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1 Specification Development for Cold In-Situ Recycling of Asphalt

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5 **Abstract**

6 In-situ cold recycling provides a valuable means to reduce the environmental impact of road
7 construction. The reduced energy requirements relative to traditional hot mix recycling can lead to
8 significant reductions in cost and associated CO₂ emissions. Worldwide, in-situ cold recycling has
9 been found to be particularly useful in the rehabilitation of rural roads where site locations are far
10 from asphalt plants. However, practical issues remain due to the evolving nature of cold bituminous
11 materials. Unlike hot-mix asphalts which gain strength quickly as they cool, cold-mix bituminous
12 materials gain strength slowly over time. This is particularly an issue in countries with cooler, wetter
13 climates, such as Ireland. Consequently the specification of cold materials poses a number of
14 challenges relating to curing and testing protocols.

15 This paper reports on the development of a specification for cold recycled materials and the
16 application to a case study in Ireland. This work was conducted as part of the CEDR funded project
17 *CoRePaSol* which focused on the development of harmonised design procedures for cold recycled
18 mixes. In collaboration with the Irish National Roads Authority a 2.5km site on a national road was
19 identified for a recycling trial. The existing guidance for Low Energy Pavements was used to classify
20 the road with respect to traffic levels and a testing programme was implemented which sought to
21 reflect best practice across Europe. A series of recycling options were assessed and four different

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22 mix designs were proposed. These included variation in the binder type (foam mix or emulsion, with
23 or without cement), binder content and recycling depth, reflecting the wide array of options
24 available to engineers seeking to promote cold recycling. Due to the lack of harmonised guidelines
25 across the Europe on design and evaluation of cold mixtures a specific focus is given in this paper to
26 the mix evaluation procedure where alternative laboratory test specimen curing and testing
27 procedures are investigated and recommendations are given.

28 Key words: Cold asphalt mix recycling, Emulsion cold mix, Foam cold mix, in-situ recycling

29 **1. Introduction**

30 **1.1. The World and EU Road Network**

31 The Worldwide road network consists of 16.3 million kilometres [1], and 30% of this network is the
32 EU road network making it the largest roads network in the world [2]. These roads fulfil a major
33 economic and social goal by facilitating the movement of goods and people throughout EU. Their
34 operational health is of utmost importance for economic and social development of the EU. As a
35 result, the EU governments invest heavily in an efficient transport system, with 42% (€4.5 billion) of
36 the EU transport network fund dedicated to road networks development and maintenance [2]. The
37 development and maintenance of this road network is very important for growth and the
38 competitiveness of EU economy. This is particularly important for small economies within EU, such
39 as Ireland.

40 Today Ireland has a road network of 96,032km (2% of EU road network) which is approximately 24m
41 of road per capita, three times the EU average [2]. Since 1995, the Irish government has invested
42 approximately €29 billion in the development of this road network [3-5]. However since the onset of
43 the economic recession in 2008/9, national investment in new road projects has declined. Instead,
44 the focus has moved to maintenance, with an average investment of €50 million per annum [2].

45 **1.2. Reduced Investment, Increased Maintenance**

46 The ageing road infrastructure requires attention in the form of repairs and rehabilitation. Although
47 the maintenance budget has stabilised, the number of maintenance projects are expected to
48 increase with time. Lack of financial investment forces the development of innovative solutions and
49 novel maintenance and rehabilitation methods. The most common method of road rehabilitation in
50 Ireland has been complete road reinstatement, i.e. removal of the old road material and complete
51 reconstruction of the road using new virgin materials. Recycling procedures have not been widely
52 utilised because of the variability in the reclaimed asphalt (RA) material and due to insufficient
53 knowledge and experience of the road recycling procedures [6]. For the past decade or so the Irish
54 National Roads Authority (NRA), together with the road construction industry have sought to build
55 confidence in use of RA in road [7]. One of the recycling methods being assessed is the cold recycling
56 process [8-10].

57

58 **1.3. Cold Asphalt Recycling**

59 The advantage of cold asphalt recycling technology is that it allows for the recycling of existing
60 pavements at the end of their service life [8-13]. Using recycled material compares favourably with
61 the use of fresh aggregates in road construction as it requires less material transportation, expends
62 less energy on material heating and consumes less of the raw materials [11]. Despite the clear
63 economic and environmental benefits of the cold asphalt mix technologies, doubts remain about
64 their long term performance. If the long-term performance of cold asphalt mixes is inferior to hot
65 mix asphalt this could negate any long-term financial or environmental benefits.

66 The disadvantages of the cold recycling process have been well-documented and include [8, 13, 14]:

- 67 i) A weak early life strength (due to trapped moisture) and
- 68 ii) Long curing times before cold-mixes to acquire maximum strength.

69 However, the main difficulty in the wider acceptance of the cold mix recycling is the poor of
70 guidance available on cold mix design and evaluation processes [13], by way of standards. Across
71 Europe, each country has adopted its own material conditioning and evaluation procedures [11].
72 This challenge has been addressed by the Conference of European Road Directors (CEDR) via the
73 *CoRePaSol* project, which has sought to harmonize cold mix property evaluation and mix design
74 procedures across Europe [11].

75

76 **1.4. Scope of the study**

77 This paper reports on the development of a specification for cold recycled materials and the
78 application to a case study in Ireland. In collaboration with the Irish National Roads Authority a
79 2.5km site on a national road was identified for a recycling trial. The existing National Guidance [15]
80 for Low Energy Pavements was used to classify the road with respect to traffic levels and a testing
81 programme was implemented which sought to reflect best practice across Europe. A series of
82 recycling options were assessed and 4 different designs were proposed. These included variation in
83 the binder type (foam mix or emulsion, with or without cement), binder content and recycling
84 depth, reflecting the wide array of options available to engineers seeking to promote in-situ cold
85 recycling as method for roads rehabilitation.

86

87 **2. Site Description and Material Characterisation**

88 The test site was selected by the NRA and is on a single carriageway national secondary route close
89 to Kilkenny city, Ireland. The section was chosen because the pavement of this section of road
90 required rehabilitation, and it is on a main commuter route with an average daily vehicle traffic
91 count of 5,750 vehicles of which 13% are HGV. Following the NRA guidance [15], this traffic level
92 would result in the road being characterised as Type 2b road. Figure 1 illustrates a satellite image of

93 the trial section and surrounding area. The length of the trial section is 2.5km and width of the road
94 is 6.5m.



