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Application of FRC in Construction of the Underground Railway Track*

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Abstract

The results of a series of tests of specimens made of fibre reinforced concrete (FRC) are reported. The tests were performed to evaluate FRC for use in the underground railway system in Warsaw. The tests were initiated as a result of the successful replacement of an ordinary plain concrete for substrate under rails with polypropylene fibre reinforced concrete, this composite material being of practically the same cost as the plain concrete. The tests performed on various mixture compositions showed considerable improvement of several properties with respect to the ordinary plain concrete. © 1996 Elsevier Science Limited.

Keywords: Fibre reinforced concrete, tests, concrete substrate, underground railway track, control of cracking.

INTRODUCTION

Extensive development of fibre reinforced concretes in the last three decades is reflected by hundreds of interesting papers and reports presenting valuable test results. Also quite a number of important theoretical analyses on FRC properties and behaviour are available in journals and conference proceedings. It seems, however, that the number, volume and importance of applications of FRC is still below the full possibilities, as shown by Mindess.[1]

There were various reasons for the relatively infrequent applications of FRC beside tunnel lining and facade claddings. They were mostly related to higher cost and increased technological difficulties with respect to traditional concretes and reinforced concretes. These reasons often were not based on any rational calculations but rather on lack of information and on negligence of the durability aspects.

Nevertheless, very frequently the FRC materials are considered as subjects for theses at universities and not as building materials for special use. It is only when something occurs in an actual structure, like cracks or extensive spalling, that the application of new materials is considered as a possible solution.

The case study described below belongs to this category, and that occasion has been used to extend the test programme for possible future application of FRC.

Plain concrete substrate was executed along a few kilometers of the first line of an underground railway line. As is shown in Fig. 1, concrete was poured directly into the lower part of cast iron tubbings, between the stiffening ribs. The rails were fixed without slippers, directly to the concrete base. Due to the relatively large dimensions of the substrate, no particular requirements were imposed on the concrete and only a minimum compressive strength of 25 MPa at an age of 28 days was expected. The concrete was hardening in relatively high humidity and in the temperature range between 10 and 15°C in the tunnel and no excessive shrinkage was expected. However, in a few weeks a system of unpleasant cracks appeared. It was a complete surprise for the

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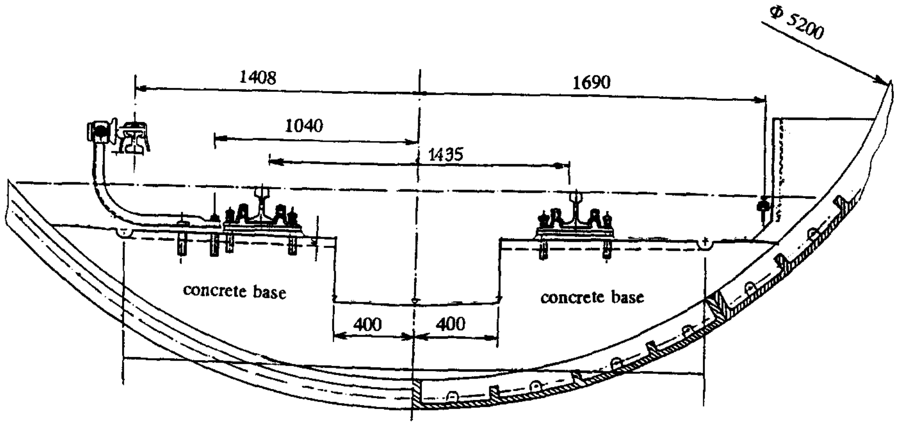

Fig. 1. Lower part of the tunnel cross-section with the concrete base.

investor. The cracks spaced between 2 and 3 m were visible on the free edges of the base and were obviously caused by a kind of restrained shrinkage, because the mixture composition was by no means designed to reduce shrinkage strain.

In view of the necessity for an immediate decision to allow further works, new mixture proportions were rapidly designed and are shown as M-0 in Table 1 with several modifications with respect to the old ones, namely:

- reduction of the Portland cement content,
- reduction of volume of water and of w/c,
- improvement of quality and grading of the aggregate,
- addition of small amount of fibrillated polypropylene fibres.

Thanks to the successful application of FRC, even at that moderate scale, an extended test programme has been accepted and sponsored by the investor. The aim of the tests was to verify the possibilities and advantages of various kinds of FRC in view of their future application in the construction of various structural and nonstructural elements in underground tunnels and stations.

