

PROJECT REPORT PPR873

Innovative Geotechnical Repair Techniques



Effectiveness of Fibre Reinforced Soil

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HAGDMS No. 30667

Report details

Report prepared for:	Highways England		
Project/customer reference:	SPaTS 1-147 Innovative Geotechnical Repair Techniques		
Copyright:	© Queen's Printer and Controller of HMSO		
Report date:	November 2018		
Report status/version:	Issue 1		
Quality approval:			
Mike Winter (Project Manager)		Bill Newton (Technical Reviewer)	

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Contents amendment record

This report has been amended and issued as follows:

Version	Date	Description	Editor	Technical Reviewer
Draft 1b	07/08/2017	Draft	R P Seddon	
Draft 1f	08/08/2017	Draft		M G Winter
Draft 1i	10/08/2017	HE review	R P Seddon	
Draft 1i	23/08/2017	Technical review		B Newton
Draft 1p	17/01/2018	HE Review	R P Seddon	M G Winter
Draft 1q	06/09/2018	Final	R P Seddon	M G Winter
Draft 1t	08/10/2018	Final HE and Project Team Review	M G Winter	B Newton
Issue 1	06/11/2048	DPA	M G Winter	R Cuerden

Document last saved on:	10/12/2018 10:25
Document last saved by:	Reviewer

Table of Contents

Contents

Executive Summary	3
1 Introduction	5
2 Details and Assessment of Trials and Previous Uses	7
2.1 A1(M) Junction 1 Northbound Slip	7
2.2 A27 Polegate/Bay Tree Lane	11
2.3 M20 Smeeth	16
3 Monitoring Results	19
3.1 A1(M) Junction 1	19
3.2 A27 Polegate/Bay Tree Lane	21
4 Effectiveness of Trials	23
4.1 A1(M) Junction 1	23
4.2 A27 Polegate/Bay Tree Lane	24
4.3 M20 Smeeth	26
5 Lessons Learnt	29
5.1 Location and Access	29
5.2 Design	29
5.3 Materials and Construction	30
5.4 Monitoring	31
5.5 Maintenance	31
5.6 Life Cycle Assessment	32
5.7 End-of-Life Considerations	32
6 Summary and Conclusions	35
Acknowledgements	37
References	39

Executive Summary

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, Fibre Reinforced Soil (FRS) and Electrokinetic Geosynthetics (EKG). These techniques were trialled to assess the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of these techniques have been undertaken over the last 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken.

This report presents an assessment of the effectiveness of FRS as a long-term slope repair technique and is one of a series for this project.

The addition of discrete randomly orientated fibres to improve the physical properties of soil is a technique that is more widely used in other countries such as the USA. The use of FRS has been reported to have benefits over other more commonly used slope repair techniques. In general, it allows the reuse of site-won material through the addition of a relatively small proportion of fibres to the soil fill.

Three trials using FRS as a slope repair technique, undertaken in the past nine years, have been assessed in this report. An initial trial was constructed on a cutting at the A1(M) Junction 1 in 2009, two slope failures on a combined embankment and acoustic bund were repaired at the A27 at Polegate in 2010 and 2011, and in 2014 an FRS trial on a cutting on the M20 near Smeeth was constructed.

The assessment of the trials was undertaken by reviewing the information contained in geotechnical reports, submitted as part of the technical approval process, and site inspections. The knowledge and understanding of the trials was augmented through discussions with technical staff from the Maintaining Agents and Highways England.

Difficulties in accurately determining the improvement to the geotechnical properties of the soils at the trial sites were reported at both the design and construction stage. For instance, at design stage, a 25% increase in the effective angle of shearing resistance was generally adopted. However, post-construction testing at the A1(M) site and slope instability at A27 Polegate suggest that the increase in effective angle of shearing resistance is much less.

Construction of the FRS trials was frequently during wet weather. This resulted in some FRS being placed wet of optimum. This potentially has reduced or masked the effectiveness of the FRS. At A27 Polegate trafficability of the ground, softened as a result of the extremely wet weather, was improved by the addition of fibres. This demonstrated a potential application of FRS for temporary works.

The use of FRS to repair failing slopes has been partly successful in the short-term on two of the sites: i.e. A1(M) Junction 1 and M20 Smeeth. At the A27 Polegate, the use of FRS to repair the slope was not successful. Overall, it is considered that the three trials have not demonstrated effectiveness of the FRS as a long-term slope repair technique.

In addition to the carbon impacts, the long-term sustainability of FRS, when using non-biodegradable fibres, may be questioned. The reuse of a soil-plastic mix, such as FRS, poses

waste management, environment and geotechnical challenges which would need to be resolved before it could comply with Highways England's ambition for a circular approach to managing resources. Resolving these end-of-life issues is considered to be key to the adoption of FRS as a slope repair technique in the future.

Given these issues it is considered that FRS technology and the knowledge for its use are not sufficiently developed for it to be adopted as a long-term slope repair technique. Nevertheless, the trials have demonstrated the potential for FRS to be used to improve trafficability of soils. It is recommended that further research is undertaken to assess the use of FRS, created with sustainable natural fibres, for temporary ground improvement and the construction of temporary roads and tracks.

1 Introduction

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, Fibre Reinforced Soil (FRS) and Electrokinetic Geosynthetics (EKG). These can be used in place of conventional approaches to overcome various issues including environmental constraints (habitat and visual), access and utility constraints, and the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of these techniques have been undertaken over the last 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report is on the effectiveness of fibre reinforced soil as a repair technique for slope defects and is one of a series for this project.

The addition of discrete fibres to improve the physical properties soil is common practice in other countries such as the USA. The use of FRS has been reported to have benefits over other more commonly used slope repair techniques. It allows the reuse of site-won material through the addition of a relatively small proportion of the fibres. The polypropylene fibres are ostensibly inert and therefore are potentially less hazardous than other soil improvement techniques that use lime or cement.

An initial research project undertaken by Mouchel (Mouchel 2010) on behalf of the Highways Agency and a subsequent full scale trial on the A1(M) at Junction 1, informed later FRS slope repair trials undertaken on the A27 at Polegate and the M20 at Smeeth.

The trial applications of FRS were primarily focussed on their use to prevent shallow slope failures and desiccation cracking. However, it became apparent during the construction works that the addition of fibres to ground softened by rainfall and plant movements allowed work to continue on site when it would otherwise have stopped.

In this report (Section 2), the available information on the use of FRS is considered for the sites at the A1(M) Junction 1, M20 Smeeth and A27 Polegate. The reported information from the trials was supplemented by site visits during February and March of 2017, also discussed in Section 2.

In Section 3, an assessment of the monitoring data available for the sites is presented. Sections 4 and 5 assess the effectiveness of the trials and detail the lessons learnt. Section 6 summarises and concludes the work presented herein.

Separate reports evaluate the effectiveness of live willow poles (Winter et al. 2018a) and EKG (Nettleton et al. 2018). The next stage of the work will draw on the lessons learnt from each of the three techniques in order to provide recommendations and guidance for the management of future trials of innovative techniques (Winter et al. 2018b). This will be followed by the preparation of design guidance and specification information for those techniques considered to have the potential for future use.

2 Details and Assessment of Trials and Previous Uses

Three FRS trials have been undertaken over the past nine years. An initial trial was constructed on a cutting at the A1(M) Junction 1 in 2009; the findings (Mouchel 2010 and Mouchel 2012) of which informed the later trials.

In 2010 and 2011, two slope failures on a combined embankment and acoustic bund on the A27 at Polegate were repaired using FRS (Balfour Beatty Mott MacDonald 2010a, 2010b and 2012a). In 2014, an FRS trial on a cutting on the M20 near Smeeth was designed and constructed (Balfour Beatty Mott MacDonald 2012b and 2015).

For all the trials, 50 to 70mm long, polypropylene tape or fibrillated fibres (Geofibers) were used which were sourced from Fiber Soils Limited in the USA.

The following section provides a summary of these trials. Further information is provided in the referenced design and feedback reports.

2.1 A1(M) Junction 1 Northbound Slip

2.1.1 *Site Location*

The trial is situated to the south east of South Mimms at National Grid Reference (NGR) TL 22733 00695 (522733, 200695) (Figure 1). It is located on a cutting slope adjacent to the A1(M) Junction 1 northbound on-slip from the M25 Junction 23. The cutting reduces in height from 9.0m adjacent to St Albans Road to 1.0m at the northern end of the earthwork. The slope in the vicinity of the soil failure (at Marker Post 23/8A) varies between 4m and 6m in height with an average angle of approximately 17°.

2.1.2 *Site Details*

The soil cutting had been prone to cyclic shrink-swell which had resulted in significant desiccation cracking and shallow slope instability.

Mouchel (2012) indicated that the geology at the location of the cutting comprises undifferentiated clay and silt of the Reading Formation from the lower part of the Lambeth Group.