95

96 **Figure 1. Satellite image of the trial road section**

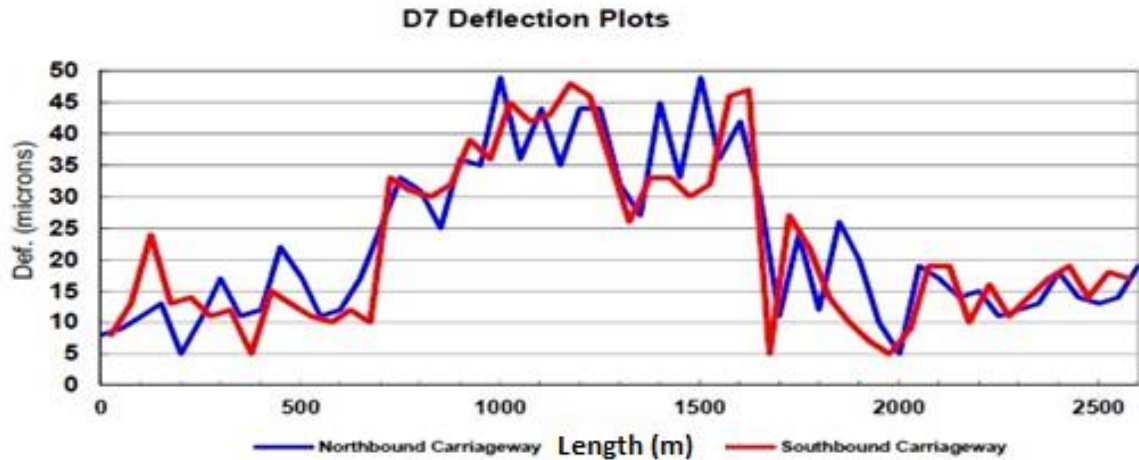
97 The initial investigation of the trial section showed a very inconsistent road structure. The images in
98 the Figure 2 illustrate the variety of materials present throughout the length of the trial section. It
99 can be seen that over the years there have been numerous overlays, patch repairs and surface
100 dressings applied. This was due to the previous fragmented nature of network management in
101 Ireland, which has resulted in a roads network with legacy issues.



102

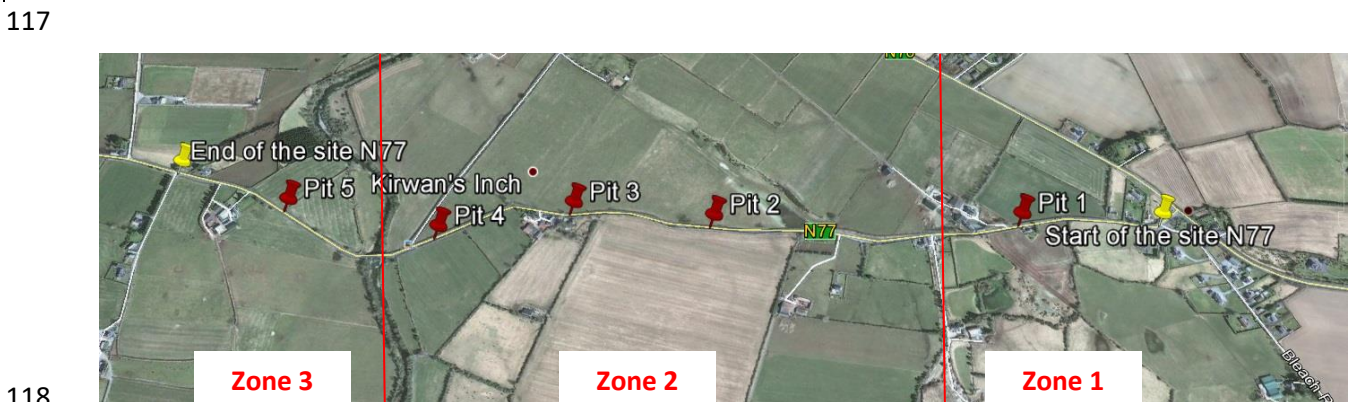
103 **Figure 2. Cores taken from existing pavement showing a large variation in material present**

104 Based on a ground penetrating radar survey it was decided that an appropriate recycling depth
105 would be 300mm. According to the existing guidance at the time [15], recycling the existing road to
106 the depth of 300mm with surface layer of 100mm is permitted for Type 2b road. The road was also
107 regularly assessed as part of the NRA's regular monitoring work and data was also available from a
108 Falling Weight Deflectometer (FWD) survey. Using this data, the D7 deflections are presented in
109 Figure 3. These illustrate that between length 700m and 1,700m the sub-base layer of the pavement
110 is weaker and was classed as 'poor'.



111
112 **Figure 3. D7 deflection data obtained from FWD survey**

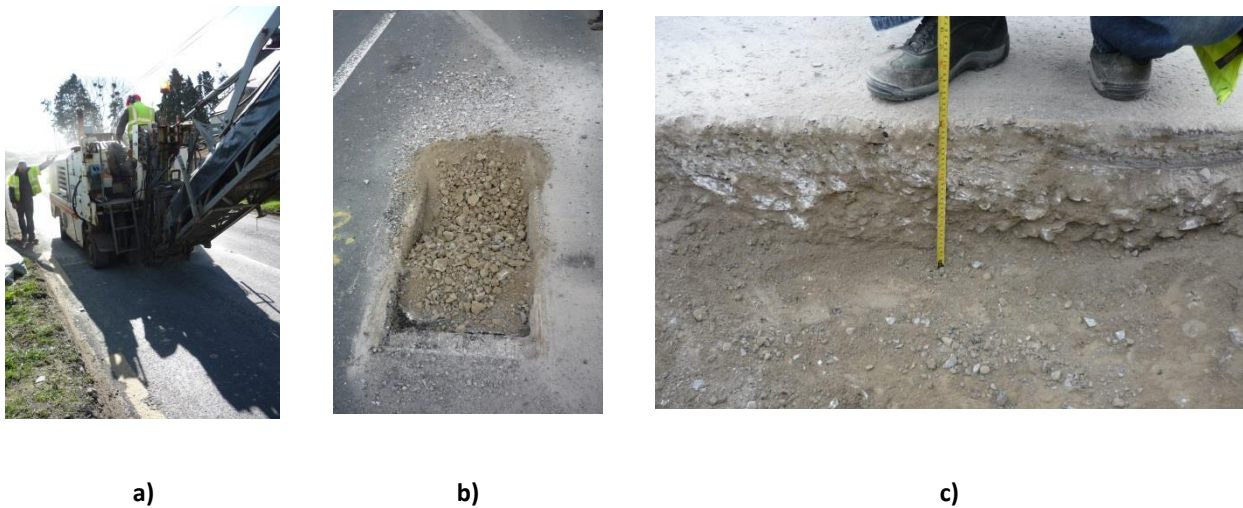
113 These results are in agreement with anecdotal evidence that the middle zone of the site is prone to
114 flooding during autumn and winter months. Therefore, in order to investigate the quality of the
115 existing material the site was separated into three investigation zones and five pits were excavated.
116 The locations of the test pits are graphically presented in Figure 4.