COMPOSITION OF FRC

Five different mixture proportions were carefully designed and they are presented in Table 1. These are: one plain concrete without fibres (mix designated M-1) and four FRC mixes with different kinds of fibres:

(i) polypropylene fibres of diameter 18 μm, length 12 mm and designated PP1 (mix M-2), $V_f = 0.067\%$,

(ii) polypropylene fibres of diameter 16 μm, length 20 mm and designated PP2 (mix M-3), $V_f = 0.1\%$

(iii) steel fibres of diameter 0.5 mm, length 30 mm with hooks at the ends, designated H30/50 (mix M-4), $V_f = 0.9\%$,

(iv) steel fibres of diameter 0.8 mm, length 60 mm with hooks, designated H60/80 (mix M-5), $V_f = 0.9\%$.

Table 1. Mixture compositions of tested FRC

Components	*Mixture proportions [kg/m^3]*					
	M-0	*M-1*	*M-2*	*M-3*	*M-4*	*M-5*
Portland cement P35	340	354	350	355	349	354
River sand $\leq$ 2 mm	600	590	578	594	584	595
River gravel 2–16 mm	1240	1236	1218	1237	1219	1250
Water	160	194	193	189	185	178
Superplasticizer	7	7.1	7	7.1	7	7.1
Fibres PP1	0.6		0.6			
Fibres PP2				0.91		
Fibres H30/50					30.0	30.5
Fibres H60/80						0.50
w/c	0.47	0.55	0.55	0.53	0.53	

The polypropylene fibres are characterized by tensile strength of 300–400 MPa, Young's modulus 6000–9000 MPa, density 0.91, surface 225 m^2/kg. All components were traditionally premixed and poured directly to the shuttering installed in the tubbings. Compressive strength at 28 days was 31.1 and 35.8 MPa at 60 days.

All measurements were made on five–six specimens and mean values are reported.

TESTS OF FRESH MIXES

The mixture proportions were designed in such a way that good workability was ensured in all cases.

Properties of fresh mixes were measured as slump of the Abrams' cone and also using inverted cone method according to ASTM C 995. The results are shown in Table 2. The results obtained by both methods are close to each other. The best workability was exhibited by mixes M-1 and M-4, the worst by mix M-3 where longer polypropylene fibres were used. In general it has been concluded that all mixes were acceptable according to their workability.

Collated steel fibres were all well dispersed without any significative decrease of workability. Higher dosages of the superplasticizer were not needed and they would be considered as non-justified increase of the cost. The test results confirmed data obtained by other authors, e.g. Ref. 2.

COMPRESSIVE AND SPLITTING TENSILE STRENGTH

Compressive strength was established on cubes of 100 mm. Splitting tensile strength was determined also on cubes 100 mm according to ASTM C 496. The results are given in Fig. 2. It may be concluded after these results, that steel fibres increased compressive and tensile strength by 20–30%. The results shown here as well as all other test results are the mean values of five–six tested specimens.

The influence of polypropylene fibre was smaller and in a few cases even negative. These results did not confirm conclusions proposed by other authors, e.g. Refs 3 and 4, where a smaller influence of steel fibres on the composite strength was reported. This difference may be attributed to relatively low strength of the plain matrix considered here as the reference material.

STRENGTH IN BENDING AND FLEXURAL TOUGHNESS

Bending tests were executed according to ASTM C 1018-89 on beams 100 × 100 × 500 mm sawn out from larger plates. The beams were loaded in an Instron 1241 testing machine with displacement controlled at a rate of 0.1 mm/min. The deflections were measured with respect to the neutral axis as it is usually reported in recently published tests, e.g. Refs 5 and 6. Thus, the values of deflections were by one order of magnitude smaller than when deflections at the bottom of the beam were measured. In such a way, possible rocking of a beam itself as well as parasite displacements of the supports were excluded from the final results.

Examples of load–deflection curves are shown in Fig. 3. Values of MOR as the tensile strength in flexure of polypropylene fibres reinforced concrete were either slightly lower (M-2) or slightly higher (M-3) than of plain matrix, see Fig. 4. For steel fibre reinforced specimens some insignificant increase of 5–10% was observed.