The ground conditions encountered during an intrusive investigation generally agreed with the published geological information, with clay/silt of the Reading or Upnor Formations being encountered to a depth of approximately 2m below ground level (bgl). This was described as soft near the surface becoming very stiff with depth. Below this, loose sand of the Upnor Formation was encountered to approximately 3.60m bgl. Underlying these superficial deposits, weathered Chalk was encountered.



Figure 1: Location of the A1(M) Junction 1 FRS trial. (Image based on OS 1:25,000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.1.3 *Geotechnical Research and Design*

Prior to construction of the FRS repairs at the A1(M), Mouchel undertook a review of the use of FRS, which is detailed in their desk study (Mouchel 2010). This included an extensive review of the published literature on the effects of mixing fibres into soil. The conclusions of this report can be summarised as follows:

- The change in the load-deformation characteristics of FRS in relation to its host soil are a result of the interaction of the fibres with the soil particles through friction, interlocking and adhesion.
- All types of man-made fibres tended to improve the soil's shear strength, with the degree of improvement depending on the quantity, distribution and geometry of the fibres added.
- For cohesive soils, an increase in the internal angle of friction of between 15% and 35% may be used for design with an optimum fibre content of 0.2% to 0.3% by dry weight. For design purposes the addition of fibres should not be considered to increase the cohesion. These recommendations were generally in line with the research undertaken by Gregory & Chill (1998).
- Wherever possible, laboratory testing should be undertaken to verify the effect of the inclusion of fibres on the physical properties of the host soil.

- Compared to the untreated soil, FRS had less post peak strength loss, thus effectively improving its durability and reducing cracks. Crack reduction is improved with increasing fibre content.
- The effort required in spreading and mixing of the fibre inclusions within the soil mass is essentially the same as that required for more conventional techniques such as lime modification.

2.1.4 Construction and Monitoring

Based upon the findings of the desk study, a full scale trial of FRS was undertaken at A1(M) Junction 1 between January 2009 and April 2009. The works comprised the following components:

- *FRS Proactive Maintenance Section 1* - This was a proactive maintenance slope repair at the southern end of the cutting and comprised the excavation, improvement with fibres and the replacement of the soil derived from the top 0.5m of desiccated material in a single 11m wide bay (Bay A).
- *FRS Full Height Repair Section 3* - A repair to the slope instability at the northern end of the cutting that comprised the excavation of the softened slipped material above the plane of failure with a benched profile and re-grading of the slope to its original line and level. This was undertaken using re-compacted site arisings improved with fibres. The repair was carried out in two 13m wide bays to minimise the risk of slope instability.
- *Control Section 2* - In between the two sections defined above, the slope was not repaired using FRS. This section enabled the comparison of the monitoring results from reinforced and unreinforced slope repairs to be undertaken.

The fibres used, called Geofibers 3620BF, were imported from Fiber Soils based in America. These were black polypropylene fibrillated fibres with a minimum length of 2inches (50mm).

The specified fibre content added to Sections 1 and 3 was 0.2% by dry weight. This was achieved at Section 3; however in Section 1 the percentage of fibres was increased to 0.3% to allow continuation of the earthworks during wet weather. The increase in fibre content increased the shear strength of the soil, preventing excessive rutting of the fill during compaction.

At the end of the construction of the FRS repairs, geotechnical instrumentation was installed to monitor the performance of the slopes (FRS Proactive Maintenance Section 1 and FRS Full Height Repair Section 3) against Control Section 2.

The FRS repairs (Sections 1 and 3) were monitored for two years from April 2009 to March 2011. Control Section 2 was monitored for a period of three years from May 2008, (before construction) to March 2011, approximately two years after construction. The slopes were monitored using a combination of inclinometers, piezometers and extensometers. Visual inspections of the slopes were also undertaken to observe and record any surface features such as desiccation.

Ground investigation was undertaken soon after completion of the works to obtain samples of the FRS from Sections 1 and 3. The samples were obtained using continuous liner dynamic sampling. This technique resulted in some disturbance to the recovered soil and only the samples considered to be the most intact and least disturbed were sent for laboratory testing. The testing included compaction and effective stress analysis.

2.1.5 *Slope Inspection*

The site inspection was undertaken on 16th February 2017 in dry, partly cloudy weather conditions with good visibility. The top of the cutting was accessed from a public footpath located close to the crest of the cutting.

The slopes were covered with heavy vegetation comprising tall grass, hydrophilic vegetation, brambles and the occasional tree. Although this vegetation had died back over the winter the majority of the surface of the slopes was masked by vegetation and vegetative debris.

Where the surface was visible, hummocky ground and some desiccation cracking were noted. This was in line with the findings reported by Mouchel (2012). No signs of the significant instability were observed on site.

Geotechnical monitoring installations were evident, including raised piezometer / inclinometer covers (Figure 2). These appeared to be in reasonable condition although some of the inclinometer covers appeared to be rotated by 3° to 5° to the east (downslope). It was considered that this could be an indication of shallow slope creep, although equally could be due to the method of installation.

Given the nature of the repair technique and the density of the vegetation, it was not possible to determine with any detail how the FRS slopes continued to perform. Nevertheless, from what was observed, it appeared that no significant slope instability or substantial desiccation cracking had occurred since construction.



Figure 2: Heavily vegetated FRS slope. Raised installation covers rotated between 3° and 5° to the west

2.2 A27 Polegate/Bay Tree Lane

2.2.1 Site Location

The trial is situated approximately 100m east of Cophall roundabout at Grid Reference TQ 57900 05720 (557900 105720) (MP 23/7A+40 to MP 23/8A+30) (Figure 3). It is located on an environmental bund and embankment adjacent to the eastbound on-slip of the A27 Polegate Bypass.

Two landslides were identified on the earthwork in February 2009. The Balfour Beatty Mott MacDonald (BBMM) Ground Investigation Report (BBMM 2010a) described the defects as large rotational slips, defined as Soil Slip1 and Soil Slip 2; these were 30m and 35m long respectively. The slips were approximately 20m apart.

The slips can be accessed from Bay Tree Lane which is adjacent to the western toe of the embankment.

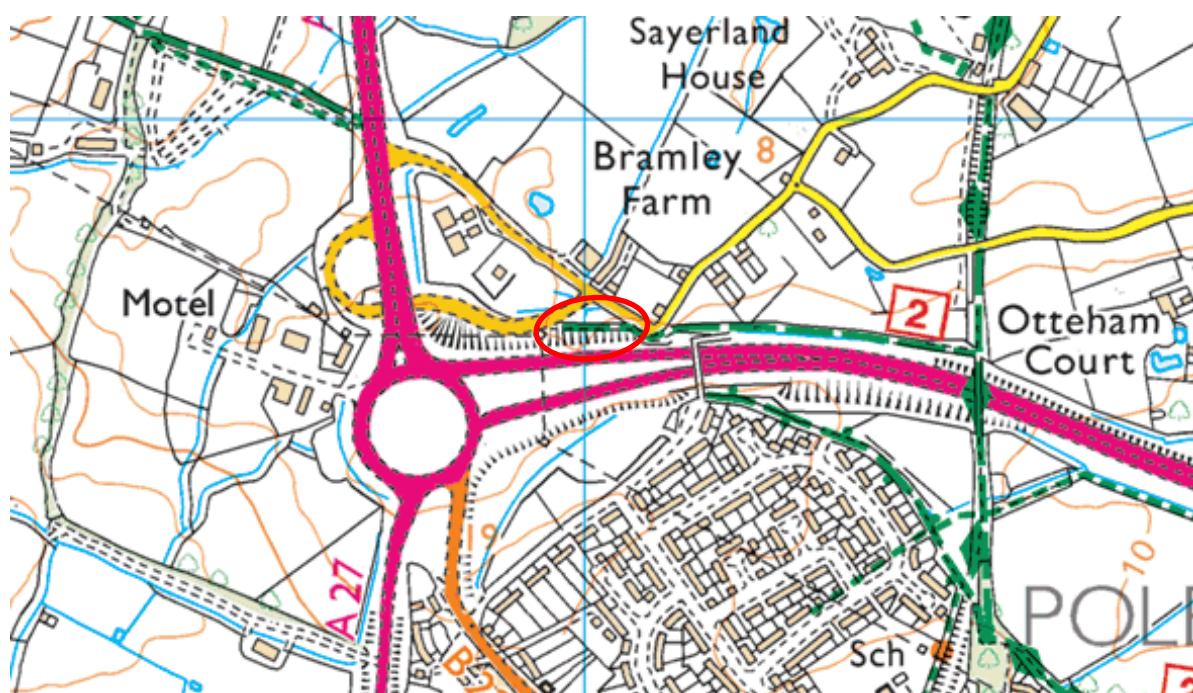


Figure 3: Location of the A27 Polegate/Bay Tree Lane FRS trial. (Image based on OS 1:25,000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.2.2 Site Details

The earthwork varies in height from approximately 16.8m at the eastern end of the site to 19.5m at the western end. Earthwork gradient varied between 15° and 24°, with locally steep sections near a pylon located towards the eastern end of the site and to accommodate the bend in Bay Tree Lane (BBMM 2010a).