117
118
119 **Figure 4. Satellite image of the trial road section, showing location of the test pits.**

120 A small milling machine (with 1m wide milling drum) was employed to excavate the trial pits, as
121 shown in Figure 5a, to obtain material samples with a grading representative of that which would be
122 achieved during the reconstruction process. Each trial pit was milled to 300mm depth and 1000mm
123 length and width. The milling process was performed in two phases. The first phase comprised
124 milling and removing the bituminous material only; this was to a depth of 100mm. In the second
125 phase the trial pit was excavated by a further 200mm and this material was also removed; this

126 comprised of the sub-base/granular layer only. Approximately 200kg of material was removed from
 127 each pit. After the milling process was complete, CBR values were obtained for the subgrade using a
 128 Dynamic Cone Penetrometer test; the results for this are shown in Table 2. The CBR results show a
 129 stronger subgrade in pits 1 and 5, and weaker subgrade in pits 2-4. These results are in agreement
 130 with FWD data and suggest a weaker sub-base between 700m and 1,700m road length. This data
 131 supported the decision to separate the site into three investigation zones, as shown in Figure 4.



132 **Figure 5. Test sample pits milling, a) milling machine, b) milled granular layer and c) full depth of a**
 133 **pit.**

134 **Table 1. CBR test results**

Pit No.	Layer	CBR	Comment
1	1	103	Refusal
	2	207	
2	1	165	End of ruler
	2	5	
3	1	104	End of ruler
	2	21	
	3	3	
4	1	164	End of ruler
	2	7	
	3	57	
	4	26	
5	1	352	Refusal
	2	140	
	3	129	

135 **2.1. Material Characterisation**

136 Approximately 1000kg of material was obtained from five trial pits for analysis. The material from
137 each pit was processed separately i.e. the bituminous (surface layer) and granular materials within
138 each batch were kept separate. On returning to the laboratory the materials were riffled and
139 representative samples of each material were taken for moisture content and grading analysis.

140 *2.1.1. Material moisture level*

141 The moisture test results are summarised in the Table 3. The moisture tests are performed according
142 to the BS 1377-2: 1990. The results show a low moisture level in both materials. A higher moisture
143 level was expected in the granular layer, but this was not observed due to the material being quite
144 coarse.

145 **Table 2. N77 material moisture content test results.**

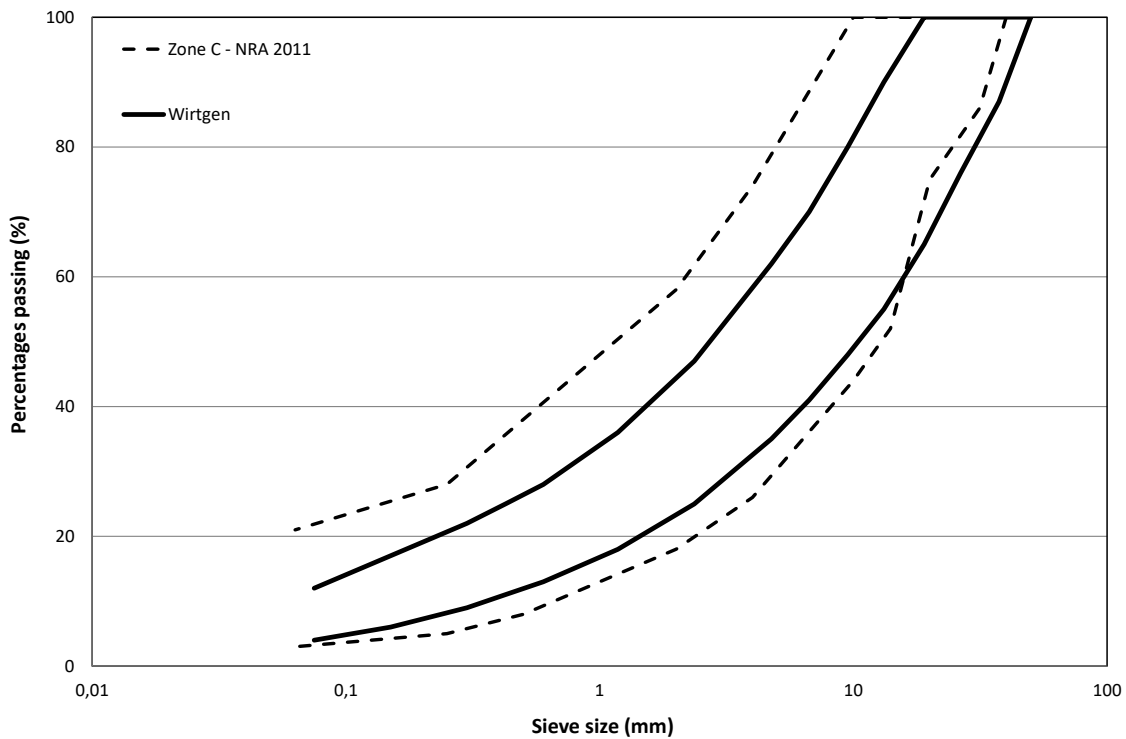
Recycled layer	Moisture Content (%)				
	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5
Surface	0.92	0.73	0.78	0.79	0.44
Granular	1.68	1.98	1.83	1.41	1.35

146

147 *2.1.2. Material grading*

148 The material grading is obtained according to the IS EN 933-1: 2012. The results for the grading
149 analysis are compared to the grading limits given by the NRA guidance for recycled materials (Zone
150 C, as per [15]) and to those in the Wirtgen cold mix manual [16]. Figure 6 shows a comparison
151 between the NRA and Wirtgen grading envelopes. Based on the initial grading results it was found
152 impossible to fit the material grading to the NRA grading curves without substantially changing the
153 structure of the material, i.e. inserting fresh aggregate. On the other hand it was found that Wirtgen
154 grading envelope is more suitable for the cold mixtures composed of recycled materials. It is
155 considered that this difficulty with the NRA grading curve is due to the fact that the NRA guidance is
156 also used for designing cold-mix asphalt using virgin aggregates; this is produced using an adjacent