After the test results the toughness indices I_{30}, I_{50} and I_{100} were calculated as well as energy absorbed up to deflection equal to

Table 2. Properties of fresh mixes

Properties tested	*Type of concrete*				
	M-1	*M-2*	*M-3*	*M-4*	*M-5*
Slump (mm)	165	120	60	150	135
Density (t/m^3)	2.381	2.347	2.384	2.375	2.415
Temperature of concreting (°C)	+ 8	+ 8	+ 8	+ 10	+ 9
Inverted cone vibration (s)	4.2	9.8	12.5	4.8	11.0

55.5 δ, where δ is the deflection corresponding to the first crack. The results are shown in Figs 5 and 6. It may be concluded that the polypropylene fibres modified only slightly the postpeak behaviour of the beams. On the contrary, the steel fibres even in small volume increased considerably the values of indices as well as the amount of energy absorbed. As it is shown in Fig. 3 the specimens reinforced with steel fibres exhibited quasi plastic behaviour up to maximum deflection of 4 mm permitted by the testing setup.

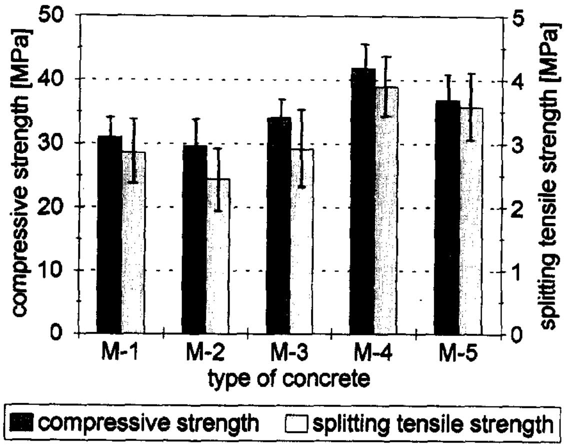

Fig. 2. Compressive strength and splitting tensile strength.

These results are in perfect agreement with reports by other authors, cf. Refs 3 and 4. However, the scale of improvement in energy absorption was perhaps higher in this case than in previous tests.

Impact resistance

The test was executed according to ACI 544 on cylindrical specimens 160 mm diameter and 78 mm height. The results are shown in Fig. 7 and the efficiency of longer steel fibres in M-5 is obvious. Polypropylene fibres modified only slightly the post-cracking impact resistance of the plain matrix and this result is different than these published by Ramakrishnan *et al.*[7] who obtained better results, however for higher fibre contents. Also Hibbert and Hannant[8] indicated that for significant higher impact resistance the fibre volume should be between 1 and 2%.

