# Durability test of retro-reflecting materials for road signs at Nordic test sites - Ageing model for retro-reflectivity after 6 years of exposure

Kai Sørensen and Sven Olof Lundkvist, May 2004

## Foreword

A durability test of retro-reflecting materials for road signs is being carried out at 9 test sites at different locations in the Nordic countries. The test sites were established in 1997 by the NMF group, a voluntary Nordic research co-operation.

The $R_A$ values (coefficient of retro-reflection) of the samples of the retro-reflecting materials have been measured in the 0,33°/5° geometry (0,33° observation and 5° entrance) on a regular basis since 1997. The measurements have been performed by local people with locally used instruments.

In the autumn of 2003, measurements were done by a single person using a single and well tested instrument, resulting in a 'reference' set of data with less variation than at previous occasions that is particularly well suited for analyses such as presented in this article.

The test sites and the $R_A$ values of the samples are introduced in section 1. An analysis is carried out in steps as accounted for in sections 2 to 4, resulting in an ageing model showing that the load of exposure differs from test site to test site and that the $R_A$ values of the materials degrade at different rates. The model is further discussed in section 5, while the implications of the model are considered in section 6.

## 1. Test sites and $R_A$ values of the samples

The test sites, 9 in total at different locations in the Nordic countries, were established in 1997, each with 4 identical test signs (only two at Reykjavik, and only two being used at Frederiksborg) placed along a representative road. Close to some of the test sites, a reference site was established with a reference sign at a convenient location, where it is not exposed to nearby road traffic.

A test or reference sign has samples of retro-reflecting materials placed in a matrix so that a row has a particular type of material in different colours, and so that the colours are aligned in columns. A location on one of these signs accordingly reflects a particular type and colour, which is referred to as a 'material' in the following. Refer to figure 1.

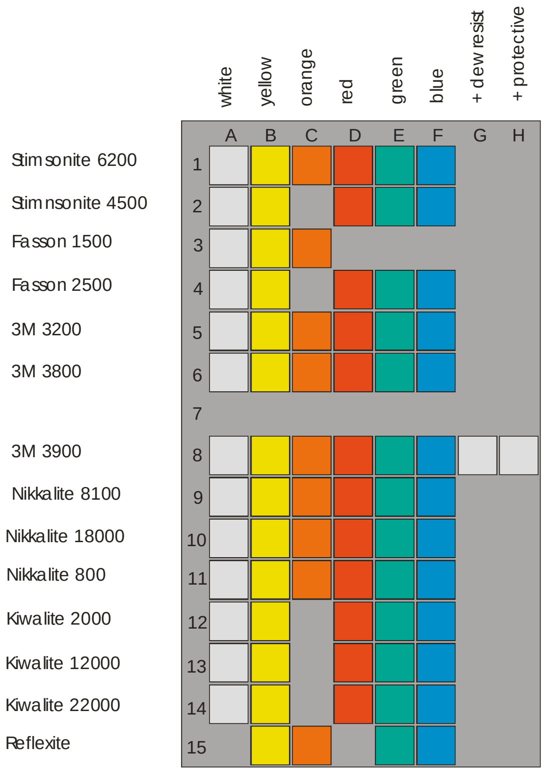
The arrangement of test signs at a test site is illustrated in figure 2, while the location of the test sites is shown in figure 3.

The $R_A$ values (coefficient of retro-reflection) of the samples have been measured in the 0,33°/5° geometry (0,33° observation and 5° entrance) on a regular basis. These measurements were performed by local people with locally used instruments.

At each occasion, the resulting $R_A$ values of the materials of a sign are provided in a table that reflects the matrix arrangement of the materials on the sign.

In the autumn of 2003, measurements were done by a single person using a single and well tested instrument, resulting in a 'reference' set of data with less variation than at previous occasions that is particularly well suited for analyses such as presented in the following.