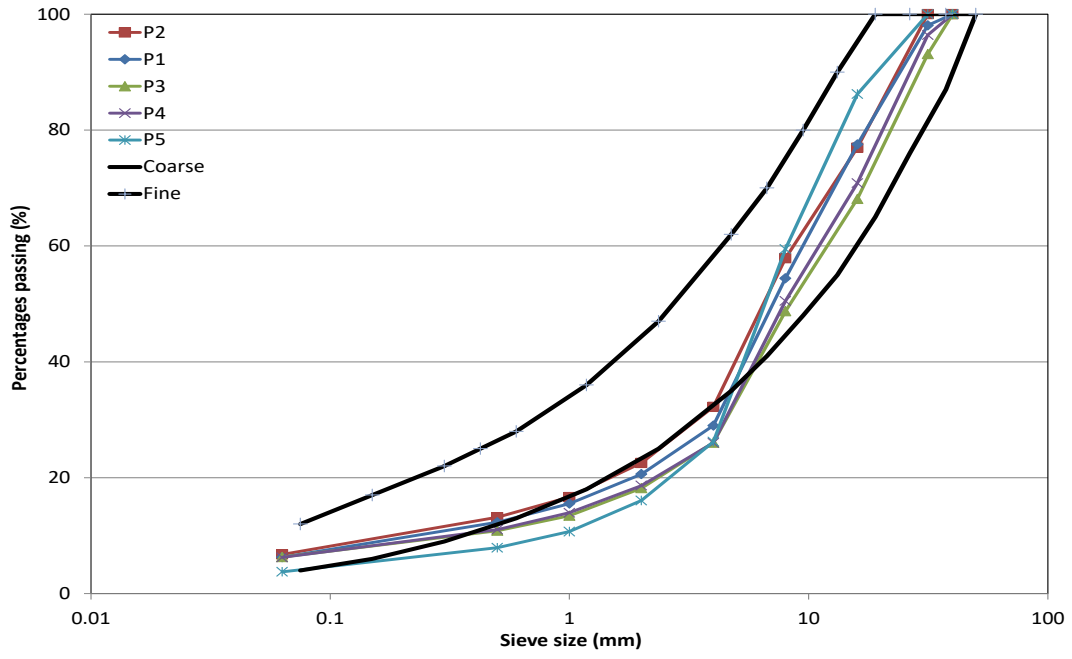
157 zone in the NRA grading curve (Zone A). The net result of this association is the development of a
158 grading envelope for recycled materials that may not be practical or achievable. Figure 7, shows the
159 grading of the combined surface and granular material from each trial pit with the Wirtgen grading
160 envelope. These gradings were created based on a recycling depth of 300mm with a 100mm surface
161 layer, giving a material ratio of surface to granular of 1:2. The initial grading results showed, see
162 Figure 7a, that the material was lacking in fines; this was addressed by the addition of 10% crushed
163 rock fines (CRF) for all mixes (new material grading in Figure 7b). The purpose of this was to allow
164 the user to proceed with the mix designs; it was considered that this would not be needed in
165 practice as a finer mix could be produced by adjusting the milling machine settings on site.



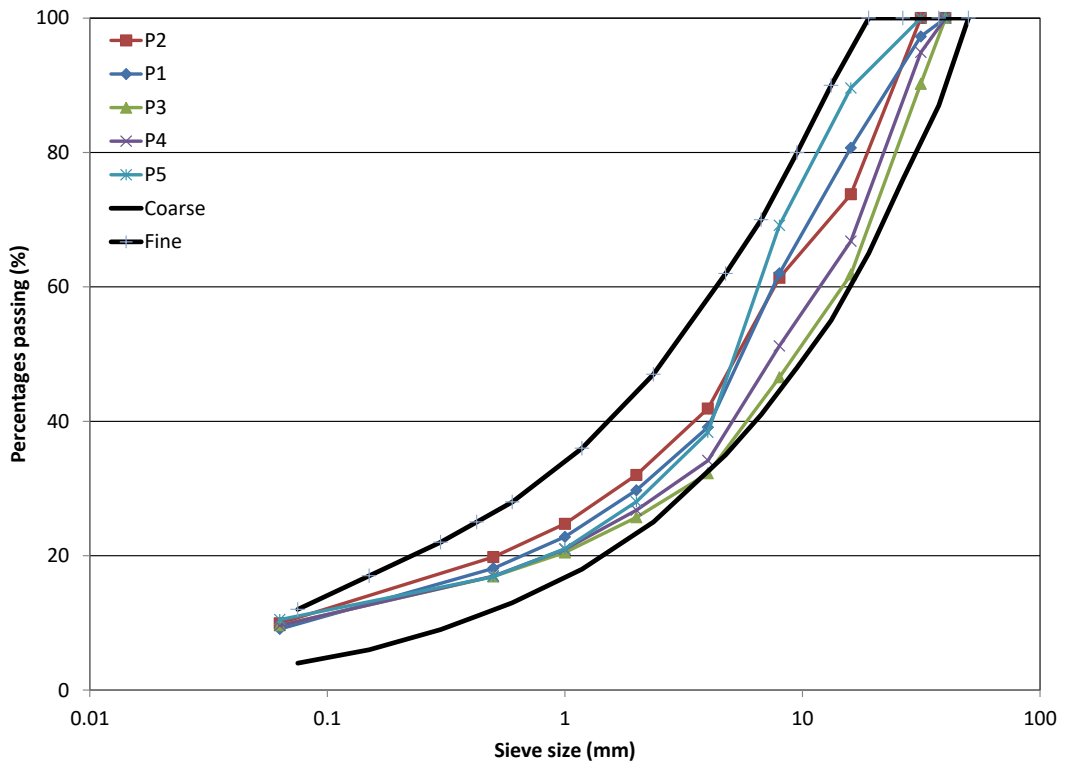
166

167 **Figure 6. Cold mix grading envelopes; IRL NRA vs Wirtgen Grading Envelope.**

168



a)

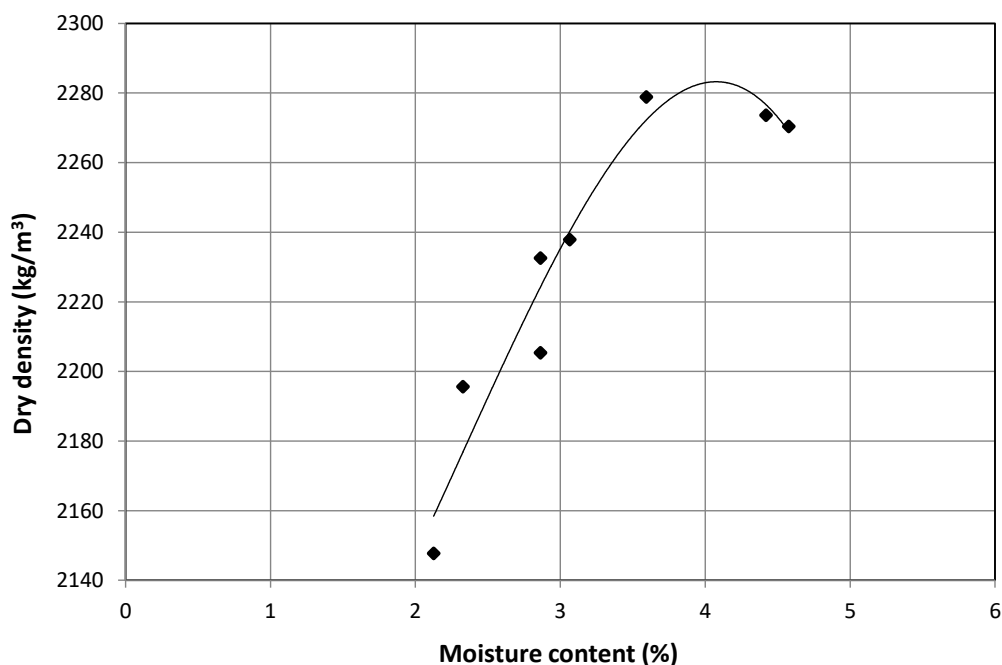


b)

169 Figure 7. Material mix grading: a) original material and b) material with 10% CRF.

170 2.1.3. Optimum moisture content

171 The optimum moisture content of the material was obtained using a procedure based on the
172 standard soils Proctor test, BS 1377- 4: 1990. The test results are presented in Figure 8 and show the
173 dry density - moisture content relationship. From the graph it can be seen that there is a clear
174 optimum moisture content for the material mix and that this is around 4%. This moisture content is
175 adopted for all material mix designs as it is just on the dry side of optimum as recommended in the
176 NRA guidance [15].