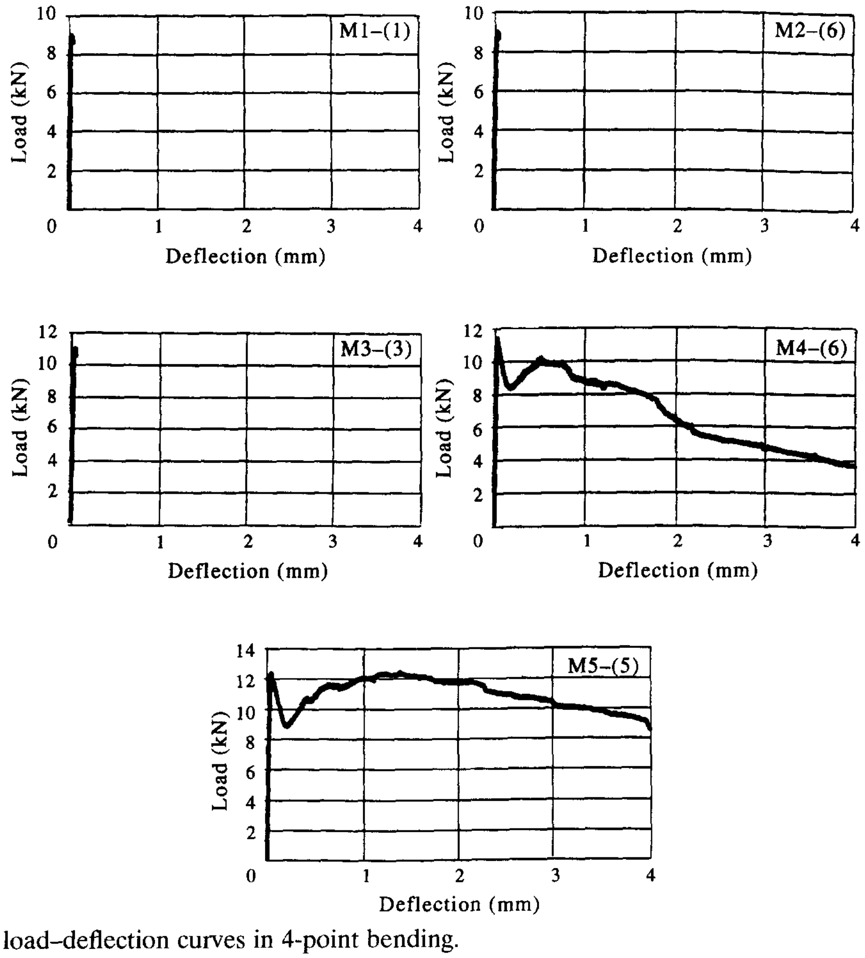

Fig. 3. Example of load–deflection curves in 4-point bending.

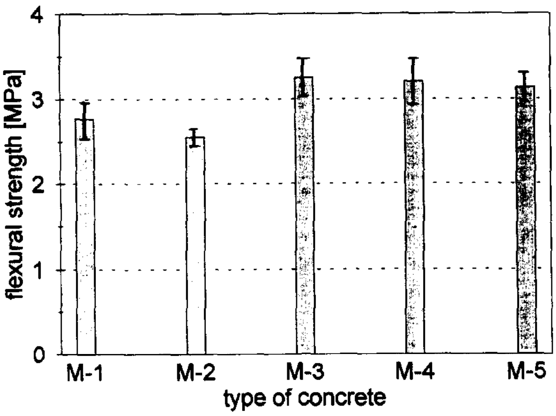

Fig. 4. Flexural strength.

Water permeability and capillary suction of water

These tests have been executed according to the Polish Standard for plain concrete PN-88/06250 on cubes of 150 mm. The permeability was defined by measuring the amount of absorbed water and of the depth of water penetration due to the pressure of 0.8 MPa imposed to the specimens. Water under pressure was applied to the surface of the radius of 50 mm on the top side of each specimen, perpendicular to the direction of casting. Lateral faces of a test specimen were sealed. After 24 h the mass of absorbed water was defined and then specimens were split to measure the depth of water penetration. Mean results both of the depth of water penetration and the amount of absorbed water are shown in Fig. 8.

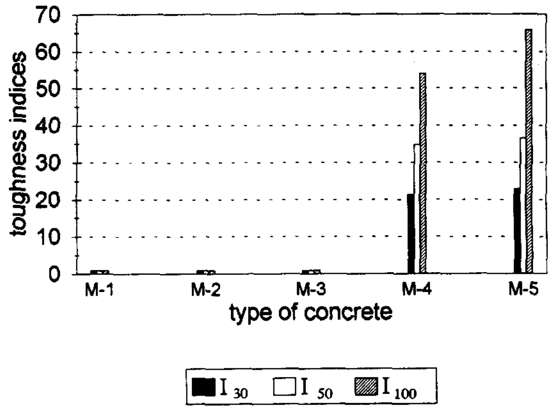

Fig. 5. Toughness indices I_{30}, I_{50}, I_{100} — mean values.

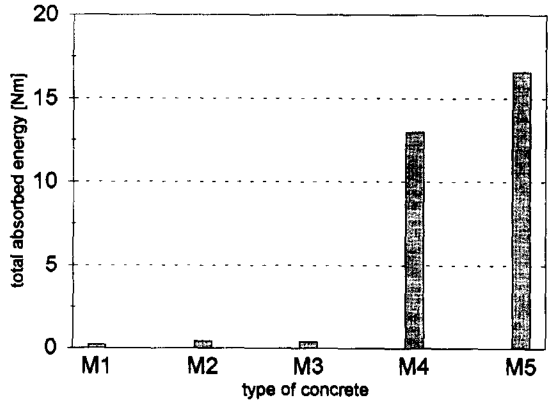

Fig. 6. Energy absorption capacity for considered types of concrete.