It was considered that the embankment and bund at Bay Tree Lane are formed from Weald Clay embankment fill won from adjacent cuttings during the construction of the A27 Polegate Bypass. Underlying the embankment is undisturbed Weald Clay, which is generally a hard blue clay.

The site was considered by the Highways Agency to be a suitable location to trial FRS to stabilise a clay earthwork slope. The aims of the trial were as follows (BBMM, 2010a):

- Stabilise the earthwork slope using a sustainable method of remediation.
- Allow detailed monitoring of the behaviour of fibre reinforced slopes.
- To trial the use of FRS as an alternative repair method.
- To provide additional information to the Highways Agency research and allow design methods to be improved.
- To provide adequate information to allow FRS to be included in the Specification for Highway Works, as a standard method of remediation.
- To reduce the cost and environmental impact of earthworks across the Highways Agency network.

2.2.3 *Geotechnical Design*

Ground investigation and geotechnical design was undertaken to determine the benefit of using FRS on the site. Laboratory testing characterised the existing ground conditions. No testing was undertaken on trial mixes of FRS.

The proposed remediation solution was to excavate the 90m length of failed slope. The majority of the excavated soil was to be mixed with 0.2% polypropylene fibres and reused to form 80m (length) of the repaired earthwork. A 10m long section between the two areas of FRS was reconstructed with site won soils that had not been reinforced with fibres. This was undertaken to provide a comparison when assessing the performance of the FRS.

The design parameters for FRS were based upon the findings and recommendations of Mouchel (2012) at the A1(M), as described in Section 2.1. At the design stage, it was assumed that fibres were to be added to the soil at a proportion of 0.2% by dry weight. It was considered that the addition of this amount of fibres would increase the effective angle of shearing resistance by 25%.

Slope stability analysis was undertaken to model the earthwork repaired using FRS (BBMM 2010b). This indicated that the FRS slopes should be stable in the long-term with factors of safety between 1.1 and 1.4, when calculated in accordance with Eurocode 7.

2.2.4 *Construction and Monitoring*

As referenced in BBMM's Geotechnical Feedback Report (BBMM, 2012b), the earthwork was split up into three sections. Bay 1 at the western end of the slope was approximately 20m long, and Bay 3, in the central and eastern parts of the site was approximately 60m long. Figure 4 below shows the approximate locations of the bays. Both of these sections were repaired using FRS with fibres being added at a rate of 0.2% by dry weight.

The fibres used, called Geofibers 3627T were imported from Fiber Soils based in America. These were black polypropylene tape fibres with a minimum length of 2.75inches (70mm).

The slipped material from these bays was rotavated and mixed with fibres in a separate processing area. The treated fill was placed on the excavated slope and compacted in 150mm layers using a sheep's foot roller. Between Bay 1 and Bay 3, a 10m long section of the slope was repaired using site won material which had not been treated with fibres. The fill in this section was handled and compacted in similar fashion to the FRS.

The construction was undertaken in two periods. During Phase 1, between November 2010 and January 2011, Bay 1 was constructed. During this period, the construction was affected by significant rain and snowfall which resulted in the site becoming saturated and the fill becoming unworkable at times. It is understood, through discussions with HE, that to improve trafficability of the fill, fibres were added to the

Bays 2 and 3 were constructed in Phase 2 between October and November 2011. During this period, no significant adverse weather conditions were encountered.

During construction, the moisture condition value and undrained shear strength was determined regularly by on site testing. No laboratory testing to determine the effective strength parameters of the FRS was reported in the Geotechnical Feedback Report (BBMM, 2012b).

On completion of the works, inclinometers (BH01, BH03, BH05, BH07, BH09 and BH11) and extensometers (BH02, BH04, BH06, BH08 and BH10) was installed across Bays 2 and 3. The purpose of the installations was to provide feedback on the effectiveness of FRS.

Baseline readings were taken In November 2011 and, based upon records received, monitored for up to fifteen months.

2.2.5 *Slope Inspection*

The site inspection was undertaken on 7th March 2017 in dry, partly cloudy weather conditions with good visibility. The site was easily accessible from Bay Tree Lane without traffic management.

The slope was predominantly covered in short grass with some patches of hydrophilic vegetation, brambles and occasional trees. The ground was generally soft underfoot and waterlogged in places. Shallow excavations undertaken during the site visit with a trowel quickly filled with water, effectively demonstrating the very high moisture content with the soil, especially in Bay 1.

An arcuate back scarp was present in the western part of the site (Figure 4). The back scarp was approximately 28m long and between 0.3m and 0.6m high. It was located about 4m (vertically) from the toe of the slope. An associated toe bulge was evident at the base of the slope.

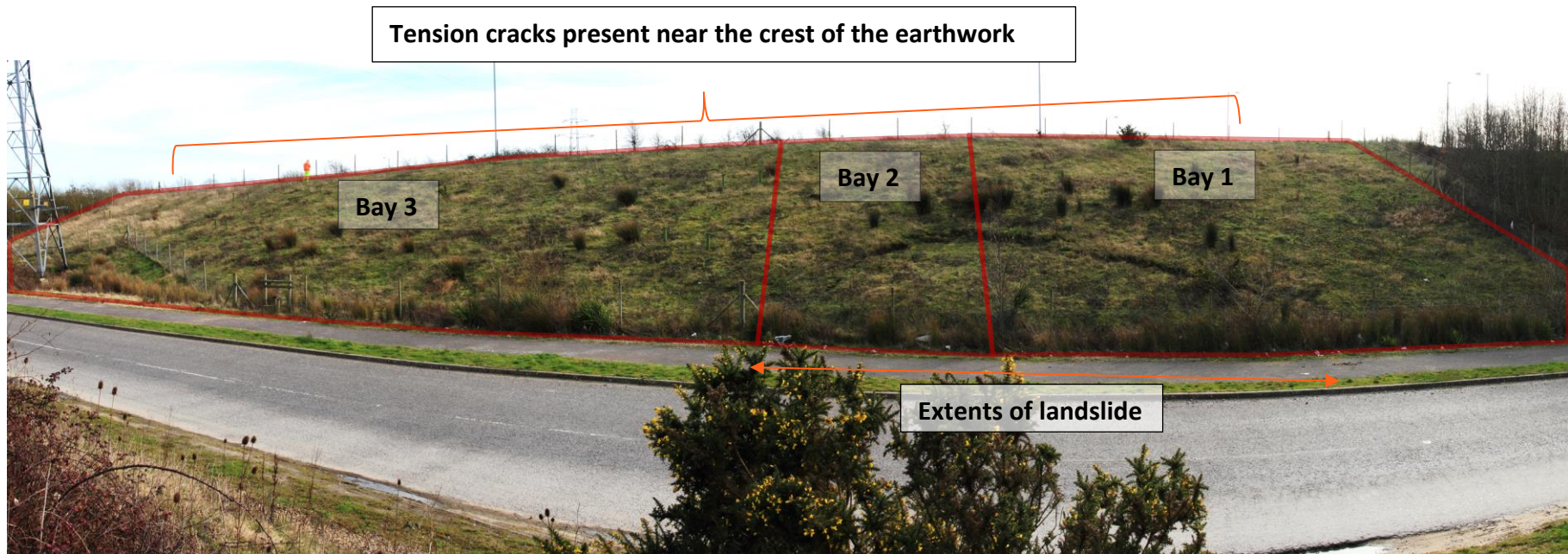


Figure 4: Photomontage of the A27 Polegate/Bay Tree Lane FRS trial. Note arcuate back scar indicating slope failure (Site Photographs 7DW_4196-4199)

The middle of the back scarp corresponds approximately to the boundary between the fibre reinforced Bay 1 and Bay 2 where unreinforced soil was used to reconstruct the slope. The back scarp extends into Bay 1 which was constructed with FRS. This corroborated by inspection of the soil exposed in the back scarp which had formed in very soft clay with fibres entrained within it (Figure 5).



Figure 5: Fibres entrained within the soil of the back scarp at A27 Polegate/Bay Tree Lane FRS trial (Site Photograph 7DW_4191)

Based upon the site observations, it is likely the slope failure initiated in the unreinforced soil of Bay 2. The failure subsequently extended into Bay 1. This would suggest that the FRS placed in Bay 1, and possibly Bay 3, does not have sufficient shear strength inhibit the slope deterioration.

Close to the crest, tension cracks and small back scarps were present. Although these were discontinuous, they were present along the majority of the embankment. Outside of the failed section of slope described above, no other signs of significant slope movement were noted. It is therefore not clear if the tension cracks and minor back scarps seen near the crest are associated with slope instability or settlement of the embankment fill.

