VOLUME 2 **HIGHWAY STRUCTURES: DESIGN (SUBSTRUCTURES AND SPECIAL STRUCTURES) MATERIALS**

SECTION 3 **MATERIALS AND COMPONENTS**

PART 9

BA 92/07

THE USE OF RECYCLED CONCRETE AGGREGATE IN STRUCTURAL CONCRETE

SUMMARY

This Advice Note provides information on the use of recycled concrete aggregate (RCA) as a replacement for coarse natural aggregate in structural grade concrete.

INSTRUCTIONS FOR USE

1. Remove Contents pages from Volume 2 and insert new Contents pages dated May 2007.

2. Insert the new Advice Note BA 92/07 into Volume 2, Section 3.

3. Please archive this sheet as appropriate.

Note: A quarterly index with a full set of Volume Contents Pages is available separately from The Stationery Office Ltd.

THE HIGHWAYS AGENCY

TRANSPORT SCOTLAND

WELSH ASSEMBLY GOVERNMENT
LLYWODRAETH CYNULLIAD CYMRU

THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND

The Use of Recycled Concrete Aggregate in Structural Concrete

Summary: This Advice Note provides information on the use of recycled concrete aggregate (RCA) as a replacement for coarse natural aggregate in structural grade concrete.

REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments

REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments

VOLUME 2 HIGHWAY STRUCTURES: DESIGN (SUBSTRUCTURES AND SPECIAL STRUCTURES) MATERIALS

SECTION 3 MATERIALS AND COMPONENTS

PART 9

BA 92/07

THE USE OF RECYCLED CONCRETE AGGREGATE IN STRUCTURAL CONCRETE

Contents

1. INTRODUCTION

Scope

1.1 This Advice Note provides information on the use of recycled concrete aggregate (RCA) as a replacement for coarse natural aggregate in structural grade concrete. It deals specifically with sourced and tracked high quality material comprising mainly crushed concrete with low levels of impurities – equivalent to RCA (II) in BRE Digest 433 – Recycled Aggregates (BRE 1998). Designers, Contractors and concrete suppliers are encouraged to consider the use of RCA.

1.2 The effects of RCA on concrete properties are described. Specific guidance is given on the specification and testing of RCA, and on concrete mix design to achieve particular concrete strengths.

1.3 Guidance is also given on the types of construction and structure for which the use RCA is appropriate and also where, for the time being it should not be considered.

1.4 The Advice Note is intended to supplement other design guides and standards for the specification and use of aggregates in structural grade concrete, particularly the Specification for Highway Works (MCHW Volume 1) and the related Notes for Guidance (MCHW Volume 2), BS EN 206-1 Concrete – Part 1: ‘Specification, performance, production and conformity’, and the complementary British Standards BS 8500-1: 2006 ‘Method of specifying and guidance for the specifier’ and BS 8500-2 ‘Specification for constituent materials and concrete’.

Development of the Advice Note

1.5 The Advice Note is based on work undertaken at BRE and subsequent research carried out at TRL on engineering and durability aspects relevant to the use of RCA in structural concrete (Calder and Roberts, 2005). This work was funded by the Highways Agency (HA). The RMC Community Fund provided additional funding to assess the susceptibility of a range of RCA to alkali silica reaction (ASR) (Calder and Mckenzie, 2005).

1.6 There are still areas where the effects of RCA on concrete properties are uncertain. These are noted in the text. Further research and experience will be needed before these issues can be resolved.

Benefits and Limitations of the Use of RCA in Structural Concrete

1.7 The principles of sustainable development require the prudent use of natural resources and maximum use of recycling of construction waste. In keeping with this approach, the UK Government is actively encouraging the use of recycled aggregate as an alternative to primary aggregate. Along with the potential for direct cost savings associated with using a waste material, there are additional economic benefits associated with incentives to use recycled material and disincentives to use natural aggregates provided through land fill tax credits.

1.8 There will however be increased costs in other areas. Recycled aggregates will require extra treatment to remove contaminants, along with a testing regime to ensure adequate and consistent quality. Dedicated processing, testing, storage and handling facilities will be needed at ready mixed concrete plants. Additional administration will be needed to deal with the logistics of combining recycled aggregate with natural aggregate, and maintaining suitable records. Materials also need to be carefully tracked from source to end-use. There are also issues to resolve to ensure compliance with waste management regulations.

1.9 From a sustainability point of view the ideal source of recycled aggregate would be a general material available from aggregate suppliers in the same way as for natural aggregate. It would come from mixed sources but meet a general specification ensuring appropriate quality. However considering the wide potential range of source materials it would be an onerous task for aggregate suppliers to achieve a consistent product.

1.10 At the moment it is likely that recycled aggregate will be obtained from two main supply streams, either preconsumer waste from concrete production (precast or ready-mix concrete plants) or from demolition projects such as disused airfield structures, concrete framed or clad buildings. Potential sources need to be able to provide sufficient quantity and consistent quality and usually be fairly close to the site where the concrete is to be used to ensure that the economics are viable. Preconsumer waste is likely to be of more consistent quality. Procedures are required to ensure that the source material is of appropriate quality. Where the source is a demolished structure, information will be needed prior to the start of the supply on the history of the structure along with inspection and testing to ensure that it is fit for purpose. This is in addition to the routine testing to ensure consistent quality once the recycled material is in use.

1.11 Whilst the use of recycled aggregate has a reasonable track record in low grade applications (eg as sub base in road construction), its use in structural grade concrete is a relatively new area, though some notable structural projects have been completed. Hence the usage of RCA is not advised for use in particularly sensitive or critical structural elements or structures, until it has a longer track record.

1.12 It is acknowledged that the sources of suitable consistent high quality materials to produce RCA may be limited at present. Similarly there are few plants able to handle and process such materials. Combined with the often limited quantities of concrete involved in bridge construction and the logistics, this may preclude the option of using RCA on economic grounds on many projects. However it is expected that this situation will change and improve over time. Hence this Advice Note provides the opportunity to consider RCA as a partial replacement for natural resources on larger projects where significant volumes of structural concrete are to be used.