177

178 **Figure 8. Dry density vs moisture content**

179 **3. Mix Designs**

180 The purpose of this pavement trial is to examine performance of both emulsion and foam cold
181 mixtures as in situ road rehabilitation processes and in turn inform the development of a new
182 specification for cold recycled materials in Ireland. To help in this, some parameters will be set for
183 the site trial, including:

- 184 • Mixtures used should allow for variation in cement content;

- 185 • Differences in binder type (foamed/emulsion) should be allowed;
- 186 • Differences in binder content should be allowed.

187 It must also be borne in mind that the output of the FWD and GPR surveys has been to show that
188 the existing pavement is relatively weak in the central area (designated as Zone 2 in Figure 4). Based
189 on these considerations a series of 4 mixtures (Mix A to Mix D) have been proposed and these are
190 listed in Table 4. As previously mentioned, the site was separated into three investigation zones
191 based on the strength of the subgrade, as shown in Figure 4. The initial mix selection was to
192 investigate two types of quick viscoelastic cold material mixes using:

- 193 i) Bitumen emulsion,
- 194 ii) Foamed bitumen.

195 Both mixes, designated as Mix A and Mix B, are tested with the minimum cement content of 1%
196 [15]. Due to its weak subgrade, Zone 2 (between 700m and 1700m) was designed using Mix B using
197 foamed bitumen with 1% cement mix. This is due to the faster gain of strength associated with this
198 material. Zones 1 (between 0m and 700m) and 3 (between 1700m and 2600m) were tested using an
199 emulsion mix.

200 As part of the CoRePaSol project it is required to evaluate different curing procedures on the
201 development of strength of cold recycled mixtures. Two additional emulsion mixes containing 0%
202 and 1.5% were added to the investigation, designated as Mix C and Mix D. These mixes are designed
203 combining the aggregates from all five pits, i.e. they are not evaluated per individual trial pit and
204 they do not contain CRF. The mix grading curve for these mixes is presented in the Figure 7 a and
205 mix designs are presented in the Table 3. The emulsion/residual binder content is reduced and
206 cement content increased in comparison to Mix A and Mix B. The rationale behind the design recipe
207 change was that by reducing the emulsion content and slightly increasing the cement content of the
208 mix, the emulsion cold mix performance can be improved while the mixes would also be more
209 economical to use. This test will also be used to examine whether lower residual bitumen contents

210 can be considered in the cold mix design; this would represent a significant change from the current
211 guidance [15] where the minimum allowed residual bitumen content is 4% for in-situ production and
212 3% for ex-situ production where 1% cement is used in both cases.

213 **Table 3. Mix designs.**

Mix No.	Mix type	Mix Constituents (%)					
		Surface Material	Granular Material	CRF	Cement	Water	Residual Binder
A	Emulsion	27.4	55.3	10	1.0	4.0	3.0
B	Foamed Bitumen	27.4	55.3	10	1.0	4.0	3.0
C	Emulsion	31.2	62.6	0	0.0	4.0	2.2
D	Emulsion	30.8	61.6	0	1.5	4.0	2.2

214

215 **4. Testing and Results**

216 **4.1. Compaction**

217 Following previous work by Hogan et al. [8] and Doyle et al. [17]), the gyratory compaction
218 procedure was adopted for this study. All of the specimens were compacted in accordance with IS
219 EN 12697-31:2007 using a Coopers Technology gyratory compactor. The static compaction pressure
220 was set at 0.6MPa with an angular velocity of 30 gyrations per minute and the gyratory angle set at
221 1.25°. A set number of gyrations are used as the compaction control target, in this case 100
222 gyrations.

223 For this study the cylindrical test specimens are compacted to target dimensions of 150mm in
224 diameter and 75mm in height. Slotted moulds are used to allow for drainage of the excess moisture
225 and thus better compaction. The same weight of material (3.0 kg) is placed into the mould for all
226 specimens. After compaction, test specimens are left in the mould to cure for 24 hours. The test
227 specimens are then extruded, and their dimensions and weight recorded. The specimens are then
228 ready for curing.

229 In order to assess the performance of the gyratory compaction as a method, maximum density tests
 230 were performed on Mix C and Mix D in accordance to the EN 12697 – 5: 2009. The results also
 231 suggest that cement content in the mix does not affect air void content. These findings are
 232 contractictory to the findings found in the literature [18] where reduction in the mix air voids is
 233 related to the increase in the cement in the mix. However, results show that air voids decrease with
 234 increase of the moisture content, which confirms the conclusion that cement content does not
 235 affect the air voids content in the mix but the moisture content in the mix. Table 4 summarises the
 236 results of the moisture content after curing, densities and void content in these specimens. A low
 237 moisture content was observed for all mixes and those containing cement do not show lower
 238 moisture content after the specified conditioning period. The air voids content is lower than
 239 expected (4%), although this may occur when working to a specified level of compaction (100
 240 gyrations). The results also suggest that cement content in the mix does not affect air void content.
 241 These findings are contradictory to the findings found in the literature [18] where reduction in the
 242 mix air voids is related to the increase of cement in the mix. However, results show that air voids
 243 decrease with increase of the moisture content, which confirms the conclusion that cement content
 244 does not affect the air voids content in the mix but the moisture content in the mix.

245 **Table 4. Max and Bulk densities and air voids content of test specimens compacted in lab.**

Mix No.	Mix type	Curing Method	Moisture Content (%)	Max Density (kg/m ³)	Bulk Density (kg/m ³)	Air voids (%)
C	Emulsion mix, 0% cement	7 days at 20°C	1.6	2,351	2,279	3.1
		14 days at 20°C	1.0	2,287	2,210	3.4
D	Emulsion mix, 1.5% cement	7 days at 20°C	1.4	2,291	2,204	3.8
		14 days at 20°C	1.5	2,343	2,279	2.8

246

247 **4.2. Curing Procedures**

248 Various curing temperatures, durations and methods are used for cold mix materials around the
 249 world [13, 15, 17-23]. Cold mix materials with bitumen emulsion develop their strength over a
 250 period of time [14]. It is therefore necessary to speed up this curing process to obtain an early

251 indication of long-term strength [14]. The NRA guidance [15] has put forward a curing temperature
252 of 40°C for duration of 28 days for cold recycled asphalt materials. However, this procedure has
253 been criticised by industry due its impracticality [8]. This curing procedure is too prolonged for an in-
254 situ cold recycling project as the project deadline may be passed before the laboratory results and
255 appropriate designs are available. This serves to make cold recycling techniques unpopular as a
256 standard practice for road rehabilitation projects.

