mortar has been developed, using inexpensive mixing and rolling techniques, which can be formed into sheets and rolled onto cementitious surfaces to develop a high bond strength.

The polymer sheets can if required be rolled together to form thicker sheets or to sandwich steel fabric reinforcement to produce ferrocement sheets which can be used to enhance the strength of structural concrete members in a repair situation.

The use of a mechanical roller with a high rolling pressure can produce a more compact and uniform thickness of the composite sheets with improved flexural and compressive strengths than can be obtained with simple hand rolling. The high flexural strengths for the PM mortar obtained with the mechanical rolling were over 3 times the flexural strength of a typical site concrete, and the higher pressure small roller could give values as high as 5 times.

A rough concrete surface provided better bond strength between concrete and the PM mortar strip than a smooth surface. SB latex added to the PM mortars (about 10% by weight of cement) also increased the bond strength especially at later ages. However, applying a bonding aid to the concrete surface before rolling on the PM mortar strip only increased the bond strength at the earliest age of 1 day. The inclusion of both SB latex and silica fume slurry in the mix markedly increased the compressive strength at later ages. However, the flexural strength of the mortar only increased slightly with the inclusion of these two materials.

The type of failure for cube specimens tested in compression parallel to the as-rolled direction was similar to that for specimens tested perpendicular to the as-rolled direction. The adhesion between the layers was so good that the cubes were more prone to fail across the layers than between the layers.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial assistance provided by the former Science and Engineering Research Council (SERC, now EPSRC) and to thank the Technical staff in the Concrete and Structures Laboratories and the Workshops for the manufacture of equipment and specimen preparation. Also Professor P. C. Hewlett, director of the British Agrément Board, for his interest and helpful comments.

REFERENCES

1. Dikeou, J. T., Review of worldwide developments and use of polymers in concrete, *Proc. of the 1st Int. Congr. on Polymer Concretes, 5–7 May 1975, Polymers in Concrete*. The Concrete Society, The Construction Press Ltd, 1976, pp. 2–8.
2. Pomeroy, C. D. & Brown, J. H., An assessment of some polymer (PMMA) modified concretes, *ibid.*, pp. 9–13.
3. Jada, S. I., Plasticrete, Part 2, PhD Thesis, University of Birmingham, October 1986.
4. Hughes, B. P. & Al-Ani, M. N. A., PFA fineness and its use in concrete. *Magazine of Concrete Research*, **41**(147), 1989, 99–105.
5. Hughes, B. P. & Evboumwan, N. F. O., Polymer-modified ferrocement enhances strength of reinforced concrete beams. *Construction and Building Materials*, 7(1), 1993, 9–12.
6. Lubis, B., High Tensile Strength Modified Mortars, MPhil Thesis, The University of Birmingham, January 1991.
7. Lubis, B., Enhanced Strength of Reinforced Concrete Members Repaired with High Strength Polymer Modified Mortars, PhD Thesis, The University of Birmingham, August 1995.
8. Swamy, R. N. (ed.), *Cement Replacement Materials, Concrete Technology and Design*, **3**, 1986, 197–255.
9. Kreigh, J. D., Arizona Slant Shear Test: A method to determine Epoxy Bond Strength. *ACI Journal*, **73**, July 1976, 372–3.
10. Neville, A. M., *Properties of Concrete*, 3rd edn. Pitman Publishing, London, 1981, 560 pp.
11. Akihama, S., Morita, H., Watanabe, S. & Chida, H., *Improvement of Mechanical Properties of Concrete Through the addition of Polymer Latex, Polymer in Concrete, International Symposium*, ACI SP 40-16, 1972, Florida, USA, pp. 320–38.
12. Nawy, E. G., Ukadike, M. M. & Sauer, J. A., Optimum *Polymer Content in Concrete Modified by Liquid Epoxy Resins, Polymer in Concrete, International Symposium*, ACI SP 58-19, 1976, Mexico, pp. 329–55.
13. Wall, J. S., Shrive, N. G. & Gamble, B. R., Testing of Bond Between Fresh and Hardened Concrete, Adhesion Between Polymers and Concrete, Bonding-Protection-Repair, *Proc. of an Int. Symp. Organised by RILEM Technical Committee 52*, Paris, 16–19 Sept. 1986, Chapman and Hall, London, pp. 335–44.
14. Ohama, Y., Demura, K., Nagao, H. & Ogi, T., Adhesion of Polymer-Modified Mortars to Ordinary Cement Mortar by Different Test Methods, Adhesion Between Polymers and Concrete, Bonding-Protection-Repair, *Proc. of an Int. Symp. Organised by RILEM Technical Committee 52*, Paris, 16-19 Sept. 1986, Chapman and Hall, London, pp. 179–229.