**Figure 1: A test (or reference) sign with 76 samples arranged in rows and columns.**



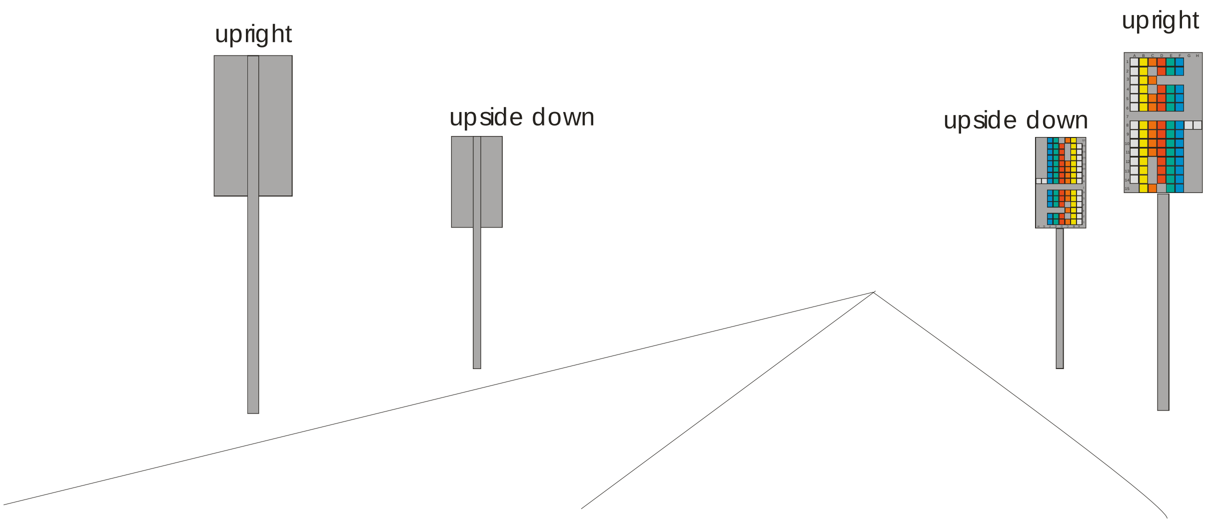




**Figure 2: Four test signs mounted at a road at a test site.**


**Figure 3: Approximate locations of the test sites.**

The roads for use for the test sites were selected with the approximate direction north-south (except at Reykjavik), with two signs facing south and two signs facing north. It was expected that the $R_A$ values would reflect this orientation (in particular that the $R_A$ values of materials facing south would decrease faster than the $R_A$ values of materials facing north), but there is no significant effect. At Reykjavik, the two signs face respectively east and west, towards and away from the dominant direction of wind; with no significant effect on the $R_A$ values.

The above does not imply that the $R_A$ values of samples of a particular material are the same for all the test signs at a particular site. The variation is in fact far from small, but as it cannot clearly be related to external agents, it is assumed to be random of nature. Likely causes are measuring uncertainties and variations from sample to sample of the same material.

Therefore, the four tables of $R_A$ values for the four test signs at a particular test site (only two at Reykjavik and Frederiksborg) are represented by a single table with average $R_A$ values for each material. This results in 9 tables of $R_A$ values, one for each of the test sites. The additional tables of $R_A$ values for the 5 reference signs bring the total number up to 14.

These 14 tables are the results of the reference measurements to be considered in the following. During this consideration it has to be taken into account that the values of these tables must themselves be attributed some uncertainty due to the above-mentioned variation.

The standard deviation of single $R_A$ values can be estimated by standard methods, when comparing $R_A$ values for test signs at the same test site. For white materials, the estimate of the standard variation is 9% as an average for all the types of materials. For most of the other colours, the percentage standard variation is somewhat higher.

## 2. Representation by average $R_A$ values

The simplest way to represent the 14 tables of $R_A$ values is to represent them all by a single table of average $R_A$ values. The assumption behind this approach would be that all the tables reflect equal conditions of exposure, and that variations between $R_A$ values of the tables are just random, carrying no information.

This approach is tested in figure 4, where the actual $R_A$ values of the 14 tables are plotted against the average $R_A$ values. Only $R_A$ values for white samples are plotted in order to keep the figure simple - if $R_A$ values for all colours were plotted details would be hidden by overlap of symbols.

Figure 4 shows a considerable scatter, at least by a factor of two, which indicates that a single table of average $R_A$ values does not provide a good representation of the actual $R_A$ values.

This probably indicates conditions of unequal exposure for the 14 tables, a matter that is discussed in the next section.