2. SUPPLY, SPECIFICATION AND PROPERTIES OF RECYCLED AGGREGATES

Types of recycled aggregate

2.1 Recycled aggregate (RA) is defined in BS 8500-1 (2006) as the generic term for aggregate resulting from the reprocessing of inorganic material previously used in construction. In addition to significant quantities of natural aggregates, recycled aggregates are likely to contain impurities such as wood, metal, asphalt and plastic; these need to be controlled to acceptable levels dependant on the proposed use of the recycled aggregate. Where the composition of the recycled aggregate is principally crushed concrete, the material is defined in BS 8500-1 (2006) as RCA. BRE (1998) subdivided recycled aggregates into three classes, dependent on the brick content (BRE Digest 433):

RCA (I) defines the lowest quality material. It could have relatively low strength and high levels of impurities. It might contain up to 100% brick or block masonry, or could comprise mainly concrete but with high levels of impurities.

RCA (II) defines a relatively high quality material comprising mainly crushed concrete with up to 10% brick by weight but low levels of impurities, less than 1.5% by weight (wood, asphalt, glass, plastics, and metals). In some cases it could contain an appreciable amount of natural aggregate.

RCA (III) defines a mixed material with up to 50% brick and high levels of impurities.

This Advice Note refers only to RCA (II) type material, and materials conforming to RCA(I) and (III) are not permitted.

BS 8500-2: 2006 also has a description of RCA which defines the quality and impurities in RCA in a slightly different way to BRE (1998). This is also acceptable. However asphalt impurities should be excluded from all concrete that is exposed, and the limit is set to < 0.5% accordingly. In such circumstances the limit of masonry impurities may be increased to <9.5% by mass, and lightweight material (floating stony materials only) less than 1000 kg/m^3 should also be < 0.1% as allowed in BS EN 12620 'Aggregates for concrete'.

Table 1 Acceptable RCA Quality

Contaminant % by mass	**BS 8500**	**BRE Digest 433 RCA (II)**
Masonry	< 5%[a]	<10%
Lightweight material < 1000kg/m^3 [c]	< 0.5%[b]	Included in other foreign material
Asphalt	< 5%[d]	Included in other foreign material
Other impurities (eg. glass, plastic and metals)	< 1%	Included in other foreign material
Other foreign material	Included in other impurities	< 1%
Wood	Not quoted but should be less than 0.1% as per EN 12620	< 0.5%
Total	< 11.5%	< 11.5%

a Limit may be increased to < 10% for exposed concrete when asphalt limit reduced to < 0.5%.
b Limit set to < 0.1% for exposed concrete.
c 'Floating stony' materials only.
d Limit set to < 0.5% for exposed concrete.

Sources and Production of RCA

2.2 RCA can be obtained from a variety of sources such as waste material from prefabricating yards, general demolition waste or demolition of individual structures. Aggregate is prepared using conventional aggregate plant with additional features to remove some of the contaminants; for example, magnetic separators to remove steel. Preparation methods influence the properties of the resulting RCA so it is important to establish a procedure to characterise the RCA and ensure fitness for purpose.

Quality Control

2.3 There are potential problems with ensuring an adequate supply of RCA of consistent quality. RCA can range from essentially new, uncontaminated concrete of known specification and history to unknown material of uncertain history. Even RCA from a single source is likely to be variable dependant on the environmental conditions that different parts of a structure may have experienced during its life. The use of mixed supply sources exacerbates such problems. It is, therefore, essential that a quality control scheme is set up to control the supply and provide an audit trail of material used so that any problems potentially associated with the use of RCA can be traced back to the source concrete used in the preparation of RCA. Mention has already been made of the differences between preconsumer waste as opposed to other sources of RCA (clause 1.10).

2.4 The design of a scheme would depend on the likely variability in source material and would have to be tailored to the likely causes of variability. For example waste material from a prefabrication yard would be less variable than demolition waste from a specific structure.

2.5 A general approach to quality control in recycled aggregate production has been prepared (BRE 2000). A Quality Protocol (2004) was prepared as part of the Waste and Resources Action Programme (WRAP) to provide a uniform control process for producers so that they can reasonably state and demonstrate that their product has been fully recovered and is no longer a waste. The protocol covers factory production control, product descriptions, specification, acceptance criteria and testing. Although the WRAP Quality Protocol was intended primarily for recycling of materials in association with road pavement construction (refer to MCHW – SHW clause 710), nevertheless the principles should be adopted where RCA is to be considered for use in structural concrete. The concrete itself should also be supplied in accordance with a Product Certification Scheme for ready-mixed concrete as detailed in Appendix B of MCHW Volume 1 Specification for Highway Works.

2.6 To standardise and document the quality procedures in a specific case a ***Quality Plan*** should be prepared. The complexity of any such plan would depend on the nature of the construction project and the source of the recycled material but should incorporate the following sections:

Definition of Product

2.7 This would describe the product and intended use in a similar manner to that used for normal aggregate eg 4/20 coarse aggregate for use in structural concrete

Specification of Product

2.8 The specification requirements of the product should be referenced; this could be an external specification or a specific section of the Quality Plan

Background Information

2.9 This would describe the source of the RCA and give details of the specification of the source concrete wherever possible. Where the source concrete comes from a demolished structure, some history of the structure should be provided along with the reasons for demolition. In particular problems such as chloride contamination, carbonation or ASR should be recorded.

2.10 Evaluation of such background information could well influence whether specific potential sources of RCA would be likely to be acceptable. However it must be accepted that information on some of these aspects may not be available.

Acceptance Criteria for Source Concrete

2.11 Acceptance criteria should be established to ensure that the source concrete to be recycled meets all statutory and regulatory requirements. The criteria should specify the types and proportions/levels of materials that are acceptable, and the methods used to establish acceptance. If necessary testing may be required. In the first instance these criteria would be applied to determine whether a potential source is suitable to supply RCA. Thereafter they would be used to ensure consistent quality.

2.12 Acceptance would normally be based on visual inspection of each delivery from the source to the processing plant, supplemented by testing where appropriate. Inspection and testing should be undertaken and managed by personnel trained with the requisite skills. Particular importance should be given to the presence of hazardous waste (eg asbestos), which should always be rejected. Some other potential contaminants are domestic waste, chemical waste, oil, felt, mastic, asphalt, metal, wood, glass, and plastic. There should be strict adherence to the definition of RCA (II) in BRE Digest 433, in terms of acceptance. A record giving supply details and test results should be kept for each delivery. Where appropriate the delivery records should be cross referenced with the source material including reference to any particular problems (eg chloride contamination or ASR in specific elements).