257 When assessing alternative curing methodologies, a number of options are considered. The first set
258 of the test specimens (Mixes A & B) are cured according to the current accelerated curing procedure
259 described in the NRA guidance [15]. This involves sealing the specimens in a plastic bag and placing
260 them in an oven for 28 days at 40°C. This is intended to represent the long-term properties of the
261 mix after one year.

262 The second set of specimens (Mixes C & D) were cured according to the methods used in Portugal,
263 the Czech Republic and Germany. The specimens without cement (Mix C) are cured unsealed for 3
264 days at 50°C as per Portuguese and Spanish practice [24, 25]. The specimens containing cement are
265 cured for 14 days at 20°C as per the Czech Republic and German standard [11]. This slower curing
266 regime for mixtures containing cement is necessary as hydraulic binders (e.g. cement and lime) can
267 hydrate too quickly at higher temperatures, resulting in specimen cracking and unreliable
268 assessment.

269 **4.3. Testing**

270 Standard asphalt testing procedures such as ITSM and ITS have been reported to be suitable for an
271 evaluation of cold mix asphalt performance [8, 13, 14, 17-21, 26, 27]. In order to evaluate the
272 mechanical performance of the cold recycled materials, two tests were employed:

- 273 1. Indirect Tensile Stiffness Modulus Test (ITSM).
- 274 2. Indirect Tensile Strength Tests (ITS).

275 *4.3.1. Indirect tensile stiffness modulus (ITSM) test*

276 The non-destructive ITSM test is conducted which complied with IS EN 12697-26: 2012. The Cooper
 277 Research Technology NU-10 testing apparatus with a pneumatic close loop control system is used.
 278 After the completion of the prescribed curing process, test specimens are removed from the sealed
 279 plastic bags and their dimensions and weights are re-recorded. They are then placed in a
 280 temperature controlled chamber at 20°C for three hours prior to testing. The stiffness value is
 281 recorded on two diameters orientated at 90° to each other, and an average of these two values is
 282 reported as the specimen stiffness.

283 *4.3.2. Indirect tensile strength (ITS) test*

284 On completion of the curing process, the specimens were stored in a temperature control chamber
 285 at 20°C. The test specimens are then conditioned at a test temperature of 25°C for three hours prior
 286 to testing. A Controls testing system is employed to complete the Indirect Tensile Strength Test (ITS)
 287 in accordance with IS EN 12697-23: 2003. The ITS test is conducted by applying a vertical
 288 compressive strip load to a cylindrical specimen. The load is distributed over the thickness of the
 289 specimen through two loading strips at the top and bottom of the test specimen.

290

291 *4.3.3. Test Results*

292 **Table 5. Laboratory mixes – ITSM test results**

Mix No.	Trial Pit No.	Mix type	Curing Method	ITSM (MPa)	ITS _{dry} (MPa)
A	1	Emulsion mix (1% cement)	28 days at 40°C	2978	0.43
	5			2364	0.43
B	2	Foam mix (1% cement)	28 days at 40°C	5503	0.57
	3			4738	0.53
	4			4824	0.56
C	Combined	Emulsion mix (0% cement)	3 days at 50°C	2254	0.35
D	Combined	Emulsion mix (1.5% cement)	14 days at 20°C	3526	0.41

293

294 The results of the ITSM test on all mixes, along with the respective curing method used, are
295 presented in Table 5. For the case of Mix A, the samples produced using material from both trial pits
296 1 and 5 showed a good level of performance and a long term ITSM value in excess of 2000 MPa and
297 a consistent indirect tensile strength of 0.43 MPa.

298 The foamed bitumen material (Mix B) was produced using material from trial pits 2, 3 and 4. The
299 ITSM values for these mixes were higher than expected with an average value at 5022 MPa. This
300 may raise some concern as to whether the material would have sufficient flexibility to accommodate
301 a poor subgrade without cracking prematurely. However, Tabakovic et al. [6] reported that the
302 stiffness value for the hot binder course mix containing 30% RA at 3.5% binder content is in range of
303 5100MPa. Which indicates that Mix B has achieved full stiffness value. The indirect tensile strength
304 was quite consistent, with an average value of 0.55 MPa.

305 The emulsion material containing no cement (Mix C) was manufactured using a blend of material
306 combined from all 5 trial pits, and yielded an ITSM value in excess of 2000 MPa. While this is in good
307 agreement with the results achieved for Mix A, it should be noted that this curing temperature is not
308 representative of environmental conditions in Northern Europe; it is also not suitable for cement
309 containing mixtures. The indirect tensile strength was also quite low, returning a value of 0.35 MPa.

310 Finally, Mix D was also produced using material combined from all 5 trial pits and cured for 14 days
311 at 20°C. The ITSM value was also quite high, yielding a result of over 3500 MPa. The indirect tensile
312 strength was slightly lower than expected, producing a value of 0.41 MPa.

313 It is worth noting that emulsion mixtures, have shown low stiffness values (between 2254 – 3526
314 MPa) in comparison to the foam mix and equivalent hot recycled binder course mix containing 30%
315 RA , which stiffness is in range of 5000MPa. However, as reported by Doyle et. al. [14] and Al-
316 Busaltan et. al. [19] it is believed that stiffness and strength gain will increase in time. This cold mix
317 behaviour will be investigated on site where regular FWD test will be carried on. It is expected that
318 emulsion mixtures will reach full strength within 12 months of its service life.

319 These results showed that all four mixes met the minimum ITSM requirement for use on site, and
320 suggested that Mix B would be the most suitable for the section of the site with the weakest
321 subgrade due to its high stiffness and tensile strength.

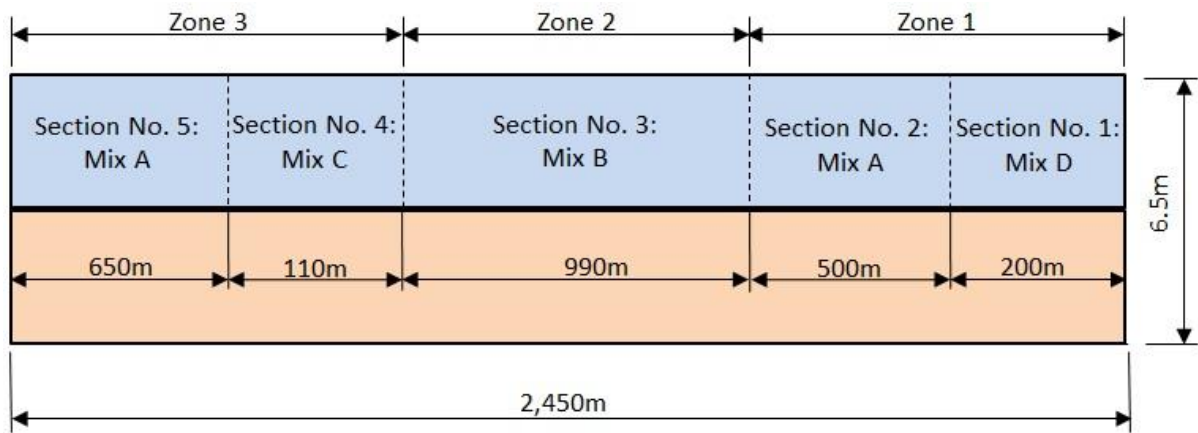
322 Mixes A and B have performed very well with a residual binder content of 3% and 1% cement.
323 However, Mix D used a lower residual binder content of 2.2% with 1.5% cement and outperformed
324 Mixes A and B. these results show that lower residual bitumen contents can be considered for in-situ
325 production than currently allowed.