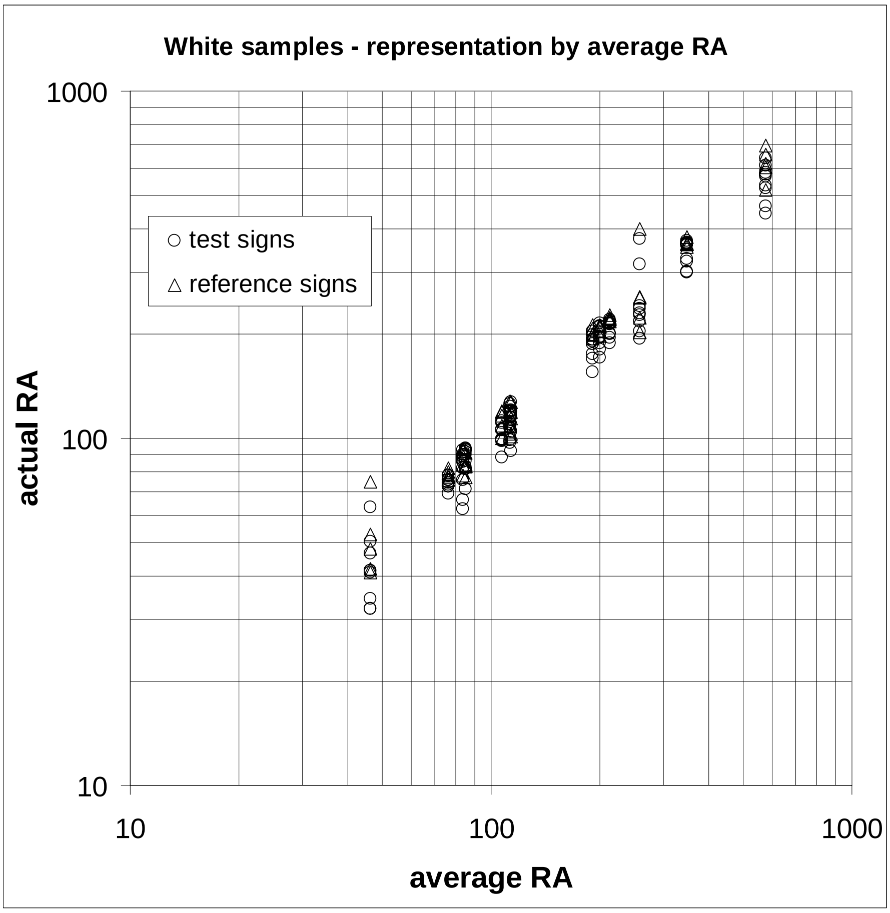



**Figure 4: Actual $R_A$ values versus average $R_A$ values for white samples.**

## 3. Representation by rescaled average $R_A$ values

When accepting that the 14 tables of actual $R_A$ values represent different conditions of exposure, the next approach would be to still represent them all by the single table of average $R_A$ values, but simultaneously allow that the scale of this table is changed in each case.

The assumption behind this approach would be that all materials are equally sensitive to exposure, for instance that the actual $R_A$ values all degrade by 5% at a given exposure. Since exposure and degradation differ between the 14 tables, these are in different scales, but proportions between $R_A$ values within a table are assumed to be the same (apart from random variation).

The scale of a table of $R_A$ values is represented by the average of the $R_A$ values within the table. Actually, the geometrical mean of the $R_A$ values within the table is used instead of the simple average in order to place the same emphasis on all materials, with low or high $R_A$ values.

Accordingly, the single table of average $R_A$ values represents a table of actual $R_A$ values, when it is first brought into the same scale.

The approach is tested in figure 5, where the actual $R_A$ values of the 14 tables are plotted against the rescaled average $R_A$ values. As for figure 4, only $R_A$ values for white samples are plotted in order to keep the figure simple.

**Figure 5: Actual $R_A$ values versus rescaled average $R_A$ values for white samples.**

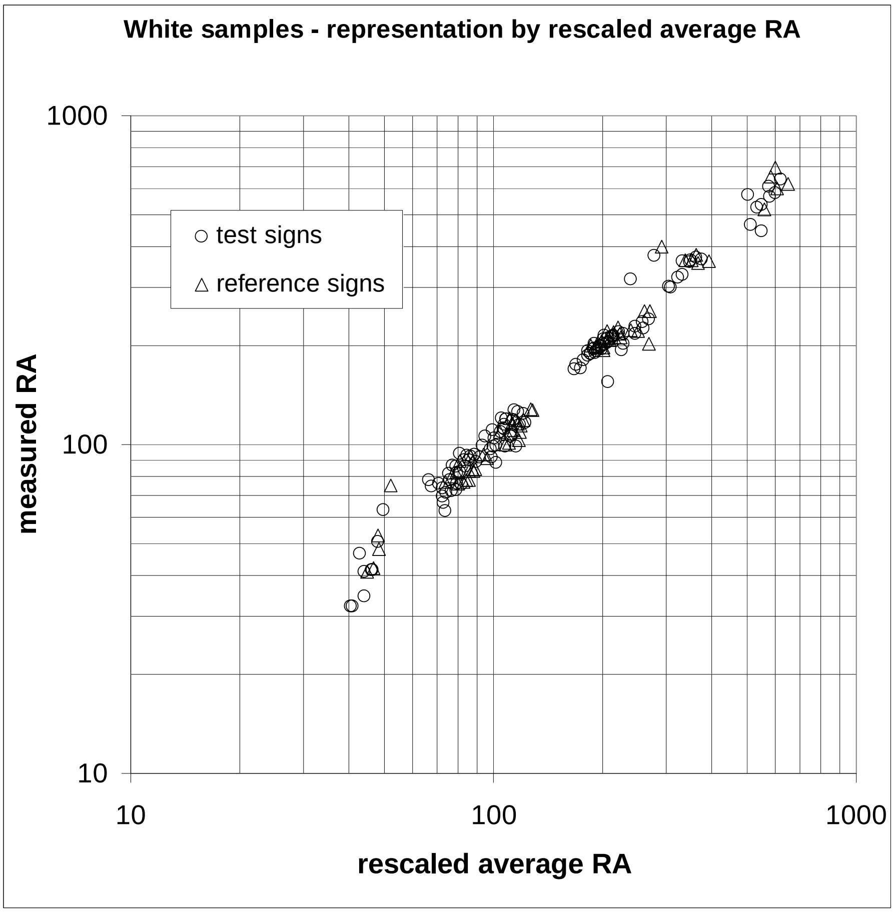


Figure 5 does show less scatter than table 4. This is assumed to prove that the 14 tables represent unequal states of exposure.