Production Method

2.13 A method statement should be prepared detailing the process by which the RCA is produced. Production methods can influence RCA properties (refer 2.16). The method statement should include details of the quality control regimes, testing, processing, and subsequent storage conditions of the RCA, prior to use in concrete.

Testing Regime for Recycled Aggregate

2.14 A testing regime shall be established with details of the tests to be carried out, acceptance criteria and frequency – this would depend on anticipated variability in properties of the RCA. It should take account of significant changes in the source of materials – either a different source or from different structural elements within the existing source location, and with different levels of contamination.

Sampling should be carried out in accordance with BS EN 932-1 (1997).

Appendix A gives a list of test requirements, acceptance criteria and typical test frequencies.

Record Management

2.15 A system of recording the information generated on incoming materials, production data and test results should be established. This should also include provision for notification of non-conformities.

Properties of RCA

2.16 Particles of RCA consist of natural aggregate partially coated with mortar or cement paste. The amount of surrounding mortar will vary depending on the method by which the RCA was produced; for example, an increasing number of cycles in a ball crusher can reduce the amount of mortar present. However there are other more efficient processing methods available, but the aim should still be to remove as much of the mortar as possible. The mortar, which is lighter and more porous than natural aggregate, affects the physical properties of the recycled material notably with respect to water absorption and density. This has implications for concrete mix design and concrete properties such as elastic modulus, shrinkage, creep and permeability. Moreover, the increased alkali content resulting from the mortar, and the presence of unknown aggregate types in the parent concrete of the RCA might increase the risk of ASR. The parent concrete could also have additional contaminants such as high chloride levels, carbonated material or ASR reaction products. In fact such features might be the reason for the concrete to have been recycled in the first place.

2.17 The differences in the properties of RCA compared with natural aggregate require special consideration in relation to concrete mix design and expected structural performance. It is crucial that the RCA is characterised by specific test procedures, and where possible from knowledge of the parent concrete mix design and subsequent history. Required test procedures are given in Appendix A.

Specification for the Use of RCA in Structural Concrete

2.18 The specification in the published 1700 series of the SHW (2004) requires that the concrete should be a designed concrete compliant with the requirements of BS EN 206-1 (2000) and BS 8500-1 (2006). The basic and additional requirements are given in clauses 4.3.2 and 4.3.3 of BS 8500-1 (2006) respectively. Although the use of RCA and RA is not expressly permitted in the published specification, this Advice Note allows the opportunity to utilise RCA within specific limitations and for particular applications.

2.19 Draft Specification clauses and Notes for Guidance have also been developed (refer clause 7.1) and are applicable to concretes in which a proportion of the natural aggregate has been replaced with RCA. There are additional requirements for the RCA as detailed below.

2.20 RCA must comply with BS EN 12620 (2002). There are several additional requirements for RCA given in BS 8500-2 (2006) and RILEM Recommendation TC121-DRG (1994). Before any RCA is proposed for the replacement of the coarse natural aggregate in structural concrete, the tests detailed in Appendix A, Table A1 must be carried out and the values obtained must meet the acceptance criteria. Once RCA from a particular source has been accepted as suitable, additional tests to determine the chloride ion, sodium and potassium oxide concentrations as detailed in Appendix A, Table A2 must be carried out. This information is required for checking the designed concretes for chloride and alkali contents.

3. DESIGN OF CONCRETE MIXES INCORPORATING RCA

Procedure

3.1 This procedure refers to designs where a proportion of the natural coarse aggregate is replaced with RCA. Due to excessive adverse effects on water demand and increased levels of contamination, the use of RCA as a replacement for fine aggregate (< 4mm) is not permitted at present.

3.2 The starting point is a mix containing natural aggregates only. This may be a well established mix design in use at a mixing plant or it may be a specifically designed mix. In the latter case, it is necessary to check the consistency and strength by carrying out trial mixes. In order to limit the risk of damaging ASR, experience has shown that it can be controlled by limiting the alkali content of the concrete and that this is practically achieved by using blends of Portland cement (CEMI) with either ggbs, pfa or fly ash. The use of low alkali content water reducing agents should also be considered. The aim is to produce a mix in which a proportion of the natural aggregate is replaced with RCA. The requirement for a particular application is to design the RCA mix with the same characteristic strength and consistence as the original mix containing natural aggregates. Dhir et al. (2001) proposed a method for achieving this.

3.3 The basis of Dhir's method is to reduce the water/cement ratio and coarse and fine aggregate contents to take account of the different properties of the RCA. Dhir et al. (2001) designed concrete mixes using natural aggregates with design strengths of 50N/mm^2, 60N/mm^2 and 70N/mm^2. Further mixes were then designed with 30%, 50% and 100% of the coarse natural aggregates replaced with RCA for each design strength. The coarse and fine aggregate contents were also reduced to achieve the required mixes. The results, reproduced from the report by Dhir et al. (2001), are given in Figure 1 and can be used as the basis of the design method to adjust the water/cement ratio and coarse and fine aggregate contents to achieve the required properties. Experience at TRL has shown that the water demand increases with increase in RCA content. It is advisable to select two or three different water/cement ratios and carry out trial mixes to achieve the required consistency for each. The 28 day strength for each water/cement ratio will be determined and the mix that gives the required strength selected. The procedure proposed for the trial mixes is given in Appendix B.

3.4 Table 2 gives an example of the method for C40/50 concretes though it should be noted that they are not completely compliant with BS 8500. Mix A contained 100% natural aggregate and for Mix B, 60% of the coarse aggregate was replaced with RCA which was crushed concrete from a precast yard in Derby. In this case the required strength of the RCA mix was achieved by reducing the water/cement ratio of the 100% natural aggregate mix by 0.01 and the coarse and fine aggregate contents by 22 kg/m^3 and 13 kg/m^3 respectively. Note that water content and the amount of water reducing agent was also increased to maintain the consistency of the mix. The mean 28 day compressive strengths of Mixes A and B were 58.5 N/mm^2 and 62.0 N/mm^2 respectively. These strengths were in the range normally acceptable for C50 concrete.