326 **5. In-Situ Cold Recycling Site Trial**

327 A key aim of this study is to validate the proposed specification against a full-scale site trial. Each of
328 the four mixes designed in the previous sections were to be used in the construction; the location is
329 shown in the schematic layout presented in **Figure 9**. It can be seen that Mix B, which produced the
330 highest stiffness and indirect tensile strength was used in Zone 2 – the section with the weakest
331 subgrade. Mix C, which produced the lowest stiffness and ITS was used in the section with the
332 strongest subgrade.

333 The recycling depth used for sections 1, 2 and 3 (Zone 1 & 2, see Figure 4) was 300mm while the depth
334 used for sections 4 and 5 (Zone 3, see Figure 4) was 250mm. Due to the nature of the Irish climate, it is
335 not permitted to use cold recycled materials in a pavement surface layer. Furthermore, this would not
336 be feasible due to the high trafficking levels on this particular road. For this particular project the cold
337 recycled material was overlain with:

- 338 • A 55mm thick layer of 6mm SMA regulation course (for Zones 1 and 3);
- 339 • A 55mm thick layer of 20mm dense asphalt concrete (for Zone 2);
- 340 • A 40mm surface layer of hot rolled asphalt (HRA 30/14 F Surf 40/60 rec; all Sections).



341

342 **Figure 9. Revised schematic representation of the trail section**

343 **5.1. Validation of Mix Design**

344 As described in Section 3, mix designs were developed in the laboratory for materials taken directly
 345 from trial pits on site. This process was followed up with testing of materials obtained from actual
 346 job site. This presents some very practical challenges as the very nature of cold recycled materials
 347 means that they gain strength with time. In this case, the distance between the site location and the
 348 research laboratory is 100 km. Furthermore, three of the four mixes contained cement which
 349 required that the in-situ produced materials be sampled and compacted on the same day. Each of
 350 the five sections within the site trail was sampled. The material collection and transport procedure
 351 was as follows:

- 352 1. Approximately 20kg of the material was taken from behind the recycling machine and
 353 placed into a plastic bag; this bag is then sealed and marked. Four sample bags were
 354 collected for each material, providing a total of 80kg for each material mix.
- 355 2. The plastic bag containing the material sample was placed within a sealed plastic container.
 356 Great care was taken to ensure that moisture from the mix did not evaporate prior to the
 357 compaction process.

358 *5.1.1. Specimen preparation*

359 The specimens are compacted three hours after the in-situ mix production. Thanaya et al. [13] have
360 previously shown the importance of compacting cold emulsion test specimens within six hours of
361 mix production. They have found that any delay in compaction allows the cement to hydrate in the
362 loose mixture. This is represented by a reduction in bond between the mineral aggregate particles
363 and ultimately a lower ITSM value. To overcome this, the material is remixed and riffled upon arrival
364 at the testing laboratory. The specimens are then compacted using the gyratory compactor as
365 described in Section 4.1. They are then extruded and cured as described in section 4.2. On
366 completion of the curing process, the specimens are tested using the ITSM and ITS test as previously
367 described in Section 4.3.1 and 4.3.2.

368 **5.2. In-Situ Material Test Results**

369 The results from the ITSM and ITS tests for the in-situ site material are presented in Table 6,
370 alongside the comparative result from the laboratory produced material. The results show that
371 Mixes A, B and D, which contain cement, have achieved the minimum stiffness requirement for
372 1 year of 2000 MPa [15]. Mix D which had a reduced binder content of 2.2% and a 1.5% cement
373 content had a stiffness in excess of 2000 MPa and has an ITS value of 0.37 MPa. Mix B had a high
374 ITSM value (over 4400 MPa) and a high ITS value, confirming that it is best suited for use in the
375 section with the lowest strength subgrade. It is however notable that Mix C (reduced binder content,
376 no cement) did not meet the 2000 MPa minimum requirement and also had the lowest ITS. This
377 material was however used in the section with the highest strength subgrade.

378

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380

381

382 **Table 6. ITSM and ITS results, In-situ and laboratory produced material.**

Zone No	Section No.	Mix No.	Mix type	Curing programme	ITSM		ITS _{dry}	
					In-situ Mixed Material (MPa)	Relative to Lab Mixed Material (%)	In-situ Mixed Material (MPa)	Relative to Lab Mixed Material (%)
1	1	D	Emulsion mix (1.5% cement)	14 days, 20°C	2283	65	0.37	90
	2	A	Emulsion mix (1% cement)	28 days, 40°C	2959	99	0.43	100
2	3	B	Foam mix (1% cement)	28 days, 40°C	4409	88	0.48	87
3	4	C	Emulsion mix (0% cement)	3 days, 50°C	1128	50	0.32	91
	5	A	Emulsion mix (1% cement)	28 days, 40°C	4,495	190	0.68	158