Given the defects apparent on the embankment it would appear that the FRS repair solution at Bay Tree Lane has only been partially successful.

2.3 M20 Smeeth

2.3.1 Site Location

The trial is located approximately 7.5km south east of Ashford Kent at Grid Reference TR 06720 39350 (606720 139350) (MP 94/4 to MP 94/6) (Figure 6). It is situated in a cutting on the east bound (coast bound) side of the M20, close to the village of Smeeth.

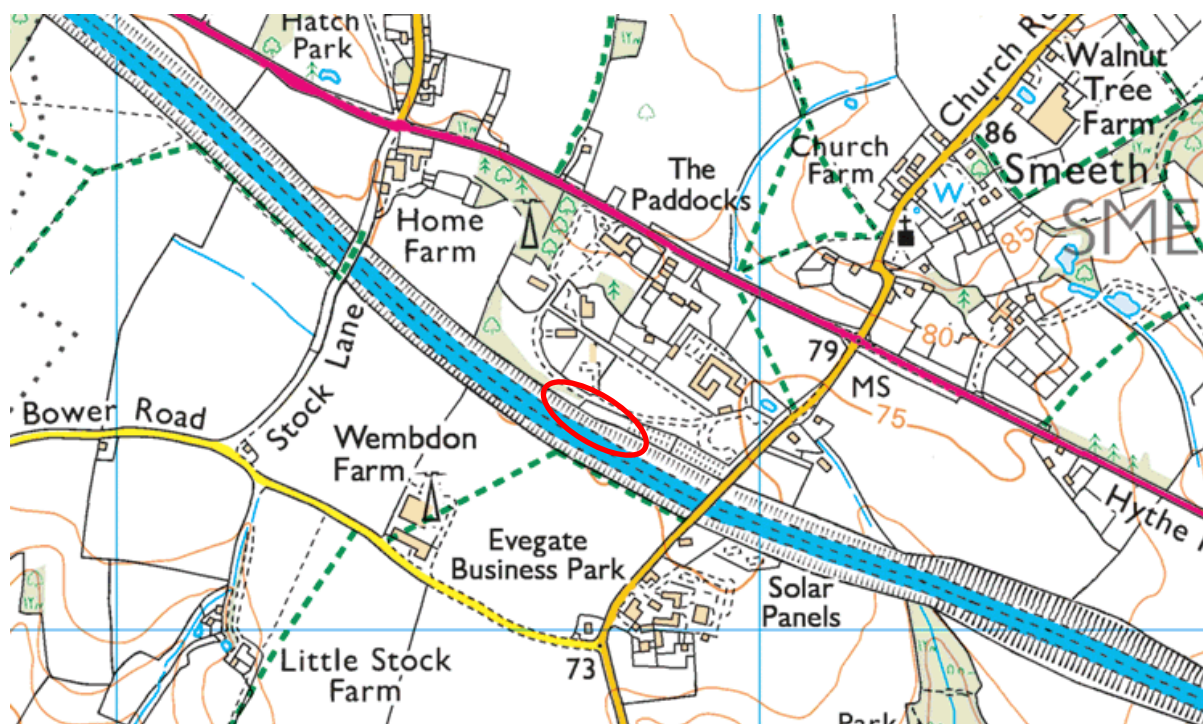


Figure 6: Location of the M20 Smeeth FRS trial. (Image based on OS 1:25,000 mapping. © Crown Copyright. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.3.2 Site Details

The cutting is approximately 490m long with an average gradient of 23° and a height of 5m at the location of the defects. The defects comprised tension cracking and toe bulges approximately 70m in total length (BBMM 2012c).

The geology at the site is indicated to be Hythe Beds. Trial pits undertaken at the site by InterRoute in 2003 encountered between 0.3m and 0.7m thick horizon of topsoil / made ground. Below this, interbedded sand and limestone were proven to a depth of 1.05m bgl (InterRoute, 2004).

2.3.3 *Geotechnical Design*

Stability analysis undertaken by InterRoute (InterRoute, 2004) demonstrated that the slope movement was occurring within the topsoil / made ground as a result of elevated pore water pressures associated with periods of significant rainfall.

To repair the slope defects, it was proposed by BBMM (2012c) to remove the topsoil / made ground from the face of the slope and treat the soil with fibres. The slope would then be reconstructed with this FRS. The main objective of the scheme was to stabilise the face of the earthwork using a suitable and sustainable method.

The design of the FRS was undertaken by BBMM and is described in their Geotechnical Design Report (BBMM 2012b). This was based upon the ground conditions described in the InterRoute report (InterRoute, 2004). Based upon the findings of the A27 Polegate scheme, described above, the addition of the 0.2% (by dry weight) of fibres was assumed to increase the angle of shearing resistance by 25%. Geotechnical analysis of the long-term stability of the repaired slope indicated that the addition of fibres to the topsoil / made ground should result in an increase in factor of safety to above 1.

2.3.4 *Construction and Monitoring*

As referenced in the Geotechnical Feedback Report (BBMM 2015), to remediate the soil slips a 111m long section of the slope was repaired with FRS between October and November 2014. The fibres used, called Geofibers 3627T were imported from Fiber Soils based in America. These were black polypropylene tape fibres with a minimum length of 2.75inches (70mm).

The made ground was excavated in a series of 0.5m high by 1m deep benches from the slope and temporarily stockpiled on the verge. Polypropylene fibres were mixed into the excavated soil at a rate of 0.2% to 0.3% by dry weight to form the FRS, which was then used to reconstruct the cutting.

During the works, significantly wet weather occurred which caused issues during the reconstruction of the slope using the FRS. The rainfall, in combination with the tendency for the FRS to form clods and the narrowness of the benches on the excavated slope, resulted in the use of the proposed Remex narrow trench compaction roller being deemed unsafe. Consequently a 13t excavator was used to compact ('track in') the FRS.

No slope monitoring was installed in the slope after construction.

2.3.5 *Slope Inspection*

The site inspection was undertaken on 7th March 2017 in dry, partly cloudy weather conditions with good visibility. The site was accessible on foot from Calleywell Lane overbridge.

The slope was predominantly covered in short grass and moss with occasional trees. In places, significant accumulations of polypropylene fibres were evident on the ground surface. The concentration of these fibres was much greater on the surface than in the freshly exposed soil. The soil exposed was a brown sandy clay and is considered to be the

made ground described by InterRoute and BBMM. Topsoil did not appear to be present in the shallow excavations formed during the site visit.



Figure 7: Fibres present on the ground surface and to a lesser degree in the exposed made ground

Tension cracks were noted in places along the crest of the slope. These tended to correspond with a concave shape within the upper slope. Where the cutting was benched, small back scars up to 0.1m high were noted at the crest of the lower slope.

The cause of the tension cracks and minor back scars may be due to minor slope instability or equally could be the result of settlement of the fill. Given the wet weather during the works and the method of compaction undertaken, it is considered that settlement under the self-weight of the fill is the probable cause.

In general, it is considered that the FRS slope repair at the M20 Smeeth has been successful in the short-term.

3 Monitoring Results

The monitoring of the FRS slopes was undertaken at the A1(M) Junction 1 and A27 Polegate. It was predominantly undertaken using a combination of inclinometers, extensometers and piezometers. The findings of the monitoring are described below.

3.1 A1(M) Junction 1

The findings summarised below were based on two years of post-construction monitoring. This corresponds to only two wetting and drying cycles. The effect of longer term repeated cycles of shrink/swell and the reduction of this through the use of FRS were not ascertained during the study.

3.1.1 Control Section 2

Monitoring in the unreinforced Control Section 2 (Figure 8) indicated that movements were consistent with shrink swell behaviour caused by season wetting and drying. The associated vertical movements were most pronounced in the top 1.0m in the upper parts of the slope. The maximum cumulative settlement measured in the extensometers over the monitoring period was 17mm which occurred at 0.1m bgl.

The cycle of swelling followed by shrinkage results in a net downward ratcheting of the soil. The cumulative downward movement of the slope measured over the monitoring period was in the order of 20mm. This movement was most pronounced at the toe of the slope. The figure below provides a graphical representation of the movement in Control Section 2.

3.1.2 FRS Sections 1 and 3

Monitoring of the extensometers in the FRS repairs undertaken in Sections 1 and 3, indicates that the vertical movements associated with shrink swell were reduced. In Section 1 (Figure 9), the cumulative settlements measured by the extensometers over monitoring period ranged between 4mm and 16mm. In Section 3 (Figure 10), over the same monitoring period, the cumulative settlement was between 6mm and 12mm.