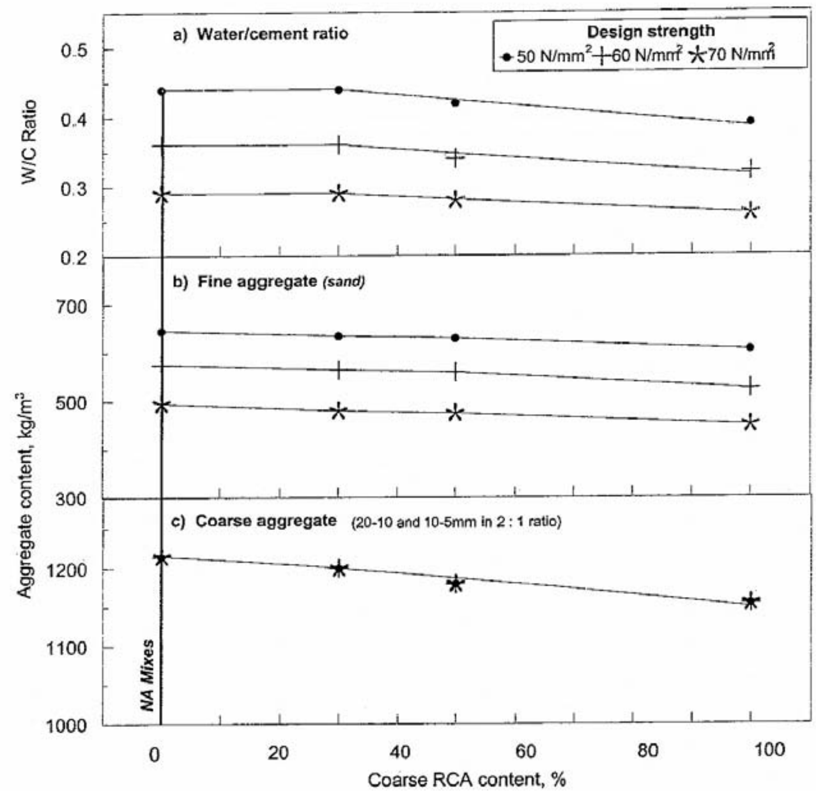

Figure 1 Mix Proportions for Mixes with Design Strength of 50 N/mm² to 70 N/mm² (Water Content Fixed at 165 kg/m³) (Reproduced from report by Dhir et al. (2001): Resolving Applications Issues with the Use of Recycled Concrete Aggregate)

Table 2 Mix designs

Item		**Mix A 100% natural aggregate**	**Mix B 60% of natural coarse aggregate replaced with RCA**
W/C		0.43	0.42
Water content (kg/m³)		165	180
CEM 1 content (kg/m³)		190	215
Ggbs content (kg/m³)		190	215
WRA content (kg/m³)		1.14	1.29
Total aggregate content (kg/m³)		1835	1780
Uncrushed gravel content (kg/m³) (SSD)	Sand	655	641
	20-10mm	825	319
	10-5mm	355	137
RCA content (kg/m³) (SSD)	20-10mm	-	596
	10-5mm	-	87

Requirements for the Designed Concrete

3.5 Clause 1704 of the SHW (2004) gives the general requirements for the concrete. It is necessary to check that the designed concretes containing RCA comply with these requirements.

3.6 The total chloride content of the concrete is calculated by summing the chloride content of each of the constituents and expressing the result as a percentage of the cement content inclusive of ggbs and fly ash when these are used as cement. It is recommended that the acid soluble method of measuring the chloride content of concrete given in BS 1881-124 (1988) should be used for the determination of the chloride content of the RCA. The chloride content of the admixtures can be taken as the certified value supplied by the manufacturer or by testing in accordance with BS EN 480-10 (1997). It should be noted that BS 1881-124 (1988) is to be replaced by a BS EN document, currently prEN 1744-5, which utilises a very similar test method.

3.7 It is also necessary to check that there is minimal risk of damage as a result of alkali silica reaction. Amendment 1 to BS 8500-2 (2002) Clause 5.2.6, published in October 2003, requires that the following 4 conditions are met:

1) The aggregate other than the RCA is not classed as highly or extremely reactive (see BRE Digest 330 (2004)).

2) The guaranteed alkali limit of any ggbs is not more than 1.0% Na_20 eq and the guaranteed alkali limit of any fly ash or pfa is not more than 5.0 % Na_20 eq.

3) Where used, the pfa conforms to BS 3892-1 (1997) and the fly ash conforms to BS EN 450 (2005) and has a loss on ignition of not more than 7%.

4) The calculated total alkali content does not exceed:

   3.5 kg/m^3 Na_20 eq where the declared mean alkali content of a cement or the CEMI component of a combination is not greater than 0.75%;

   3.0 kg/m^3 Na_20 eq where the declared mean alkali content of a cement or the CEMI component of a combination is 0.76% or greater.

3.8 Guidance for each of these conditions is given below:

1) BRE Digest 330 (2004) considers that crushed greywacke, greywacke-type sandstones or mudstones, or combinations containing more than 10% of these are highly reactive.

   All other aggregates can be considered to be of low or normal reactivity.

2) If the alkali limits of the additions (cement replacement) are not guaranteed by the supplier, it will be necessary to determine these by measuring the sodium and potassium oxide contents in accordance with the methods described in BS EN 196-2 (1995). The % Na_2O eq is equal to (%Na_20 + 0.658%K_20).

3) Conformity with BS EN 450-1 (2005) requires the loss of ignition test to be carried out in accordance with BS EN 196-2 (2005) with an ignition time of one hour.

4) The total alkali content expressed as the Na_2O eq of the mix is calculated as the sum of the alkali contents of each of the constituents and compared with the values given:

   (i) The alkali content of the cement is determined from the sodium and potassium oxides and is equal to (%Na_20 + 0.658%K_20). No account needs to be taken of the alkali in the ggbs or pfa if used at or above the minimum recommended proportions (BRE Digest 330-2 (2004)).

   (ii) The alkali contributed by the salts in the natural aggregates are calculated from the measured chloride ion concentration and expressed as the equivalent sodium oxide % Na_2O eq = 0.76 x Cl^- . BRE Digest 330-1 (2004).

   (iii) The alkali contribution from RCA shall be either:

      a) 0.20 kg Na_20 eq per 100 kg of RCA; or

      b) where the composition of the RCA is known (eg surplus precast units; fresh concrete returned to a plant, allowed to harden and then crushed), the alkali content calculated for the original concrete.

