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THE EFFECTS OF COLOUR CONTRAST AND PAVEMENT AGGREGATE TYPE ON ROAD LIGHTING PERFORMANCE

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ABSTRACT

This paper focuses on studying the effects of colour contrast and pavement aggregate type on road lighting performance. Road lighting visibility experiments are conducted to study the visibility of achromatic and coloured targets in metal halide (MH) lamp and high pressure sodium (HPS) lamp road lighting installations. Pavement measurements are made to investigate the effects of aggregate lightness and aggregate colour on reflectance properties of pavements. Finally, the effects of vehicle windshields on driver's visibility and road lighting performance are discussed.

The results of visibility experiments show that colours have a major effect on target visibility if the road is illuminated with a light source with adequate colour rendering properties. Thus in road lighting design it cannot always be assumed that targets on the road are achromatic and visible to the driver only because of the adequate luminance contrast. As expected, colours have more significant effect on target visibility when illuminated with MH lamps compared to HPS lamps.

The results of pavement measurements show that aggregate colour and especially aggregate lightness have a significant effect on pavement reflection properties. For the most of the measured pavements the relative reflectances were higher for the long wavelength region of the visible spectrum. The pavement measurement results suggest that due to the higher content in the long wavelength region HPS lamps are more effective than MH lamps in terms of light reflected from the pavements. According to the results it can be concluded that road pavement is a very important parameter in optimisation and development of road lighting energy efficiency.

Keywords: road lighting, target visibility, achromatic and coloured targets, pavement spectral reflectance, aggregate lightness and colour, vehicle windshield transmittance

1. INTRODUCTION

The primary purpose of road lighting is to make people, vehicles and targets on the road visible to the driver. In the development of design criteria for road lighting it has been assumed that targets are visible to the driver only if they have adequate luminance contrast to their background [De Boer 1967, Van Bommel 1980]. However, it can be argued that colour contrast can also be effective at revealing a target from its background, especially in the case of road lighting installations with good colour rendering properties. In this paper visibility experiments with achromatic and coloured targets are conducted to study the effects of different colours on target visibility. The main hypothesis of the experiments is that all targets located on the road in road lighting environments can not be considered to be achromatic and that different colours affect target visibility differently in various road lighting conditions.

For the perception of colour contrast it is important that the road is lit with a light source with good colour rendering properties. With the development of metal halide (MH) lamps and LEDs for road lighting use the effect of colours on target visibility have become more important.

Road lighting standards in Europe and North America are expressed mainly in terms of three luminance metrics: average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio [EN 2003, IESNA 2005]. The luminance of any point of road surface is a function of the illuminance on the road and the reflection properties of the road surface [CIE 1982]. The reflection properties of the road surface, on the other hand, are determined by the pavement material and the aggregate type used. In this paper the effects of aggregate lightness and aggregate colour on reflectance properties of pavements are studied under metal halide (MH) lamp and high pressure sodium (HPS) lamp.

The main hypothesis of the pavement measurements is that the lightness of the aggregate has a significant effect on pavement reflection properties and thus also a major effect on the road lighting performance. It can be argued that despite the higher costs of light aggregate, significant road lighting energy savings could be achieved by using light aggregate for the road surface pavements. This of course requires that quality factors of the light aggregate, such as for example wearing properties, are adequate for the road traffic use.

The other hypothesis of the pavement measurements is that the aggregate colour also affects road lighting performance and that the same pavement can result in different reflection factors when different light sources are used.

Also the transmittance of the vehicle windshield and changes in the spectrum of transmitted light has an effect on the visual performance of the driver. The effects of windshields' spectral transmittances on drivers' visibility and road lighting performance are introduced and discussed in the paper.

2. MEASUREMENT SET-UP

In Lighting Unit of Helsinki University of Technology two identical road lighting installations were built in an underground tunnel to simulate viewing conditions on roads at night-time. The length of the tunnel is 200 m, the height is 3.5 m and the width is 5 m. The advantage of the tunnel is that the exterior conditions remain constant. Thus it was possible to carry out visibility tests with test subjects in exactly the same visibility conditions [Eloholma 2005]. The road surface of the tunnel consisted of coarse sand.

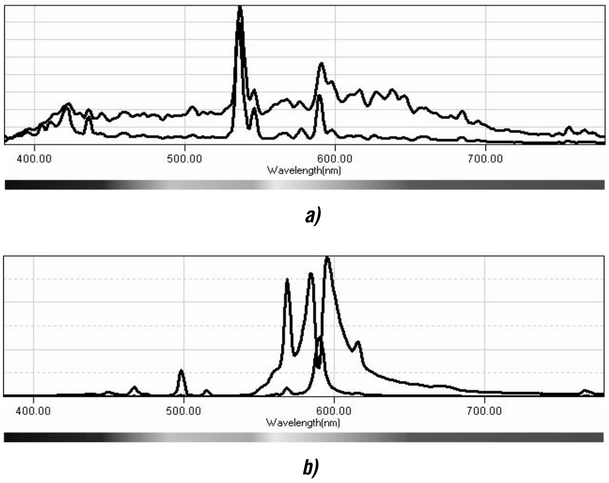


Fig. 1. The relative spectral power distributions of the a) MH lamp and b) HPS lamp at 100 % lumen output and at 40 %/15 % lumen output levels

In both installations the luminaires were positioned in four luminaire groups with 8 m spacing. The first installation consisted of four Osram HCI-TS 70 W/942 NDL metal halide (MH) lamps and the second one of four Osram NAV-TS Super 70 W (SON-TS Plus) high pressure sodium (HPS) lamps. HPS lamps were selected for the study, because they are very commonly used in road lighting installations in Finland. MH lamps were selected because of their good colour rendering properties and significantly different spectral distribution compared to HPS lamps. Both road lighting installations were dimmable.