The shallow cumulative downward movement of the slope measured over the monitoring period ranged from 0mm to 8mm in Section 1 and from 8mm to 13mm in Section 3. This movement was most pronounced in the middle and toe of the slope as defined in Figure 9 below

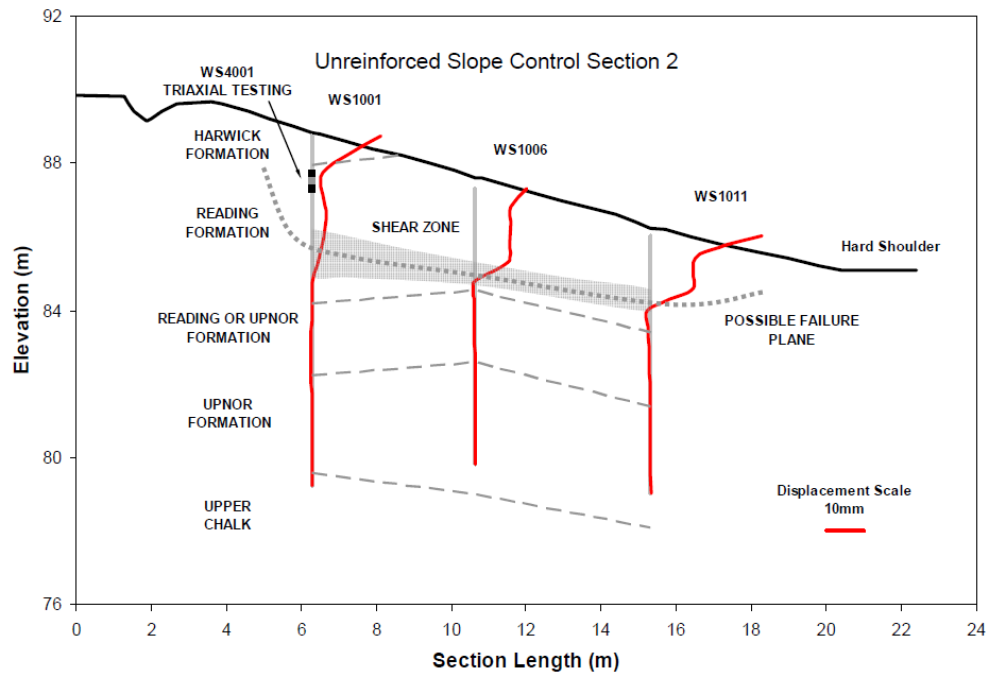


Figure 8: A1(M) J1 Control Section 2 inclinometer data, May 2008 to March 2011 (Mouchel 2012)

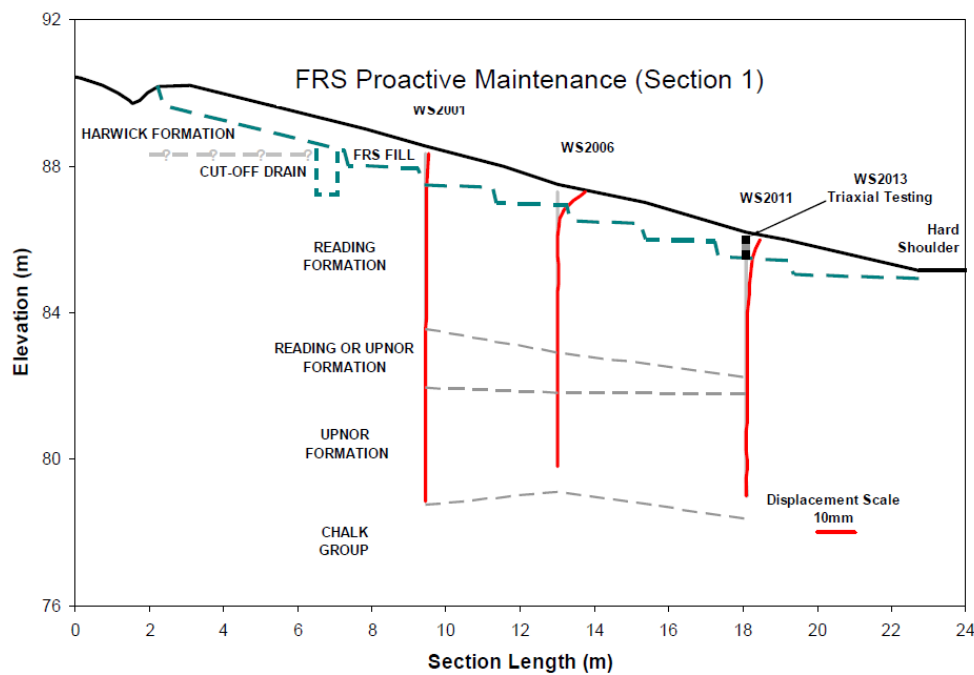


Figure 9: A1(M) J1 proactive maintenance Section 1 cumulative movement, April 2009 to March 2011 (Mouchel 2012)

The reduction in down slope movements in Section 3 was less. It was considered by Mouchel (2012) that this may have been due to existence of pre-existing shears which were not removed during the excavation and reconstruction of that section as shown by the ‘possible failure plane’ in Figure 10.

The visual inspections undertaken during the monitoring period indicated that the inclusion of fibres reduced the overall desiccation cracking and the crack depth but not the crack width. The polygonal tiles resulting from desiccation were between 25% and 50% larger in the FRS than the unreinforced ground. It was also noted that the fibre inclusions tended to prevent 'healing' of the cracks during the winter swelling cycle.

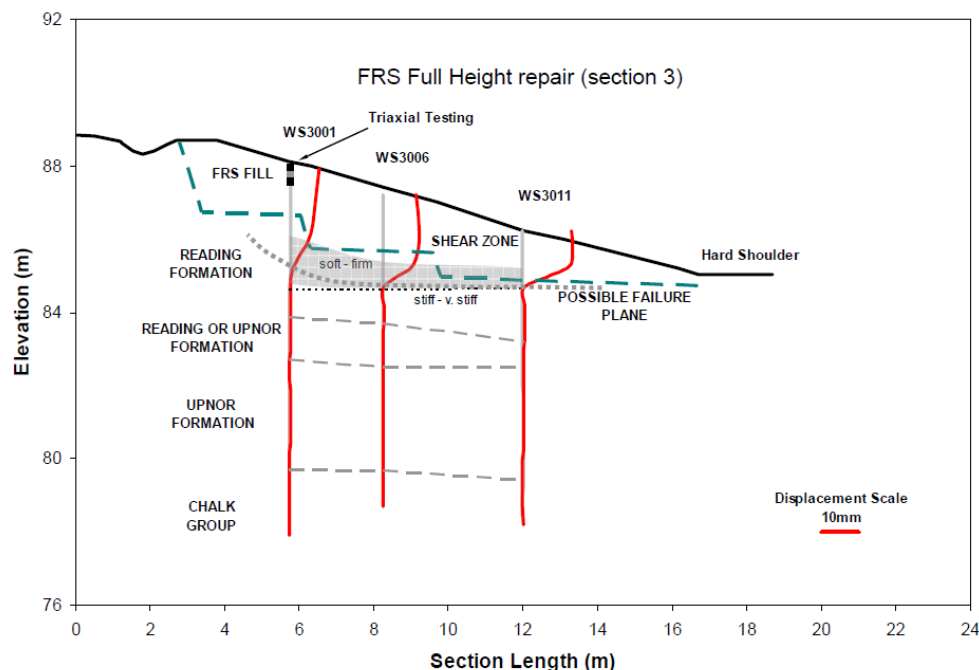


Figure 10: A1(M) J1 full height repair Section 3 cumulative movement, April 2009 to March 2011 (Mouchel 2012)

3.2 A27 Polegate/Bay Tree Lane

Monitoring was undertaken between December 2011 and March 2013.

Two inclinometers (BH01 and BH03) were installed in Bay 2. These recorded up-slope movement of the FRS from the surface to a depth of approximately 4m. It is unclear why the inclinometers would show up-slope movement however it is possible that this is due to erroneous alignment of the positive and negative sides of the inclinometer. Extensometers in this area (BH02 and BH04) do not show any significant movement vertical movement, indicating that the FRS has not undergone notable self-settlement.

Four inclinometers (BH05, BH07, BH09 and BH11) were installed in Bay 3. These appear to indicate that there has been up to 30mm of down slope movement of the FRS from the surface to a depth of around 4m. Extensometers (BH06, BH08, BH10 and BH12) in this area recorded some downward vertical movement, with extensometer BH10 recording more than 60mm near the surface indicating that the FRS has may have undergone self-settlement. It is considered that this is likely to be a result of consolidation and possibly shrinkage of the fill that was placed wet of optimum.

In summary the monitoring demonstrates that soon after construction the FRS slopes started to creep. This is likely to be an indication that the inclusion of fibres did not

significantly increase the effective angle of friction. This is likely to have been exacerbated by the placement of the fill wet of optimum.