However, the scatter shown in figure 5 is still considerable. There is in fact a strongly significant interaction between the test site and the type of material (for each colour), which shows that the variation in figure 5 is larger than random variation.

This may indicate that the different materials are not equally sensitive to exposure; i.e.: that some materials degrade faster than other materials. This is discussed in the next section.

## 4. Representation by an ageing model

An actual $R_A$ value from one of the 14 tables is labelled $R_A$ (i,j,k),

where i = 1,2,3 ... refers to the rows in a table corresponding to different types of materials
j = 1,2,3 ... refers to the columns in a table corresponding to different colours of the materials
and k = 1,2,3 ... refers to the 14 tables of actual $R_A$ values

The ageing model assumes that each of the $R_A$ (i,j,k) values can be approximated by a model value obtained from the following equation:

$$R_{A,model}(i,j,k) = R_{A,average}(i,j) - F(k) \times D(i,j) \qquad \text{(equation 1)}$$

where $R_{A,model}$ (i,j,k) are the model values that approximate $R_A$ (i,j,k)
$R_{A,average}$ (i,j) are the average values of $R_A$ (i,j,k)
F(k) are exposure factors, one for each of the 14 tables of actual $R_A$ values
and D(i,j) are factors expressing degradation rates for the different materials

Equation 1 shows that the ageing model allows for unequal degradation rates of the materials as well as for unequal states of exposure, by means of respectively the table of degradation rates D(i,j) and the exposure factors F(k).

All the factors (D(i,j) and F(k)) are determined so that the model values $R_{A,model}$ (i,j,k) fit as well as possible to the actual $R_A$ (i,j,k) values. The criterion is that the RMS (root-mean-square) difference between the two sets of values is minimum.

The actual procedure, which has been used, is to determine the exposure factor values F(k) in an iterative trial and error procedure, with recalculation of the exposure factor values D(i,j) for each change of the factor values F(k). The exposure factor values F(k) actually converge quite quickly, and the recalculation of the exposure factor values D(i,j) can be done in an automatic procedure.

NOTE: The sum of square differences is $\Sigma( R_{A,model}(i,j,k) - R_A(i,j,k))^2$, where Σ means summation for the 14 tables (k = 1,2,3 ... 14). The RMS difference is minimum with respect to D(i,j), when the derivative of the sum with respect to D(i,j) is zero; which is the case when $D(i,j) = \Sigma(F(k) \times ( R_A(i,j,k) - R_{A,model}(i,j,k)))/\Sigma F^2(k)$.

The results of the ageing model are indicated in figure 6, where the actual $R_A$ (i,j,k) values are plotted against the model $R_{A,model}$ (i,j,k) values. As for figures 4 and 5, only $R_A$ values for white samples are plotted in order to keep the figure simple.

Figure 6 does show less scatter than figures 4 and 5. This is assumed to prove that the different materials are not equally sensitive to exposure; i.e.: that some materials degrade faster than other materials.

The question is if the scatter shown in figure 6 is solely due to random variation, or if some of it indicates some lacking of the ageing model. The standard deviation of random variation for single readings of $R_A$ values is 9% according to section 1 (for white materials). The standard deviation of single readings with respect to the predictions of the ageing model is slightly higher, but this is significant at a low level. Therefore, the ageing model does provide a good representation of the measuring data, but does probably not account for all variations between test sites.

Figures 7 and 8 are similar examples for other colours (respectively red and blue).