Alternatively, the sodium and potassium oxides of the RCA can be determined by the method described in BS 1881-124 (1988) and these values are used to calculate the $\%Na_2Oeq$ in the RCA ($\%Na_2O + 0.658\%K_2O$). However it should be noted that this method has a tendency to overestimate available alkalis, and BS 1881-124 (1988) does permit alternative methods.

(iv) The contribution of alkali from the additions will be calculated from the certified acid soluble value supplied by the manufacturer or tested in accordance with BS EN 480-12 (1998).

3.9 A worked example of the calculation of chloride and alkali contents of mix design B given earlier is shown in Appendix C.

4. PROPERTIES OF RCA CONCRETE

General

4.1 The approach to mix design described earlier was aimed at producing a concrete with a particular characteristic strength. As the level of replacement of natural aggregate with RCA increases, the changes from the starting concrete mix based on natural aggregate become more pronounced. This can lead to changes in physical properties of the concrete and potential effects on durability. Areas where there are likely to be differences compared with similar strength concretes made with natural aggregates are given below:

Effect on Physical Properties

4.2 **Density** is reduced. The degree of reduction increases as the proportion of RCA increases. As an example for 100% RCA replacement in concrete mixes of blended CEMI/fly ash and CEMI/ggbs C40/50 concrete, the density is reduced by up to 5% (Calder and Roberts, 2005).

4.3 **Modulus of elasticity** is reduced. Measurements of dynamic modulus after 28 days for C40/50 concretes incorporating blended CEMI/fly ash and CEMI/ggbs with various RCA replacement levels gave reductions of about 4% with 20% RCA replacement, about 13% with 60% RCA replacement; and 20% with 100% RCA (Calder and Roberts, 2005).

4.4 BS 5400-4 (1990) states that concrete made from some aggregates may have a modulus ‘substantially’ outside the normal range. These are permitted provided the modulus used to check load/deflections are measured values and not values based on cube strength (as is often used for normal concrete), as the relationship between cube strength and modulus may be different.

4.5 **Shrinkage** is increased. Increasing levels of RCA lead to increased shrinkage. Drying shrinkage measurements carried out by TRL after six months on C40/50 concretes incorporating blended CEMI/ggbs with varying levels of RCA gave a shrinkage increase of about 11% for 20% RCA replacement but increased to 50% for 60% replacement and 90% for 100% replacement.(Calder and Roberts, 2005). It has been proposed that the maximum cement content permitted for structural concrete should be reduced from 550kg/m^3 to 450kg/m^3 when RCA is used, as the hardened cement paste attached to the aggregate contributes to creep and shrinkage. However, Calder and Roberts (2005) showed that the shrinkage of CEMI/ggbs mixes with cement contents of less than 450kg/m^3 were similar to the equivalent CEMI/flyash mixes which had cement contents up to 615kg/m^3. Based on these results it would appear that to limit the cement content of mixes that contain RCA may be conservative, although there may be a problem with creep. Further work is required to investigate this.

4.6 BS 5400-4 (2000) gives some guidance on shrinkage for normal concrete but states that ‘the type of aggregate may seriously affect the magnitude of shrinkage and creep’. Advice is given on how to make allowances for the restraining effect of the reinforcement.

4.7 **Permeability** is increased which could result in more rapid ingress of contaminants.

4.8 There are possible effects on other concrete properties: creep – particularly in relation to prestressing, coefficient of thermal expansion, tensile strength, and bond strength. These require further evaluation before advice can be given on likely effects. Until such research has been undertaken and evaluated, the use of RCA in prestressed or post-tensioned concrete is not permitted unless a fully justified aspect not covered by standards submission (departures procedures) is agreed. The departure is to include both design and specification requirements. The limit for replacement in such cases is 20% of coarse aggregate.

4.9 The effects outlined above need to be taken into account in the design of concrete structures where RCA is used. As there is only limited information available on the degree of such effects, it would be prudent to adopt a conservative approach to the use of RCA in critical structures or elements (refer section 9).

Effect on Durability

4.10 **Alkali silica reaction** needs greater consideration where RCA is used. The mortar surrounding the aggregate particles will increase alkali levels and there is the possibility that the source concrete for the RCA included reactive aggregates, although the risk of expansion would be reduced because of the higher porosity of RCA. If the specification for the original source concrete is known then the aggregate reactivity could be assessed but this will not always be the case. There is also the possibility that partial replacement of natural aggregates with RCA could result in pessimum proportions – the concentration of reactive aggregates where the reaction is maximised. Until recently a very conservative approach was taken by considering all RCA as highly reactive. This restriction was relaxed in an amendment to BS 8500-2 (2002) Clause 5.2.6 in October 2003 so that RCA can be classed as having normal reactivity for concrete mix design provided some other conditions are met (see Appendix C). However if it is known that active ASR or significant quantities of ASR were present in a source structure this would preclude its use as a source of RCA. Moreover if there is any reason to believe that there might be reactive aggregates in the RCA, a petrograhical examination should be carried out.

4.11 **Freeze thaw resistance** is generally similar in comparison with natural aggregate concrete, provided that compliant and consistent quality controlled RCA has been used.

4.12 **Corrosion resistance** depends on the reaction of RCA concrete to carbonation, chloride ingress and the rate of corrosion once initiated.

4.13 As RCA concrete is more permeable than natural aggregate concrete carbonation may proceed more rapidly but will depend on the moisture content. However the increased alkalinity conferred by RCA may mitigate any effects. Ongoing research at TRL has shown no significant increase in the rate of carbonation after 12 months accelerated testing (Calder and Roberts, 2005).

4.14 The increased permeability may also increase the rate of chloride ingress and could lead to higher corrosion rates. However the increased alkali content could assist in raising the threshold chloride level which triggers corrosion. Research is underway at TRL to investigate the relative corrosion resistance of RCA and natural aggregate concrete but no conclusions can be drawn at the time of writing.

4.15 Current practice is to apply a hydrophobic pore-lining impregnant such as silane to at risk structural concrete to limit ingress of moisture and associated chlorides. This requirement should also apply to concrete containing RCA.

4.16 **Sulfate attack** can result in expansive disruption of concrete. In some cases sulfate contamination could be present in RCA (eg from plaster). It is important that this is taken into account in choosing source material for RCA. Resistance to external sources of sulfate would be similar to natural aggregate concrete. Testing for acid soluble sulfates must be included in the specification for RCA – the limit being < 1% as required in BS 8500-2.