4 Effectiveness of Trials

The measurement of the effectiveness of geotechnical trials is dependent on the desired objectives and outcomes. These objectives are often site and/or scheme specific but in essence can be summarised into the following two criteria:

- To provide a cost effective and robust slope remediation solution.
- To provide technical data that can inform future slope repairs

The following section discusses the effectiveness of the three trials in addressing these objectives.

4.1 A1(M) Junction 1

The reported aim of the scheme was to investigate the potential benefits of using FRS as a proactive, potentially cost effective and sustainable approach to the geotechnical maintenance of highway slopes (Mouchel 2012).

As an initial step to achieving this goal, existing published information was reviewed and summarised. This informed the subsequent ground investigation, design, construction and monitoring of the FRS trial.

A robust ground investigation was undertaken resulting in a good understanding of the geology and the ground conditions before the trial took place. Not only did this allow the scheme specific geohazards to be suitably understood and controlled, but it also provided a basis for applying the knowledge and lesson learnt from the scheme to future schemes in similar ground conditions.

The design was based upon the findings of the research and ground investigation. This allowed the formulation of a representative ground model and the determination of characteristic design parameters for both the existing and fibre reinforced materials.

Construction was undertaken using 'industry standard' plant. This demonstrated that the technique could be used in the UK without the need for specialist plant. It also demonstrated potential issues of undertaking the works in poor weather conditions and what actions could be carried out to alleviate the problems associated with this (i.e. soil workability and issues of plant movement on softened ground). However, constructing the slopes in such wet weather conditions is likely to have resulted in the FRS materials being placed at moisture contents significantly wet of optimum. This may subsequently have influenced the nature of the shrinkage and cracking observed.

Extensive ground monitoring instrumentation was installed before and after construction. This was supplemented by a rigorous visual inspection regime to record any deterioration of the newly constructed slope.

The monitoring was undertaken over three years (two years post-construction). This provided data for a quantitative assessment of the performance of the FRS (Sections 1 and 3) and comparisons with the unreinforced Control (Section 2). The results of the analysis provided insight into the short-term effectiveness of the FRS as a method of repairing slopes that are prone to shrink-swell and the associated reduction in stability of the slope. The findings of this assessment can be summarised as follows:

- The recommended optimum fibre content for FRS is 0.2% by dry weight. This may be increased to render the ground workable during construction, particularly during wet weather
- The addition of fibres did not prevent shrink-swell within the soil but reduced the overall incidence of desiccation cracking and the crack depth; it did not reduce the crack width.
- The addition of fibres reduced the cyclic ratcheting slope movements due to the increased tensile resistance in the FRS; the potential for the formation of deeper shear surfaces was also reduced.
- The fibre inclusions tended to prevent 'healing' of the cracks during the winter swelling cycle.
- The reduction in desiccation cracking and crack depth was not a function of fibre dosage, but was largely controlled by the thickness of the FRS repair. The minimum thickness recommended for proactive slope repair using FRS is in the order of 1.0m
- The addition of fibres reduced but did not stop slope movement. From the post-construction ground investigation and laboratory testing, plus the slope monitoring data it was apparent that the shear strength characteristics of the soil were improved and an increased factor of safety against shallow slope failure was thus attained.
- The inclusion of between 0.2% and 0.3% fibres resulted in an increase in the angle of friction of between 7% and 11%. This was less than the 15% to 35% recommended by Gregory and Chill (1998) and may be due to the high moisture content of the as-placed FRS.
- Where testing is limited or not available for small scale highways remedial works in over consolidated clays, a 10% increase in the effective internal angle of friction and no increase in cohesion were recommended for conventional slope stability analyses.

On the basis of the findings summarised above, it is considered that the scheme provided a workable and partially successful slope remediation solution. However, given the monitoring duration, this assessment can only apply to the relatively short-term. The long-term effectiveness of using FRS cannot be determined from the monitoring undertaken as the effects of repeated shrink swell cycles are not known.

The scheme did however provide an excellent summary of the prior research into FRS (Mouchel 2010) and the full scale trial application of the techniques provided good knowledge and insight that formed the basis of future trials. In this way the trial can be considered to have been highly effective.

4.2 A27 Polegate/Bay Tree Lane

The aims of this scheme were to repair the failed earthwork and provide data on FRS to allow design methods to be improved.

Comprehensive ground investigation data was available to determine the nature of the existing defects and effectively determine the ground conditions at the site. Similar to the

A1(M) Junction 1 trial, this resulted in a good understanding of the geohazards on site and for a suitable trial to be designed. The comprehensive reporting (BBMM 2012a and 2012b) of these resulted in dissemination of the knowledge and understanding gained of the application of FRS in such ground conditions.

However, as part of the ground investigations no laboratory testing was undertaken to determine the physical effects of adding fibres to the soil. Consequently, the design of the trial relied upon the findings of the A1(M) Junction 1 scheme, using an assumed increase in angle of shearing resistance of 25% for the FRS. This is in line with the recommendations Gregory and Chill (1998) but is much higher than the increase in angle of friction recommended by Mouchel (2012) on the basis of their post-construction testing on samples of the as-placed FRS at the A1(M) Junction 1.

Validation testing was undertaken during the construction works, however this was limited to undrained shear strength and MCV. As no pre-construction testing was undertaken on the FRS, it is unclear what the acceptable limits were for these parameters. Post-construction ground investigation to allow samples to be retrieved for effective stress testing was not undertaken. Consequently, the adopted geotechnical design parameters used in the slope stability modelling cannot be verified.

Construction of the trial was partly completed in poor weather conditions which resulted in the FRS (in Bay 1) and the unreinforced soil (in Bay 2) being placed at moisture contents wet of optimum. This is likely to have resulted in the saturated state noted during the inspections.

The post-construction monitoring appears to show that down-slope creep within the FRS started shortly after construction. Up to 30mm of downslope movement had been recorded in the 15 months after construction in Bay 3. Although no monitoring was undertaken in Bay 1 a significant landslide is evident in Bays 1 and 2.

It is likely that the landslide started in the control section which was unreinforced. However, from inspection of the back scar it is apparent that this encroaches into the adjacent FRS sections. Furthermore the arcuate shape of the back scar does not change as it passes into the FRS sections, which would indicate no significant increase in strength between the reinforced and unreinforced sections. The fibres in these sections do not appear to have sufficiently strengthened soil to prevent lateral extension of the back scar. This is corroborated by the slope creep measured by the inclinometers which suggests that the addition of fibres did not significantly increase the effective angle of friction of the fill.

Elsewhere on the slope (mainly in Bay 3), tension cracks and small back scars were noted near the crest. With reference to the post-construction monitoring it is considered that they can be predominantly associated with settlement of the soil and slope creep.

With regards to broadening the knowledge and understanding of the application of FRS, the A27 Polegate trial can be considered to have been of mixed success. It is evident from the defects present in the slope that the FRS has not been successful in repairing the failed earthwork and preventing further failure. Furthermore, the lack of laboratory test data on the as-placed FRS prevents an assessment of its design and as-built geotechnical properties.

Nevertheless, the difficulties encountered during construction may provide valuable lessons should future trials be undertaken. This trial also demonstrated the potential for FRS to be

used as a temporary works solution to treat ground that is soft and waterlogged to improve trafficability.

4.3 M20 Smeeth

The reported aims of the scheme were to stabilise the face of the earthwork using a sustainable and suitable method, thus reducing the requirement for continual monitoring and future works at the site (BBMM 2012b).

Limited ground investigation and laboratory testing was undertaken and the design was based upon the findings of the A27 Polegate scheme. It was assumed the addition of the 0.2% (by dry weight) of fibres would increase the angle of shearing resistance by 25%. An in depth understanding of ground conditions and the improvement of the physical properties of the soil through the inclusion of fibres was not attempted.

Construction of the trial was again undertaken in inclement weather and thus similar issues were experienced during the works related to the workability of the material, plant trafficability, etc. as were encountered during the A27 Polegate trial. The experiences of the previous two trials allowed these issues to be overcome. The level of compaction achieved with the excavator tracks is unclear. Furthermore, the wet weather is likely to have resulted in the as-placed moisture contents of the FRS being wet of optimum. As a consequence, there is uncertainty regarding the performance of the placed material.

Upon completion of the scheme, topsoil was not placed, although the exposed FRS was grass seeded. From the site inspection (Section 2.3.5), it was apparent that significant amounts of the polypropylene fibres used for the soil reinforcement were lying on the surface. Figure 7 illustrates a single clump of fibres. In Figure 11, light is seen reflecting off multiple clumps of the fibres (this can be difficult to see on printed copy but is more visible on digital copy, especially when zoomed in). The cause of this was not clear but may simply be due to insufficient mixing of the fibres leading to clumping which is visible at the surface. This was unsightly, and the fibres may migrate into the highway drainage. Unless these are removed this could result in additional plastic in waterways and ultimately the sea.