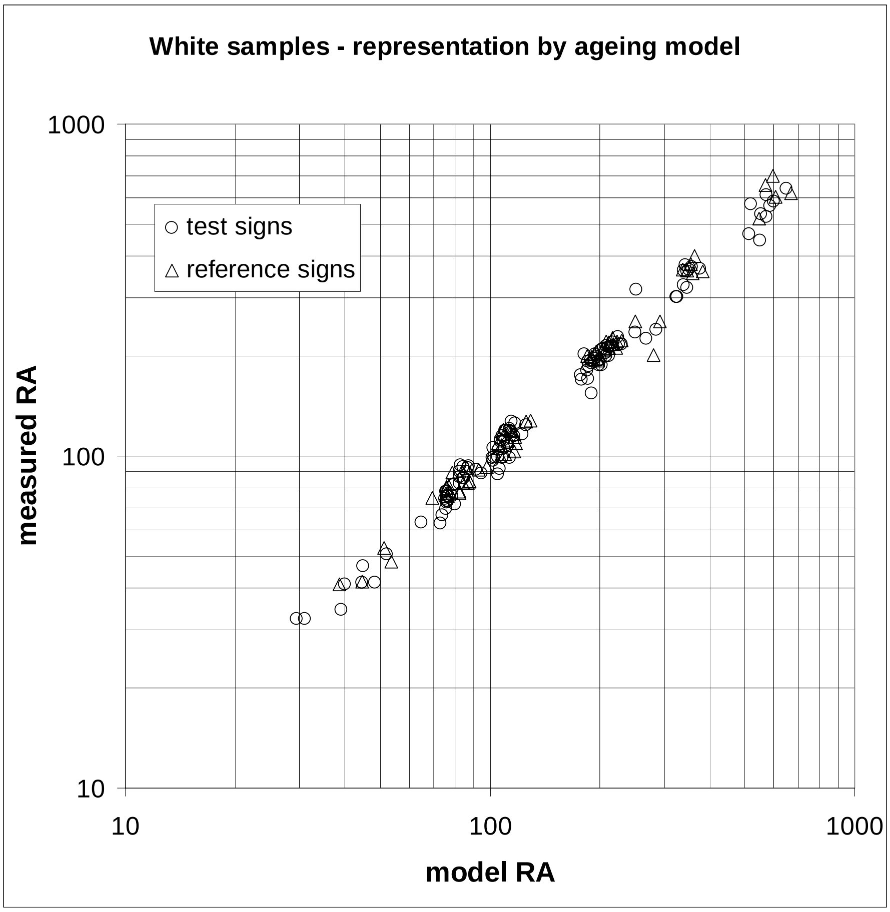



**Figure 6: Actual $R_A$ values versus model $R_A$ values for white samples.**

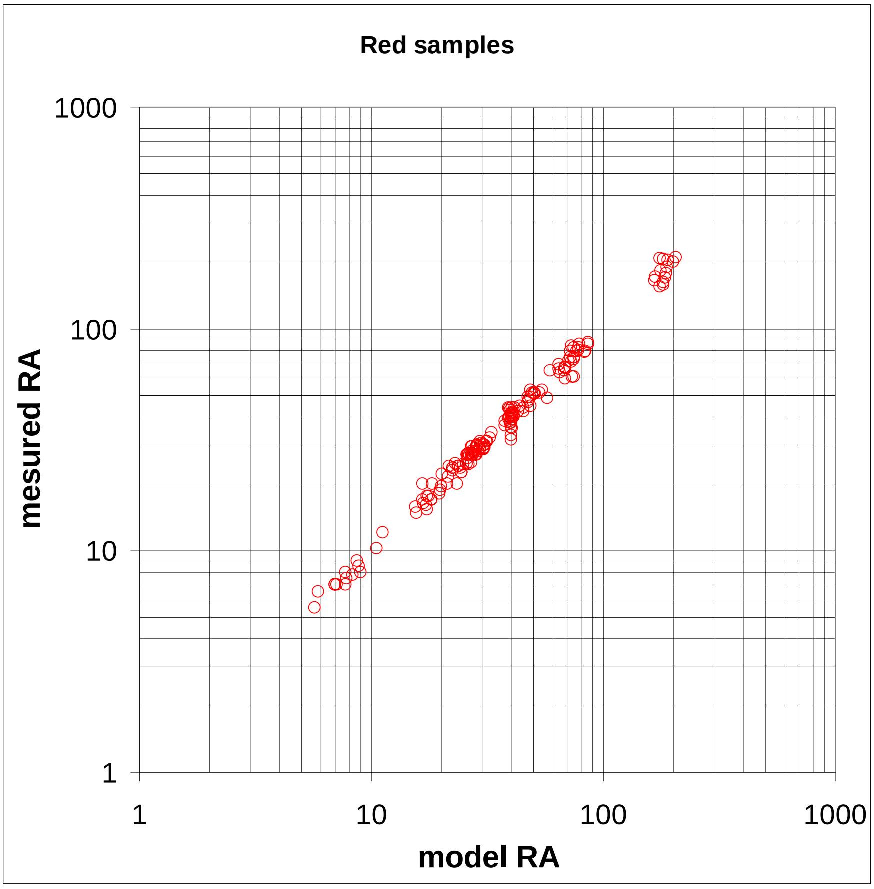



**Figure 7: Actual $R_A$ values versus model $R_A$ values for red samples.**

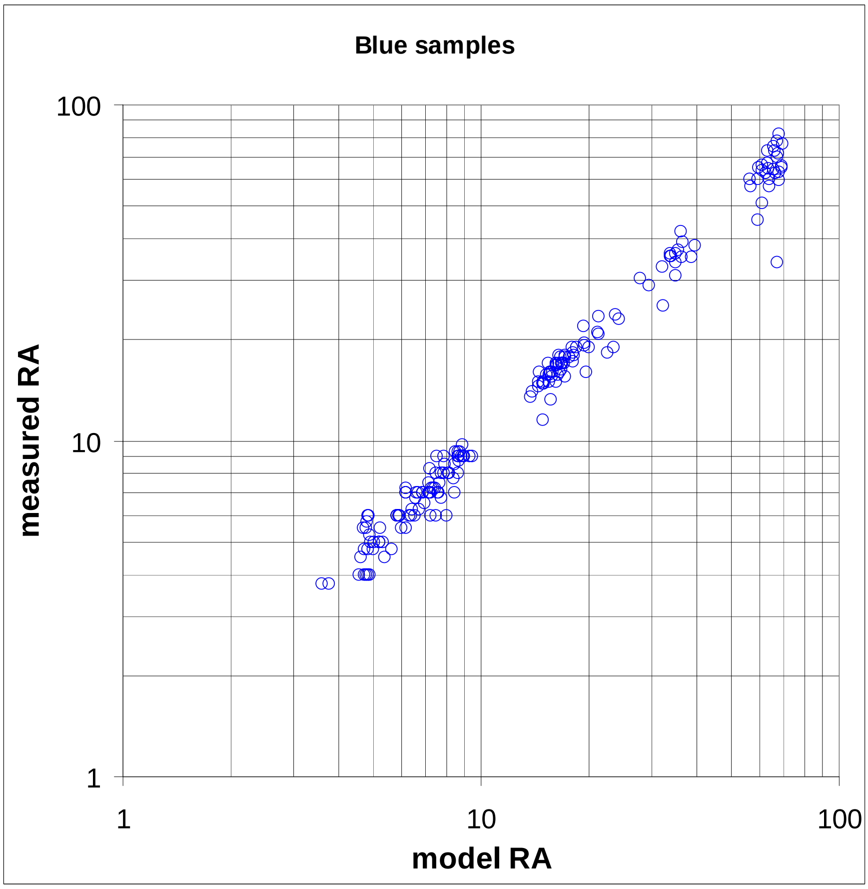



**Figure 8: Actual $R_A$ values versus model $R_A$ values for blue samples.**

## 5. Further interpretation of the ageing model

The site at Røros may be considered to lead to little degradation of the signs. For the reference sign in particular, the $R_A$ values have hardly decreased during the 6 years of exposure and the samples still look like new.

At some other sites, on the other hand, the degradation is strong. The $R_A$ values of some samples have been strongly reduced and some samples show visible symptoms of ageing.

This is reflected by the values of the exposure factors F(k). The values are small for the signs at Røros (actually negative because degradation is less than average) and large for signs at Arendal and the two Danish sites at Frederiksborg and Ribe.

Simultaneously, it may be noticed that the exposure factors F(k) and the table of degradation rates D(i,j) enter the model equation (equation 1) through the products $F(k) \times D(i,j)$. This implies that the scale of the exposure factors can be selected, when also setting the scale of degradation rates accordingly - to make the products constant.

The scale has been set so that the range of the exposure factors F(k) has a width of a little less than 6 so as to represent years of equivalent exposure at sites with strong degradation. The range goes from -3,03 for the reference sign at Røros to 2,19 for the test signs at Ribe. The $R_A$ table for the initial condition can also be put on this scale (by applying the model), and corresponds to -3,81, so that the width of the total range is 6.

After adjusting the above-mentioned range to 0 to 6 instead of -3,81 to 2,19, the equivalent exposure at the different sites are as shown in figure 9.

With this scale of the exposure factors, the degradation rates are in the scale of loss of $R_A$ value per year of equivalent exposure. If converted to percent of the average $R_A$ values, the degradation rates appear as in table 1. The table of average $R_A$ values is shown in table 2.