5. COMPATIBILITY ISSUES

5.1 In general RCA concrete would not be expected to pose any difficulties in relation to the usual cement replacements and admixtures that could be used in concrete. However trial mixes should be used if there is any reason for concern. Additions (cement replacements) such as fly ash and ggbs are compatible with RCA and generally would be adopted.

5.2 The use of porelining hydrophobic impregnants (eg Silane) are unaffected. Requirements are contained in BD 43 and are no different for concrete containing RCA.

6. DESIGN ISSUES

6.1 Design related issues have been identified throughout this Advice Note and should be addressed by designers if RCA is to be selected (refer clause 9.1 and 9.2).

6.2 If RCA is to be adopted it should be identified in the Approval in Principle documentation for particular structures and the associated specification will be subject to departure procedures in accordance with BD 2.

7. SPECIFICATION

7.1 Alongside the research work at TRL, a Specification and related Notes for Guidance for RCA has been developed. It is proposed that this will not be formally published for the present as part of the MCHW, as they are likely to evolve and develop through experience with RCA, but can be made available by contact with Overseeing Organisations. For the time being any use of RCA and its specification should be considered as an aspect not fully covered by standards and will require submission and approval through the Overseeing Organisation's departures processes, as part of technical approval arrangements and in compliance with BD 2. All such submissions will require fully detailed specifications together with proposals for quality control. Where levels of replacement are between 20% and 60% of natural aggregate (refer clause 9 below), or is for pre-stressed or post-tensioned applications, the submission should also include proposals for design considerations.

7.2 It is strongly recommended that trial mixes are undertaken when the use of RCA is proposed, including the construction of trial panels to check on finishes and methods of placement. On occasion it may be necessary for such panels to be tested by coring to verify adequate compaction, and integrity of concrete surrounding reinforcement.

8. IN SERVICE ISSUES

8.1 Inspection of structures incorporating RCA should be carried out in the same way as for structures with natural aggregate. Special inspection and testing techniques (eg half cell potential measurement, chlorides, resistivity) will not be affected and will have the same assessment criteria.

8.2 Concrete repair procedures should not be affected.

8.3 As-built records should be provided with documentation to identify the source, type and quantity of any RCA used in a structure, test results and the locations where the materials have been used in accordance with BD 62. Where required it should also be recorded in electronic structures management information systems. This will assist in relating any defects which might subsequently develop to the presence of RCA in the structural concrete.

9. LIMITATIONS

Recommended Replacement Levels

9.1 Research and experience suggest that replacement of 20% of natural aggregate with RCA for reinforced concrete should have minimal effect on concrete properties or design issues and no special additional measures need be undertaken. This limit has been included in the specification clauses.

9.2 At increased replacement levels effects on some concrete properties assume more importance and need careful consideration during design. Based on current experience a maximum replacement level of 60% is recommended. However for replacement levels between 20% and 60% trial mixes are essential at an early stage and designers must consider design and structural performance implications. At these higher replacement levels designers will require a justified aspect not covered by standards via departures procedures, including details of any proposed changes in design parameters.

Types of Structure

9.3 The use of RCA in structural concrete is a relatively new application. Hence until a significant track record of performance is available, a cautious approach is being taken to its use in structural concrete. The type of RCA available will also be of relevance in deciding whether or not to use RCA in any particular application. A known high quality source such as waste from a pre-casting yard would pose fewer risks than, say, general demolition waste.

9.4 Based on the potentially higher drying shrinkage, RCA is not to be used in prestressed and post-tensioned concrete applications above the 20% replacement limit and only then with an agreed departure from standard. It is also recommended that RCA is not used in structurally critical insitu concrete bridge elements, such as mid to long span bridge decks greater than 20 metres. Where the concrete is buried or difficult to access for future inspection the maximum 20% replacement limit should be adopted. It is anticipated that the main initial uses will be in large exposed areas of less structurally critical concrete such as abutments, piers, retaining walls and foundations.

10. REFERENCES

British Standards Institution (1988). *Testing concrete. Methods for analysis of hardened concrete*. BS 1881-124. London: British Standards Institution.

British Standards Institution (1990). *Steel, concrete and composite bridges. Code of practice for design of concrete bridges* British Standard BS 5400-4. London: British Standards Institution.

British Standards Institution (2005). C*ement. Composition, specifications and conformity criteria for common cements.* BS EN 197-1. London: British Standards Institution.

British Standards Institution (2005). *Methods of testing cement. Chemical analysis of cement*. BS EN 196-2. London: British Standards Institution.

British Standards Institution (2005). *Fly ash for concrete. Definitions, specification and conformity criteria.* British Standard BS EN 450-1. London: British Standards Institution.

British Standards Institution (1996). *Specification for sulfate-resisting Portland cement* British Standard BS 4027. London: British Standards Institution.

British Standards Institution (1997). *Admixtures for concrete, mortar and grout. Test methods. Determination of water soluble chloride content.* BS EN 480-10 (1997). London: British Standards Institution.

British Standards Institution (1997). *Tests for general properties of aggregates. Methods for sampling.* BS EN 932-1. London: British Standards Institution.

British Standards Institution (1997). *Pulverized-fuel ash. Specification for pulverized-fuel ash for use with Portland cement.* British Standard BS 3892-1. London: British Standards Institution.

British Standards Institution (1997). *Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method.* British Standard BS EN 933-1. London: British Standards Institution, London.

British Standards Institution (1997). *Tests for geometrical properties of aggregates. Determination of particle shape. Flakiness index.* British Standard BS EN 933-3. London: British Standards Institution, London.

British Standards Institution (1998). *Admixtures for concrete, mortar and grout. Test methods. Determination of the alkali content of admixtures.* BS EN 480-12. London: British Standards Institution.

British Standards Institution (1998). *Tests for geometrical properties of aggregates. Determination of shell content. Percentage of shells in coarse aggregates.* British Standard BS EN 933-7. London: British Standards Institution, London.

British Standards Institution (1998). *Tests for mechanical and physical properties of aggregates. Methods for the determination of resistance to fragmentation.* BS EN 1097-2 London: British Standards Institution.

British Standards Institution (2000). *Concrete. Specification, performance, production and conformity.* BS EN 206-1. London: British Standards Institution.

British Standards Institution (2000). *Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption.* British Standard BS EN 1097-6. London: British Standards Institution.