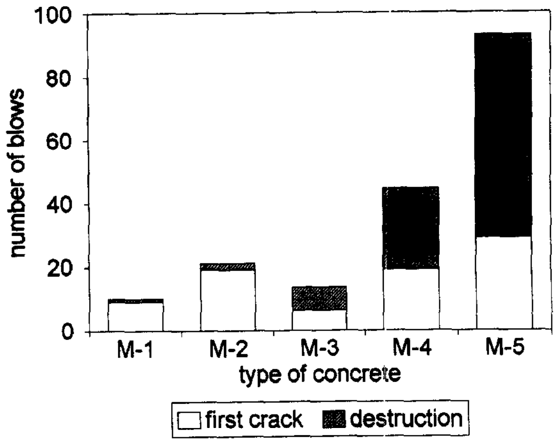

Fig. 7. Impact resistance.

The capillary suction was measured by placing the specimens in water to half of their height. When no further increase of specimens mass was observed, the full saturation of concrete was assumed, and specimens were dried at a temperature of 105–110°C to a constant weight. Water absorption was calculated as a relation of the increase in weight due to the water soaking to the weight of dry specimens, see Fig. 9.

All kinds of fibres enhanced permeability of the plain matrix, probably due to increased porosity. It should be mentioned, however, that the unloaded specimens were tested. In such a

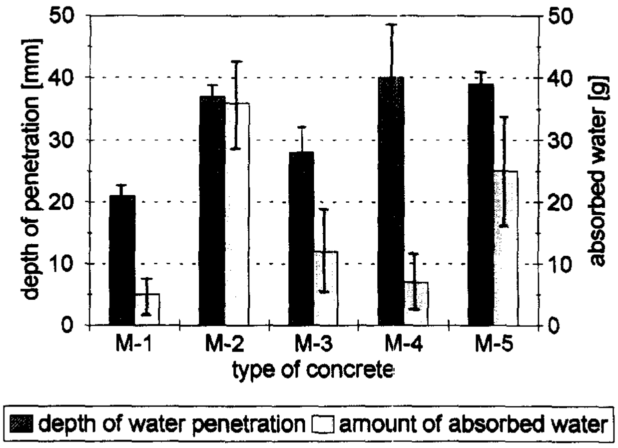

Fig. 8. Results of water permeability test.

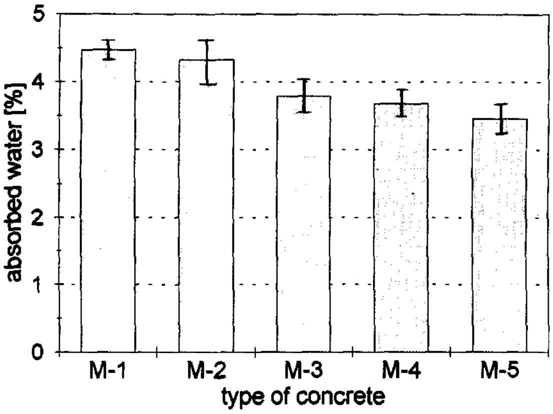

Fig. 9. Results of capillary suction of water.

test the influence of crack control exerted by fibres cannot be reflected in the results. Results of absorption tests indicate the different influence of the fibre reinforcement. While fibres PP1 in specimens M-2 slightly decreased percentage of absorbed water, other fibres PP2 and steel fibres reduced it considerably probably decreasing the average pore dimension. The prescriptions issued by Public Road Administration impose a limit of 4% for all road and bridge structures and that limit is considered as quite severe. According to Fig. 9, three mixture proportions satisfied that requirement.

Drying free shrinkage

Drying free shrinkage was measured on specimens 100 × 100 × 500 mm sawn out of large plates and stored in constant temperature of +20 ± 1°C and RH equal to 70 ± 2%. The mean values of readings are shown in Fig. 10. It appears that the influence of fibre reinforcement on free shrinkage was small.

Values of shrinkage at the long term evaluated for all tested series of specimens after 50 days measurements may be considered as corresponding to values generally observed for plain concrete, i.e. below 600×10^{-6}. For plain concrete specimens the value of about 400×10^{-6} was obtained after 50 days. Shrinkage at 50 days for concrete containing PP2 fibres reached 600×10^{-6}. For longer steel fibres H60/80 shrinkage strain was reduced by approximately 20% with respect to the plain matrix specimens and this confirms the results published by several authors, e.g. Malmberg and Skarendahl.[9] There is a need for more systematic investigation of the influence of fibre on the shrinkage of concrete.