During the walkover, the earthwork appeared to be stable although small tension cracks, back scarps and toe bulges were noted. These may be indications that the stability of the slope is deteriorating but they may also be attributable to settlement under the self-weight of the fill due to insufficient compaction and high placement moisture contents. Depending on which mechanism is occurring, and the impact this will have on the FRS slope, will dictate how effective the solution is considered to be in the long-term. Given the lack of post-construction monitoring data, it is difficult to comment on how successful the scheme is likely to be in providing a long-term, robust solution. In the short-term, from site observations, the FRS appears to be performing adequately.

As a case study of the application of FRS, the M20 Smeeth trial provides limited additional knowledge and understanding in the short-term. Nevertheless, through repeat inspection of earthworks the trial may provide more insight into the long-term stability of FRS.

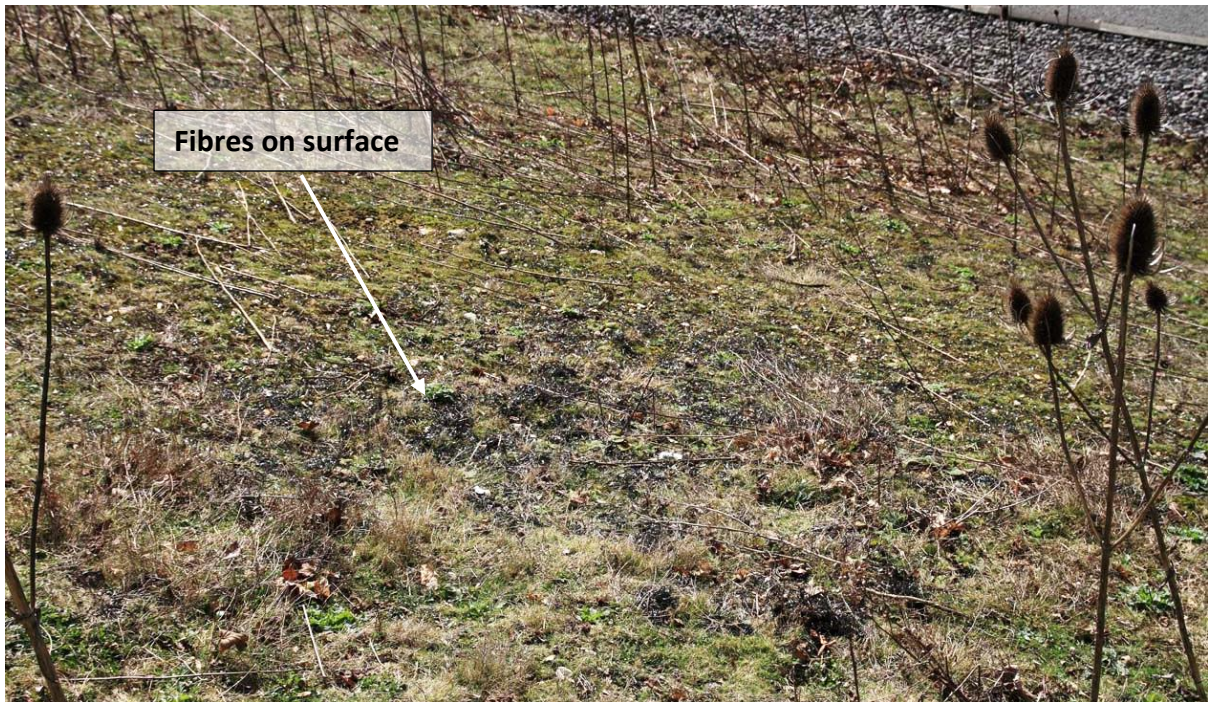


Figure 11: M20 Smeeth showing sunlight reflecting off multiple areas where fibres are present at the surface of the slope (Site Photograph 7DW_4185)

5 Lessons Learnt

The lessons that can be drawn from this work relate to both the structure and formulation of trials in general and to specific issues related to FRS.

5.1 Location and Access

At a prosaic level, determining the precise location of, and safe access to, the trial sites has on occasion proved problematic.

It is recommended that the reporting of future trials should include the trial location expressed both on an Ordnance Survey map, either 1:50,000 or 1:25,000 and any other scale deemed suitable, and as an alphanumeric and fully-numeric NGR of one or more salient locations (e.g. NY 52030 28247 and 352030 528247).

In addition, the safe access for observation, monitoring and maintenance should be clearly reported with a clear indication of a safe area or areas for parking, and a walking route to the trial site itself. Any constraints regarding the need to obtain permission from landowners should also be itemised.

It is considered that these items should be reported in the Geotechnical Feedback Report (GFR), which is routinely placed in HAGDMS. It is recognised that the access may change after the trial. However, this could be readily updated by means of a short, supplement to the GFR and be placed in HAGDMS as necessary.

5.2 Design

The design of the FRS undertaken at the trials used standard limit state principles which are considered to be a suitable method for the current application. It is based upon well understood principals and allows efficient and easily reproducible slope stability designs, based upon total and effective stress parameters.

However, there are still challenges in the derivation of the characteristic strength parameters for the design of the FRS. In two of the three trials, good ground investigation was undertaken to characterise the ground conditions and the physical properties of the soil. However, laboratory testing was not undertaken on trial mixes prior to construction, possibly due to potential difficulties with laboratory testing of FRS. Therefore, the detailed design was generally undertaken on an assumed increase of the angle of shearing resistance of 25% based upon published findings and the assumptions used for the A1(M) trial. These assumptions were based upon the review of published data, in particularly the findings of Gregory and Chill (1998) who stated that the addition of fibres increased the angle of friction by between 15% and 33%. The choice of 25% for the initial trial could therefore be considered to be reasonable, albeit higher than a moderately conservative value that would be often adopted in geotechnical engineering practice.

The findings of post-construction laboratory testing on samples of the as-placed FRS at the A1(M) Junction 1 trial indicate that the increase in the angle of friction achieved was between 7% and 11%. Mouchel (2012) recommended that an increase in the effective internal angle of friction of 10% may be adopted for the design of the FRS repair with no increase in cohesion. Given the range of results of the laboratory testing, this may be

considered to be optimistic with a value of 8% being more appropriate for a moderately conservative design. In reality, the increase in angle of friction using 8% or 10% will be similar (ie a difference of less than a degree) and therefore a value of 10% is considered a reasonable value to adopt for initial design.

At design stage the trials at A27 Polegate and the M20 Smeeth both assumed an increase in angle of friction of 25% instead of the 10% recommended by Mouchel (2012). In light of the laboratory testing on the as-placed FRS at the A1(M) Junction 1 and the slope defects that have occurred in the FRS repair at the A27 Polegate, it is considered that assuming 25% increase in angle of friction is optimistic.

Without laboratory testing, for initial design purposes the use of 10% is considered to be more appropriate. Nevertheless, for future schemes using FRS appropriate laboratory testing should be undertaken to inform the detailed design.

Given that this method of repair is still new to the UK and there are uncertainties in the actual degree of soil improvement / strengthening that can be achieved, a robust approach to the investigation, design and construction should be adopted. This could be akin to the approach that is defined in HA74/07 for lime and cement stabilised soil and could include site trials of the FRS in demonstration areas.

It is appreciated that there are difficulties in forming representative FRS samples in the lab or sampling FRS in the field. Furthermore, testing of the FRS is not necessarily a simple operation if reliable results are to be achieved. Indeed, Mouchel 2012 identified this issue as a topic that required further research. It is considered that the development of better sampling and testing techniques would increase understanding (and confidence) of the likely benefits of the reinforcing soils with fibres and thus result in wider adoption of this method on future slope repair schemes.

5.3 Materials and Construction

For all three of the trials, fibres were sourced from Fiber Soils based in the USA as they are not readily available in the UK. For the purposes of the trials, this was considered to be a reasonable approach. However this is not a sustainable approach if FRS becomes more widely adopted. In this situation, a UK based source of tape or fibrillated fibres would need to be established. Alternative types of fibres or materials which are currently available or easily manufactured, such as shredded tyres or nature fibres, could also be considered.

Construction of the FRS slope repairs appears to have been predominantly undertaken during the winter months in poor weather conditions. The addition of fibres allowed the soil to remain workable in conditions where earth-working operations would normally have stopped. Although this demonstrates the resilience of FRS to changes in weather, this did result in the fill, at times, being placed at moisture contents that were too wet of optimum.

It is envisaged that placing the soil too wet of optimum has resulted in poor compaction, elevated pore water pressures and softening of the ground. This is potentially corroborated by the monitoring at the A27 Polegate, where settlement of over 60mm has been measured in the FRS.

To better demonstrate the effects of fibre inclusions in soil, future trials should aim to place the soils within the required optimum moisture content range.