British Standards Institution (2000). *Testing hardened concrete. Density of hardened concrete.* BS EN 12390-7. London: British Standards Institution.

British Standards Institution (2000). *Testing fresh concrete. Slump test.* British Standard BS EN 12350-2. London: British Standards Institution.

British Standards Institution (2002). *Testing hardened concrete. Compressive strength of test specimens.* BS EN 12390-3. London: British Standards Institution.

British Standards Institution (2002). *Tests for general properties of aggregates. Methods for sampling.* British Standard BS 932-1. London: British Standards Institution.

British Standards Institution (2006). *Concrete. Complementary British Standard to BS EN 206-1. Method of specifying and guidance for the specifier.* British Standard BS 8500-1. London: British Standards Institution.

British Standards Institution (2006). *Concrete. Complementary British Standard to BS EN 206-1.Specification for constituent materials for concrete.* British Standard BS 8500-2. London: British Standards Institution.

British Standards Institution (2002). *Aggregates for concrete.* British Standard BS EN 12620. London: British Standards Institution.

British Standards Institution (2002). *Testing hardened concrete. Compressive strength of test specimens.* BS EN 12390-3. London: British Standards Institution.

Building Research Establishment (1998). *Recycled aggregates.* BRE Digest 433. Garston: Building Research Establishment Ltd.

Building Research Establishment (2004). Alkali-silica reaction in concrete. BRE Digest 330. Garston: Building Research Establishment Ltd.

Calder, AJJ and Roberts, CP (2005). *The use of recycled aggregate in structural concrete.* TRL Published Project Report PRR036. Crowthorne, TRL Ltd.

Calder, AJJ and Mckenzie, M (2005). *The susceptibility of recycled concrete aggregate to alkali silica reaction*. TRL Published Project PPR037. Crowthorne, TRL Ltd.

CSS, Quarry Products Association, Highways Agency, DETR, BRE (2000). *Quality control the production of recycled aggregates.* Garston: Building Research Establishment Ltd.

Dhir RK. MC Limbachiya and A Beggs (2001). *Resolving application issues with the use of recycled concrete aggregate.* Confidential Report CTU/1601. Dundee: University of Dundee.

RILEM (1994). *Specifications for concrete with recycled aggregates, 121-DRG*. Materials and Structures, 27.

The Highways Agency, Quarry Products Association, WRAP. *The quality protocol for the production of aggregates from inert waste*.

The Highways Agency, the Scottish Office Development Department, the Welsh Assembly Government (Y Llywodraeth Cynulliad Cymru) and the Department of the Environment for Northern Ireland (2004). Manual of Contract Documents for Highway Works. Volume 1: Notes for Guidance on the Specification for Highway Works. London: The Stationery Office, London.

The Highways Agency, the Scottish Office Development Department, the Welsh Assembly Government (Y Llywodraeth Cynulliad Cymru) and the Department of the Environment for Northern Ireland (2004). Manual of Contract Documents for Highway Works. Volume 2: Notes for Guidance on the Specification for Highway Works. London: The Stationery Office, London.

The Highways Agency, the Scottish Office Development Department, the Welsh Assembly Government (Y Llywodraeth Cynulliad Cymru) and the Department of the Environment for Northern Ireland. BD 2 Technical Approval of Highway Structures

The Highways Agency, the Scottish Office Development Department, the Welsh Assembly Government (Y Llywodraeth Cynulliad Cymru) and the Department of the Environment for Northern Ireland. BD 62 As Built, Operational and Maintenance Records for Highway Structures.

The Highways Agency, the Scottish Office Development Department, the Welsh Assembly Government (Y Llywodraeth Cynulliad Cymru) and the Department of the Environment for Northern Ireland. BD 43 The Impregnation of Reinforced and Prestressed Concrete Highway Structures using Hydrophobic Pore-Lining Impregnants.

11. ENQUIRIES

All technical enquiries or comments on this Advice Note should be sent in writing as appropriate to:

Chief Highway Engineer Floor D2 No. 5 Broadway Broad Street Birmingham B15 1BL	S SMITH Chief Highway Engineer

Director of Trunk Roads: Infrastructure and Professional Services Transport Scotland Trunk Road Network Management 8th Floor, Buchanan House 58 Port Dundas Road Glasgow G4 0HF	A C McLAUGHLIN Director of Trunk Roads: Infrastructure and Professional Services

Chief Highway Engineer Transport Wales Welsh Assembly Government Cathays Parks Cardiff CF10 3NQ	M J A PARKER Chief Highway Engineer Transport Wales

Director of Engineering The Department for Regional Development Roads Service Clarence Court 10-18 Adelaide Street Belfast BT2 8GB	R J M CAIRNS Director of Engineering

APPENDIX A TEST REQUIREMENTS FOR ACCEPTANCE OF RCA

The tests listed in Table A.1 refer to basic properties of the aggregate. Tests listed in Table A.2 refer to additional tests required principally for the design of appropriate concrete mixes. However if chloride levels are particularly high this could preclude a particular source of RCA from consideration.

Table A.1 Schedule of Aggregate Tests

Property	**Test Method**	**Standard**	**Acceptance criteria**	
Grading	Determination of particle size distribution	BS EN 933-1	Sand content	< 5%
Impurities	Determination of shell content	BS EN 933-7[a]	Brick/masonry	< 5%
			Asphalt	< 5%
			Lightweight material[b]	< 0.5%
			Other foreign material[c]	< 1%
Bulk density and water absorption	Determination of particle density and water absorption	BS EN 1097-6	Dry density[d]	> 2000kg/m^3
			Water absorption[d]	< 10%
Particle shape	Determination of particle shape. Flakiness index	BS EN 933-3	Flakiness index shall not exceed 35	
Strength	Method for determination of resistance to fragmentation	BS EN 1097-2	LA coefficient shall be less than 40	
Sulfate content	Method for analysis of hardened concrete	BS 1881-124[e]	< 1% by mass of sample	

Notes

a The standard test is to determine the shell content of a sample of aggregate. To determine the content of each of the impurities, the 'name of each impurity' was substituted for 'shells' in the standard. An alternative is to use the test in BS 8500-2 Annex B.

b Material with a density less than 1000kg/m^3 but excluding 'floating non-stony' materials.

c eg: glass, plastics, metal.

d Can be declared where known or tested.