Abrasion

The degree of abrasion was defined by the decrease in weight of specimens due to the mechanical abrasion in special device with rotating steel cylinder filled with sand. Cylindrical specimens with a diameter of 78 mm and a height of 160 mm were placed in the device and subjected for 4 h to the abrasion process. The results of the decrease in weight are shown in Fig. 11. It appeared that a slight improvement in abrasion resistance may be expected with the application of steel fibres. The test results corroborated other published data but it should be concluded that for more significant improvement of abrasion resistance higher content of steel fibres is required.

In situ behaviour

The effects of the modification of the mixture proportions and of application composition designated as M-0 are presented in Table 3 where the results of *in situ* inspection performed approximately two months after

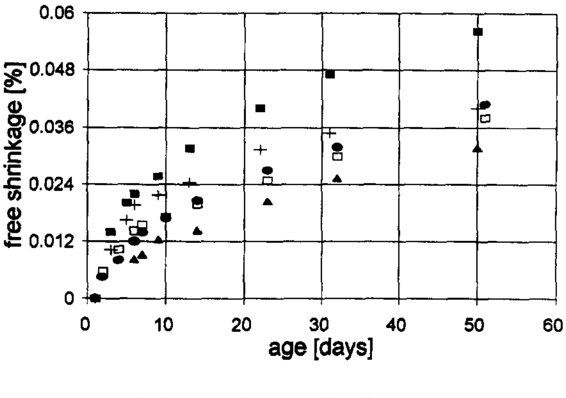

Fig. 10. Results of shrinkage test.

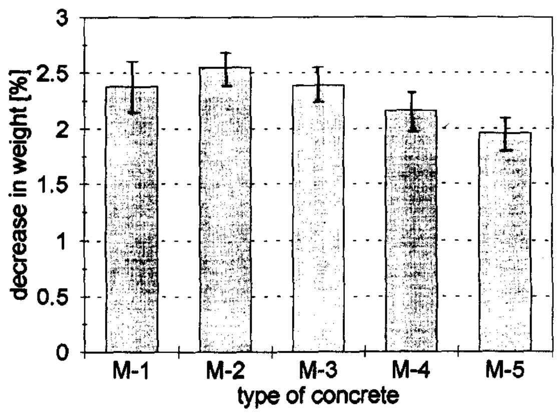

Fig. 11. Results of abrasion test.

Table 3. Results of inspection of crack in the concrete base *in situ*

	Symbols of sections of the tunnel							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Date of concreting, 1993	12.1 0	12.1 0	21.1 0	7.1 0	7.1 0	20.1 0	9.12	15. 12
OC or M-0	OC	OC	OC	OC	OC	M-0	M-0	M-0
Positions of observed cracks	*)	*)	*)	*)	*)	12/3 8 **)	28/50 **)	34/ 45 **)
Width of crack (mm)	1.5	1.3	2.0	1.6	1.8	1.1	0.7	0.6

Here OC means ordinary plain concrete applied initially and M-0 is FRC according to the mixture proportions indicated in Table 1.

*) Cracks spaced approximately 2–3 m.

**) Single crack in section between joints of the tubbings; numbers gives distance expressed in meters to left and right joints.

concreting are indicated. Single cracks found in the concrete substrate made of FRC have no importance for safe behaviour under traffic. It is also interesting to add that all modifications introduced to the mixture proportions did not require any significant increase of cost, nor have complications of execution been reported.

Concluding remarks

The results of the tests have confirmed that even by applying dispersed fibre reinforcement in only quite a small volume, considerable improvements to plain concrete may be obtained, provided that the fibres are well selected. The application of low modulus and low strength polypropylene fibres was probably the best solution in the considered case.

The polypropylene and steel fibres have entirely different influences on the composite material characteristics. Therefore, both kinds of fibre should be applied in the situations corresponding to their respective performance.

The quality of the matrix itself is not less important than its reinforcement. For all applications the matrix should be carefully designed taking into consideration all imposed requirements.

It seems obvious, that in many situations the use of dispersed fibres as reinforcement is often technically and economically justified. As that conclusion is obvious for researchers working in that field, the investors should always be persuaded in simple cases. From this viewpoint, the tests presented here were quite successful and the investor decided to apply FRC in several constructions. Also, substantial support is expected for further research in view of other applications of FRC for various structural and non-structural elements in the construction of the underground railway system in Warsaw.

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