At the A27 Polegate trial, fibres were added to the ground to improve trafficability of the soil and allow plant movements to continue in wet conditions. This demonstrates the potential for FRS to be used for temporary roads, in situations where more traditional techniques, such as aggregate or trackway systems are not deemed to be practicable. However, the potential environmental impacts of using non-biodegradable plastic fibres (as further discussed in the following sections) probably negates their use in most temporary works situation. Ideally the fibres used for such a purpose would be natural biodegradable fibres from a sustainable source. Further studies and site trials into the use of such natural fibres as a method of temporarily improving the trafficability of soil are required. Such studies should consider *inter alia* the relationship between the design life of the works and the time taken for biodegradation of the fibres.

At the M20 Smeeth trial there was a considerable number of fibres present on the surface. Given the potential for these fibres to migrate into drainage and waterways, it is considered that encapsulation of FRS is essential. On many earthworks, this may simply mean providing a sufficient depth of topsoil above the FRS. However, in places where erosion is likely, such as at the edge of water courses or on land liable to flood, additional measures may be required.

5.4 Monitoring

Monitoring of slope movement and deformation was carried out at the A1(M) and A27 Polegate sites. The monitoring undertaken at these sites generally provided data for a semi-quantitative assessment of the success of FRS as a repair technique. However, this monitoring was undertaken for a maximum of two years after construction, so whilst it gave a good insight into the short-term performance of the FRS, the long-term benefits remain unclear.

For current and future schemes, in order to fully evaluate the performance of FRS, a monitoring period of 15 to 20 years is recommended, albeit that monitoring intervals need not be overly frequent. A caveat is that if the monitoring frequency is insufficiently frequent, then problems with continuity of process, people and data can come to the fore. It is therefore recommended that a frequency of no greater than 24 months be maintained and ideally that the organisation (and preferably people) undertaking the assessment on behalf of HE remain the same. To achieve this, it may be appropriate to resource and fund such trials separately from the highways maintenance contracts that tend to be retendered every four to five years.

5.5 Maintenance

Given the nature of FRS slope repairs, it is considered that maintenance is required to allow monitoring to continue. On the A1(M) Junction 1 scheme, since the monitoring period the vegetation had become dense, thus making visual inspection of the slope (and desiccation

cracking) difficult. Furthermore, if monitoring is to be undertaken in the long-term, then provision should be made for routine maintenance of the installations.

5.6 Life Cycle Assessment

A cradle-to-site Life Cycle Assessment (LCA) has been conducted for the three techniques – willow poles, FRS and EKG – and a crushed granular fill control technique. The results of the LCA are reported in detail by Leal et al. (2018) and included consideration of two failure depths of 1.0m and 2.5m (the 1.0m failure depth was not considered for EKG) and various transport distance options. It was found that at both failure depths, and for all transport cases, the greatest environmental impact was for the Granular Rock Fill Replacement control. At 1m and 2.5m failure depths this technique resulted in an impact of 51 to 80 kgCO₂e/m² and between 109 and 174 kgCO₂e/m² of failed slope respectively, depending on the transport distance assumed.

Willow Poles had the least impact, resulting in 4 to 8 kgCO₂e/m² to 8 to 12 kgCO₂e/m² of failed slope respectively. For the 2.5m failure depth EKG was the second best performing technique, with an average impact of 14 kgCO₂e/m². FRS had an impact ranging between 16 and 35 kgCO₂e/m². For techniques requiring large quantities of materials and movements of these materials across substantial distances (e.g. Granular Rock Fill Replacement and Willow Poles), it was found that transportation accounts for more than half of the total impact.

5.7 End-of-Life Considerations

In addition to the carbon impacts, the long-term sustainability of FRS, when using non-biodegradable fibres, may be questioned. Fundamentally the long-term efficacy of introducing non-biodegradable plastic inclusions to the soil environment needs further consideration. Unlike other, generally planar, geosynthetics it is considered that these fibres will be very difficult to separate from the soil matrix in the future. Therefore, to be a viable sustainable geotechnical application and to achieve Highways England's ambition for a circular approach to managing resources, FRS (using plastic fibres) should be suitable for reuse in the future, ideally in a manner comparable to other engineering fills.

Based on the Waste Framework Directive (2008) FRS that has been excavated would be defined as a waste, and thus require permitting, unless it can be managed using CL:AIRE's code of practice (CL:AIRE 2011). In both cases excavated FRS may be reused if it can be determined that it does not pose a risk to human health or the environment. Given the potential for fibres to migrate into water courses (as demonstrated at the M20 Smeeth site) in some situations FRS may be considered to pose a risk to the environment and would be considered unsuitable for reuse. Furthermore as awareness and understanding of the impact of plastic in the environment develops it is unclear whether the use of disseminated plastic fibres in soil will be permissible in the future.

In terms of the geotechnical suitability of FRS for reuse, based on the current Specification for Highways Works (SHW) Series 600, it is likely that it would be difficult to demonstrate its acceptability in terms of permitted material constituents and in determining its acceptability through standard geotechnical laboratory tests. As demonstrated in the trials, retrieving suitable samples for testing and then obtaining getting reliable laboratory results is difficult.

Additionally, the durability of the polypropylene fibres needs further research as embrittlement of these will result in a reduction in the performance of the FRS. Consequently, from an engineering point of view the FRS would only be suitable for reuse in non-engineering elements such as within landscaped areas or noise bunds. The alternative would be to dispose of the FRS in landfills.

Given the above use of the FRS as engineered fill is unlikely to become a standard technique in the future due to the environmental and waste difficulties, plus the issues surrounding the determination and confirmation of performance.

Resolving these end-of-life issues is considered to be the key to the adoption of FRS as a slope repair technique in the future.

6 Summary and Conclusions

Three trials of FRS have been examined in terms of their potential to enhance the stability of shallow failures. Each of the sites was inspected in early-2017.

Lessons learnt from the trials have been detailed in the previous section. General issues apply that apply to the trials of FRS or of other innovative methods or techniques include:

- ensuring that the purpose and limitations of a trial are clearly set-out,
- the need to continue the monitoring for a period longer than two to three years in order to fully evaluate the success or otherwise of the trial,
- the need to ensure that the location of and access to the trials are clearly and accurately recorded and updated in the light of any subsequent changes, and
- sufficient provision is made for the maintenance to allow effective long-term monitoring of the trial.

Site observations and, where undertaken, monitoring of the trials, reveals that in general terms the use of FRS to repair failing slopes has been partly successful in the short-term on two of the sites i.e. A1(M) Junction 1 and M20 Smeeth. At the A27 Polegate, the use of FRS to repair the slope was not successful.

Difficulties in accurately determining the improvement to the geotechnical properties of the soils at the trial sites were reported at both the design and construction stage. At design stage, a 25% increase in the effective angle of shearing resistance was generally adopted. However, post-construction testing at the A1(M) site and slope instability at A27 Polegate suggest that the increase in angle of friction is less.

It is considered that the three trials have not demonstrated effectiveness of the FRS as a long-term slope repair technique. To achieve this the following aspects would need further consideration:

- In-situ sampling and laboratory testing techniques need to be further developed to better determine the effect the addition of fibres has on the geotechnical properties.
- Further research is needed into effective methods of sampling FRS for post-construction validation testing.
- Construction needs to be controlled to prevent FRS being placed too wet of optimum.
- FRS needs to be encapsulated to prevent erosion and fibres migrating into drainage and water courses.
- Further consideration needs to be given to the long-term sustainability and reuse of FRS.

The above would require further research prior to the implementation of the future trials. Given these issues plus the potential environmental challenges associated with reuse it is considered that FRS technology and knowledge are not sufficiently developed for it to be adopted as a long-term slope repair technique. Nevertheless, the trials have demonstrated the potential for FRS to be used to improve trafficability of soils. It is recommended that further research is undertaken to assess the use of FRS, created with sustainable and

biodegradable natural fibres, for temporary ground improvement and the construction of temporary roads and tracks. Such studies should consider the relationship between the design life of the works and the time taken for biodegradation of the fibres.

Acknowledgements

The authors are grateful to a number of individuals and organisations and they are gratefully acknowledged for their help in organising access to the trial sites, namely, Verity Smith and Gemini Murthen (Atkins), Martine Mildon and Mike Tandy (A-one+ Integrated Highway Services).

The Highways England Project Sponsor, Jan Marsden, and colleagues provided invaluable support and insight into the various research and trials that have been conducted over the last 10 years.

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Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, fibre reinforced soil and electrokinetic geosynthetics. These techniques were used in place of conventional approaches to repair in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and to address the need to reduce the scale and/or cost of traffic management and traffic delays. Trials of the techniques have been undertaken over the preceding 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report presents an assessment of the effectiveness of fibre reinforced soil as an aid to increased stability and is one of a series for this project.

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ISSN 2514-9652

ISBN 978-1-912433-69-8

PPR873