Table A.2 Additional Tests for Chloride and Alkali Content

Property	**Test Method**	**Standard**
Chloride content	Method for analysis of hardened concrete	BS 1881-124*
Sodium oxide and potassium oxide	Method for analysis of hardened concrete	BS 1881-124 **

* It should be noted that BS 1881-124 (1988) is to be replaced by a BS EN document, currently prEN 1744-5, which utilises a very similar test method.

** Refer to clause 3.8 for further guidance.

Table A.3 Frequency of Testing*

Property	**Test Method**	**Standard**	**Frequency**
Grading	Determination of particle size distribution	BS EN 933-1	1 per week
Impurities	Determination of shell content	BS EN 933-7[a]	1 per day**
Bulk density and water absorption	Determination of particle density and water absorption	BS EN 1097-6	1 per week
Particle shape	Determination of particle shape. Flakiness index	BS EN 933-3	1 per month
Strength	Method for determination of resistance to fragmentation	BS EN 1097-2	1 per month
Sulfate content	Method for analysis of hardened concrete	BS 1881-124	4 per year
Chloride content	Method for analysis of hardened concrete	BS 1881-124	4 per year
Sodium oxide and potassium oxide	Method for analysis of hardened concrete	BS 1881-124	4 per year

* The frequencies given are typical values. These may be adjusted to take account of the source of the RCA and the nature of the construction project. If there was reason to suspect changes in levels in particular parts of a structure supplying the source concrete for the RCA, more frequent testing is required.

** Where successive test results are well below the limiting values the frequency may be reduced to one per week coupled with a daily inspection of the stockpile. If from an inspection an increase in the impurities content is suspected then further tests shall be made. For supplies from consistent sources like preconsumer waste then frequency of tests may be reduced to one per month, subject to satisfactory daily inspections.

APPENDIX B PROCEDURE FOR TRIAL MIXES USING RCA

The following procedure for carrying out the trial mixes is recommended:

The aggregate content of each fraction is specified as the saturated surface dry (SSD) weight per cubic metre, w_{ssd}. The water absorption measured by the method given in BS EN 1097-6 (2000) is denoted as *wa*.

All the aggregates should be stored in the laboratory for a few days prior to being used. A representative sample of each aggregate is taken and the moisture content (*mc*) determined in accordance with BS EN 1097-5 (1999).

For each fraction,

the weight of aggregate W_{ag} is calculated as:

$$W_{ag} = w_{ssd} \frac{(1+mc)}{(1+wa)}$$

and the excess water w_e is:

$$w_e = w_{ssd} \frac{(mc - wa)}{(1+wa)}$$

These formulae are used to calculate the weight of stock material of each aggregate size required and the adjustment needed to the total water in the mixture to account for the moisture in the aggregate prior to mixing. The total water to be added to the mixture w_m is then calculated as:

$$w_m = w_f - \sum w_e$$

where w_f is the specified free water content and is $\sum w_e$ the sum of the excess water in each fraction.

The aggregates and water (including the water reducing agent) are first batched and placed in the pan mixer. These are mixed for four minutes to allow the aggregates to become close to saturation. The cement is then added and mixing continued for a further three minutes.

It is recommended that the slump is measured on the mixed concrete in accordance with BS EN 12350-2 (2000) and 100mm cubes are cast to determine the density (BS EN 12390-7 (2000) and compressive strength (BS EN 12390-3 (2002)).

APPENDIX C CALCULATION OF CHLORIDE CLASS AND ASSESSMENT OF ASR SUSCEPTIBILITY FOR A CONCRETE MIX DESIGN INCORPORATING RCA

This example shows the calculation of the chloride and alkali contents of a mix containing 60% RCA replacement of coarse aggregate. This is mix B in clause 3. The calculated values are then used to give a chloride class and to assess potential ASR reactivity.

Calculation of chloride and alkali levels is shown in Table C1. The chloride ion and sodium and potassium oxide contents of each of the constituents are determined by the appropriate test methods or from certified values from the manufacturers.

Table C.1 Calculation of Chloride Ion and Alkali Contents

Item		Chloride ion content (%)	Sodium oxide content (%)	Potassium oxide content (%)	Sodium oxide eq (%)	Mass of each constituent (kg/m^3)	Mass of chloride ion (kg/m^3)	Mass of alkali (kg/m^3)
Cement		0.06	0.11	0.72	0.584	215	0.13	1.26
GGBS		0.08	0.31	0.35	0.540	215	0.17	-
WRA		0.00	-	-	0.050	1.29	0.00	0.00
Natural marine	Sand	0.05	-	-	0.038	641	0.32	0.24
	20-10mm	0.03	-	-	0.023	319	0.10	0.07
	10-5mm	0.02	-	-	0.015	137	0.03	0.02
(RCA)	20-10mm	0.01	0.01	0.03	0.030	596	0.06	0.18
	10-5mm	0.01	0.01	0.04	0.036	87	0.01	0.03
Total							0.81	1.80

Check on Chloride Content of Mix

The mass of chloride ions in each constituent is summed to give the total chloride content of the mix. This is expressed as the percentage by mass of cement (inclusive of the ggbs) to be 0.19%. The chloride ion content for this particular mix would be classed as Cl 0,20 and would be permitted for concrete containing embedded metal. Note that this mix would not be acceptable for prestressed concrete, heat cured concrete containing embedded steel (Chloride content class: 0,10).

Check of Risk of Damage from ASR

The mix design is checked against the four conditions set out in amendment to Clause 5.2.6 to BS 8500-2 (2002):

1) The natural aggregate is a dredged flint gravel and therefore is classed as normally reactive.

2) The alkali content of the ggbs is less than limit of 1.0% Na_20 eq.

3) This clause was not applicable as pfa is not used for this concrete.

4) The sodium oxide equivalents for the cement, ggbs and RCA are calculated from the sodium and potassium oxide contents as (%Na_20 + 0.658%K_20). The sodium oxide equivalent for the natural marine aggregate is calculated as 0.76 times the chloride ion concentration. The certified value supplied by the manufacturer is used for the WRA.

   The calculated total alkali content of the mix (1.80kg/m^3) is less than the limit of 3.0kg/m^3 specified for a cement or a CEMI component of a combination which is not greater than 0.75%.

Points 1-4 above demonstrate that the risk of Mix B developing ASR is minimal.