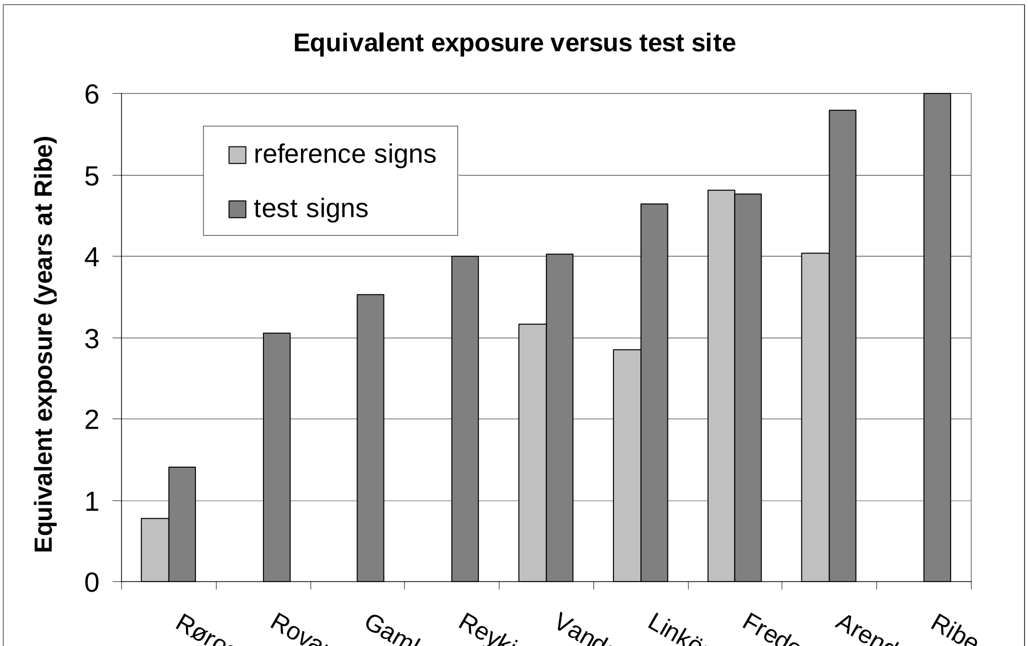



**Figure 9: Equivalent exposure versus test site.**

**Table 1: Degradation rates in percent of average $R_A$ values.**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1. Stimsonite 6200 (PM) | 5,1 | 3,9 | 5,6 | 4,0 | 4,5 | 4,0 | | |
| 2. Stimsonite 4500 (PM) | 13,6 | 16,8 | | 7,8 | 17,3 | 11,6 | | |
| 3. Fasson 1500 (EG) | 0,5 | -2,3 | 1,3 | | | | | |
| 4. Fasson 2500 (SEG) | 2,2 | 2,1 | | 0,7 | 6,6 | 5,9 | | |
| 5. 3M 3200 (EG) | 16,5 | 9,0 | 1,6 | 13,2 | 2,4 | 15,3 | | |
| 6. 3M 3800 (HI) | 3,5 | 3,4 | 3,6 | 3,6 | 5,8 | 5,0 | | |
| 7. (empty row) | | | | | | | | |
| 8. 3M 3990 (PM) | 3,2 | 4,0 | 4,9 | 4,7 | 3,8 | 4,1 | 2,6 | -5,5 |
| 9. Nikkalite 8100 (EG) | 3,1 | 4,1 | 3,8 | 5,2 | 3,1 | 1,3 | | |
| 10. Nikkalite 18000 (SEG) | 3,3 | 2,5 | 3,2 | 5,7 | 2,5 | 3,0 | | |
| 11. Nikkalite 800 (HI) | 2,5 | 1,8 | 3,3 | 3,6 | 3,1 | 4,2 | | |
| 12. Kiwalite 2000 (EG) | 5,7 | 8,6 | | 4,7 | 7,2 | 6,9 | | |
| 13. Kiwalite 12000 (SEG) | 4,7 | 3,4 | | 5,2 | 6,0 | 6,2 | | |
| 14. Kiwalite 22000 (HI) | 3,5 | 2,2 | | 3,0 | 3,2 | 3,9 | | |
| 15. Reflexite (PM) | | -7,3 | 4,8 | | -1,0 | -1,9 | | |

**Table 2: Average $R_A$ values ($cd \cdot lx^{-1} \cdot m^{-2}$).**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1. Stimsonite 6200 (PM) | 577 | 517 | 290 | 183 | 91,0 | 61,6 | | |
| 2. Stimsonite 4500 (PM) | 258 | 138 | | 69,7 | 39,8 | 21,8 | | |
| 3. Fasson 1500 (EG) | 76,2 | 50,8 | 25,4 | | | | | |
| 4. Fasson 2500 (SEG) | 107 | 66,3 | | 40,2 | 23,3 | 7,6 | | |
| 5. 3M 3200 (EG) | 46,3 | 35,8 | 29,6 | 8,0 | 10,9 | 5,4 | | |
| 6. 3M 3800 (HI) | 200 | 162 | 93,5 | 49,1 | 35,8 | 17,4 | | |
| 7. (empty row) | | | | | | | | |
| 8. 3M 3990 (PM) | 349 | 303 | 350 | 75,6 | 70,1 | 35,2 | 531 | 319 |
| 9. Nikkalite 8100 (EG) | 85,1 | 62,5 | 48,1 | 17,5 | 15,4 | 4,8 | | |
| 10. Nikkalite 18000 (SEG) | 114 | 86,9 | 30,0 | 22,6 | 19,0 | 8,7 | | |
| 11. Nikkalite 800 (HI) | 213 | 138 | 112 | 29,7 | 42,2 | 16,4 | | |
| 12. Kiwalite 2000 (EG) | 83,4 | 63,8 | | 27,4 | 13,8 | 6,3 | | |
| 13. Kiwalite 12000 (SEG) | 113 | 79,2 | | 27,3 | 24,8 | 7,3 | | |
| 14. Kiwalite 22000 (HI) | 192 | 134 | | 40,2 | 27,7 | 15,0 | | |
| 15. Reflexite (PM) | | 388 | 200 | | 134 | 66,8 | | |