383

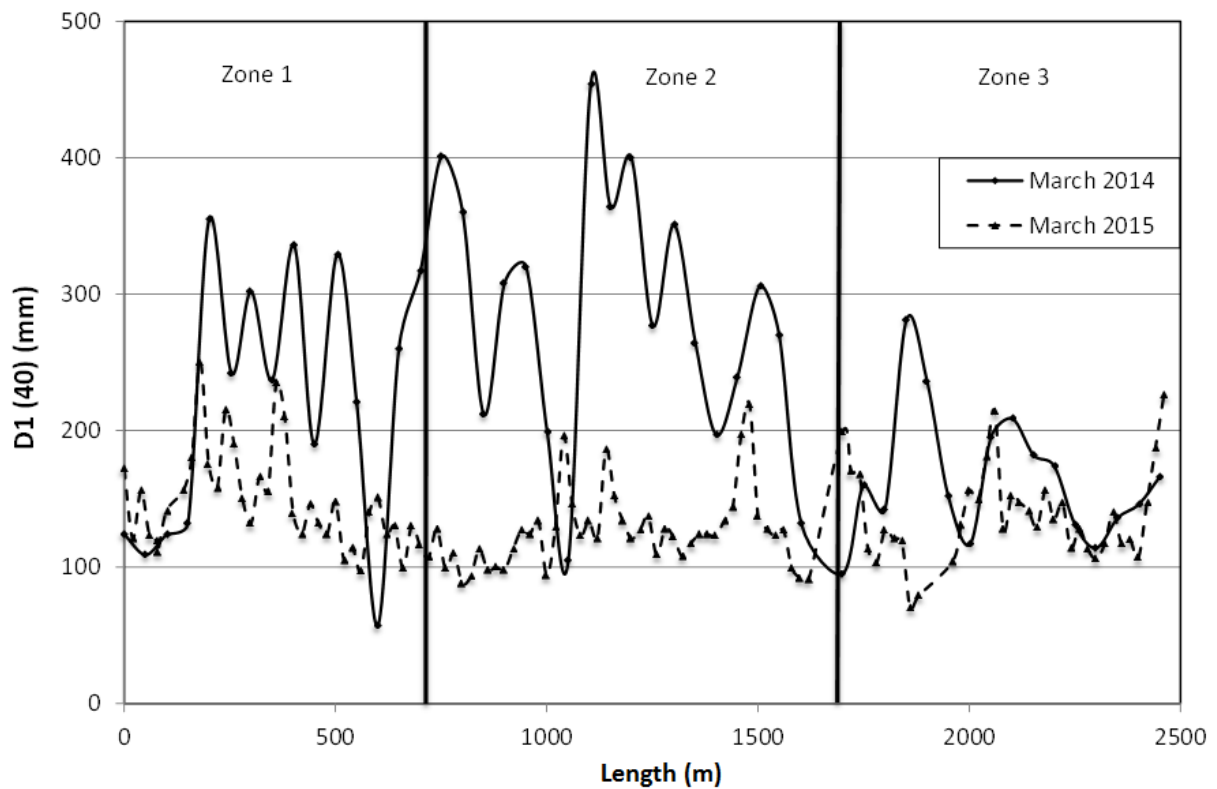
384 When one compares the performance of the site mixed materials relative to the lab mixed materials,
 385 there are some interesting comments that may be made. The use of site mixed materials from
 386 Section 5 for Mix A produced surprisingly high ITSM and ITS values (4495 MPa and 0.68 MPa
 387 respectively). When the same design was used with material arising from Section 2, the values
 388 produced were significantly lower (ITSM of 2959 MPa and ITS of 0.43 MPa). It is postulated that
 389 there may have been some cementitious material present in the recycled component. This is
 390 possible as cores in the Figure 2 showed variability of the material found on the site, core 3 in the
 391 figure clearly shows content of the cementitious material in the pavement layers.

392 When the results produced using the ITS and the ITSM are compared, it can be seen that there is
 393 much more variability in the ITSM data. If the particular case of Mix A in section 5 is omitted, it can
 394 be seen that the variability relative to the lab data is quite high, with stiffness values ranging from 50
 395 to 99% of their lab-mixed counterparts. The situation is more consistent for ITS, with ITS values
 396 ranging from 87 to 100% of their lab-mixed counterparts. This would suggest that the ITS test is
 397 more robust and potentially better suited for assessing performance of site-mixed cold recycled
 398 materials.

399 **5.3. Follow-up Survey**

400 The final piece of information available on the performance of the material relates to the periodic
 401 FWD surveys that are carried out as part of the normal maintenance operations. This particular

402 section of the roads network was surveyed in March 2014 (4 months before the works) and again in
403 March 2015 (8 months after the works). In this case the parameter of most interest is the central D1
404 (40) deflection – a measurement of how the pavement deflects when subjected to a typical wheel
405 load of 40kN. This deflection (expressed in microns) is an indicator of how well the upper layers of
406 the pavement structure are performing, with lower values being more desirable. The results of this
407 survey are shown below in **Figure 10** and show a considerably improved performance, particularly in
408 central section where the weaker subgrade is located. This road will be surveyed on an ongoing
409 basis, but the results to date offer confidence that the cold-recycled materials can successfully be
410 used to remediate issues associated with legacy roads.



411

412 **Figure 10. Results of FWD survey before and after the cold recycling scheme**

413 **6. Discussion**

414 To date the biggest obstacle in applying cold recycling processes in road regeneration has been
415 uncertainty about the material behaviour. This was further compounded by material evaluation

416 procedures that were conservative and excessively long. The curing process in the material
417 evaluation and mix design process was one of the biggest issues highlighted by industry [8, 14]. This
418 raised practical issues in the project procurement process, leading to delays in project time line and
419 reluctance to specify the use of cold mix recycling as the preferred road rehabilitation process. The
420 curing procedure specified by the NRA guidelines [15] requires curing of 28days at 40°C, irrespective
421 of cement content in the mix. This is significantly longer than the times associated with traditional
422 asphalt testing, where mix evaluation procedures take less than a week.

423 This study has shown that a modified specification with significantly reduced curing times is possible.
424 Two curing streams have been adopted: 3 days at 50°C for mixes containing less than 1% cement,
425 and 14 days at 20°C for mixtures containing more than 1% cement. Consequently, the mix
426 performance can be evaluated employing standard asphalt mix evaluation test procedures for
427 stiffness (as per EN 12697-26) and indirect tensile strength (as per EN 12697-23)

428 The test results further showed that reduction in of the residual binder in the mix can be
429 compensated by increase of the cement in the mix. This finding will help in reduction of cost of the
430 mix production as the cost of the emulsion is high in comparison to the cost of the standard cement
431 binder. This will lead to improved financial performance, and making the mix design and evaluation
432 process more efficient will undoubtedly encourage greater usage of cold mix asphalt as a road
433 rehabilitation procedure.

434 **7. Conclusions**

435 The results from this study have illustrated that cold mix recycling is a valuable rehabilitation process
436 for legacy roads, where the material composition of the road is unknown. The study has shown that
437 both cold recycling processes (emulsion and foam) can adequately improve the strength of the
438 material so as to achieve an extended service life without the need for complete road regeneration.
439 This leads to financial and environmental savings.

440 The following additional conclusions can be drawn from the study:

- 441 • For legacy roads where the material variability can be high, it is important to obtain
442 sufficient samples before site works commence. This shows the importance of preliminary
443 investigations and gives confidence to subsequent mix designs.
- 444 • For the cold mix recycling procedures lower end of the IAN grading envelope [15] should be
445 lowered in order to allow better curve fit and unnecessary inclusion of the fresh material.
446 The results have shown that mixtures without additional fines (CRF) have performed well.
447 The Wirtgen grading envelope [16] is a suitable grading envelope for grading of recycled
448 material for both emulsion and foam mixtures.
- 449 • Samples containing $\geq 1\%$ cement were cured unsealed for 14 days at 20°C for the samples,
450 while samples containing $< 1\%$ cement were cured unsealed for 3 days at 50°C. Both
451 methods have been found to be suitable for specification purposes.
- 452 • The standard ITS and ITSM testing procedures proved to be adequate test procedures for
453 evaluation of both emulsion and foam cold asphalt mixtures.

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