## 6. Implications of the model

The details of the ageing model should probably not be taken too serious.

The model is linear of nature, assuming a constant loss of retro-reflectivity year by year (refer to equation 1), where a percentage decrease might be more natural and might fit the measuring data slightly better. Further, the estimates of the exposure factors, refer to figure 9, and of the degradation rates, refer to table 1, are liable to be associated with considerable uncertainty. However, the model is interesting by showing a number of features, which are undoubtedly true.

The equivalent exposure is widely different at the different test sites in the Nordic countries and some thought should be given to what factors determine this.

With the exception of the test site at Frederiksborg, the equivalent exposure is less for the reference signs than for the test signs, which indicates that road conditions lead to additional degradation. A probable cause could be abrasion by particles carried in the wake of vehicles. Røros, which has little traffic and a road covered by snow during winter, has the lowest equivalent exposure.

It may be that there is less exposure to global radiation with higher latitudes, and thereby less degradation. A comparison of figure 3 with figure 9 would indicate some correlation between latitude and equivalent exposure. The correlation is most clear for the reference signs, refer to figure 10.

It may also be that closeness to a salt water sea has an influence by means of salt carried by the wind. The test sites at Ribe and Arendal both have high equivalent exposures; they are close to respectively the North Sea and the Skaggerak.

Washing the signs may also be a factor. The signs were never washed at Røros.

In any case, the model does show that the expected life, or the degradation of $R_A$ values, depends on the location of the road signs. The matter that the model can include both test signs and reference signs seems to indicate that the two kinds of exposure affect the proportions of the $R_A$ values in a table in at least approximately the same manner.

Materials with high degradation rates should not be used at locations with high equivalent exposures.

If a permanent test site is introduced in the Nordic countries, it should for practical reasons be placed at a location with a high equivalent exposure, so as to keep the test as short as possible.

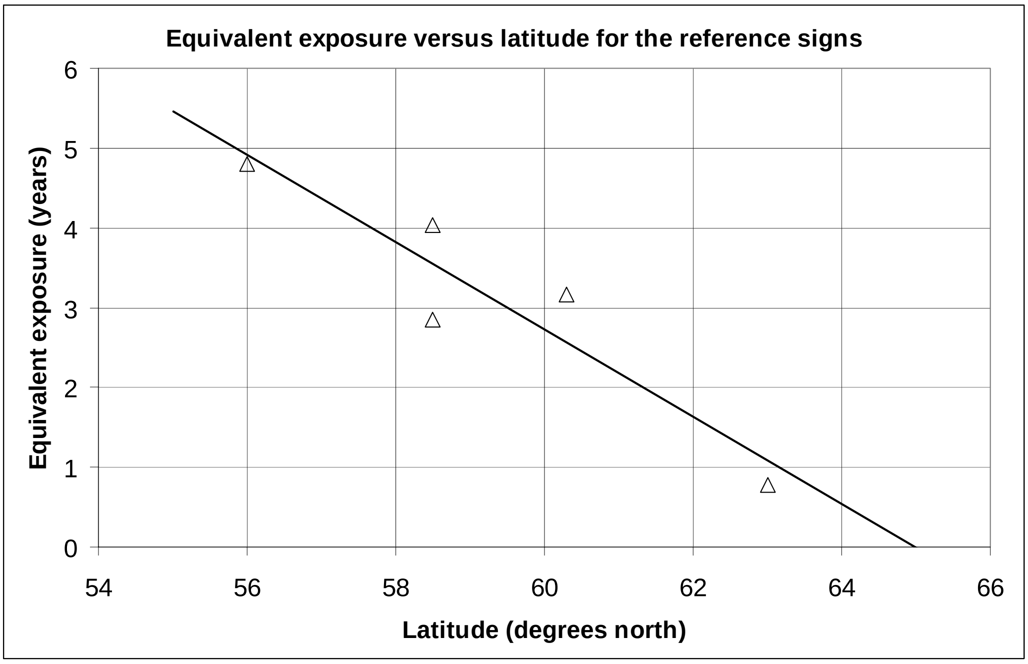



**Figure 10: Equivalent exposure versus latitude of the test site for the reference signs.**