For the purposes of this paper, four different road lighting conditions were used: two light spectra (HPS/MH) and two luminance levels. Fig. 1 shows the relative spectral power distributions of the MH and HPS lamps at the two dimming levels; the full lumen output and the minimum lumen output. The measured average road surface luminances were 1.35 cd/m^2 (100 % lumen output) and 0.52 cd/m^2 (40 % lumen output) for the MH installation and 1.71 cd/m^2 (100 % lumen output) and 0.27 cd/m^2 (15 % lumen output) for the HPS installation.

Fig. 2 shows power and lumen output of MH and HPS lamps as a function of dimming levels. The dimming was done by using voltage as a control parameter. The control values used in the experiments were 10 V (100 % lumen output) and 1.5 V (40 % lumen output) for the MH installation, and 10 V (100 % lumen output) and, 1 V (15 % lumen output) for the HPS installation.

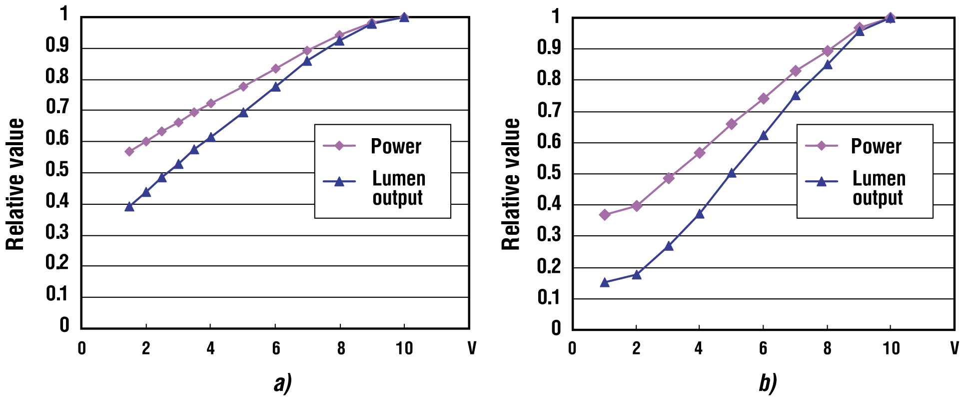


Fig. 2. Measured power and lumen output of a) MH lamp and b) HPS lamp as a function of control voltage

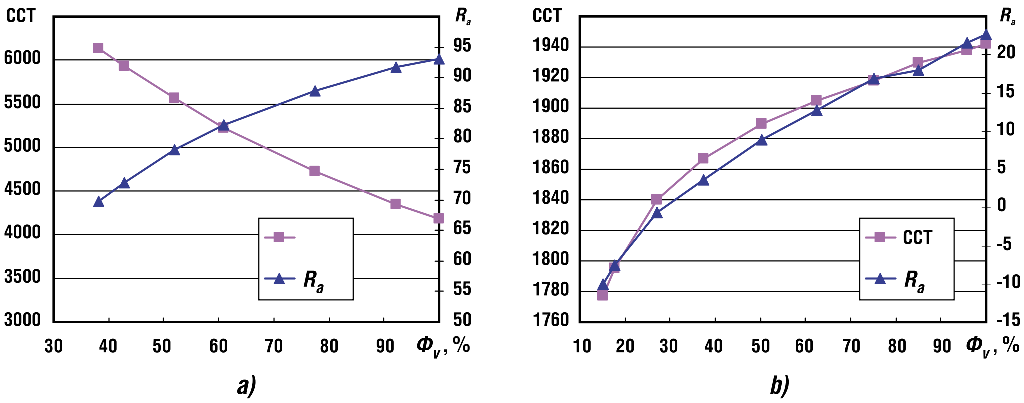


Fig. 3. Colour temperature (CCT) and colour rendering index (Ra) of a) MH lamp and b) HPS lamp as a function of lumen output

Fig. 3 shows the colour temperatures and the colour rendering indexes of MH and HPS lamps as a function of the lumen output. The correlated colour temperature (CCT) of MH lamp was 4182 K without dimming and increased to 6134 K when the lumen output was decreased to 40%. The colour rendering index (Ra) decreased from 93 to 70. In the case of HPS lamp the correlated colour temperature (CCT) decreased from 1942 K to 1777 K and the colour rendering index (Ra) decreased from 23 to –10.0 as the lumen output was decreased from 100% to 15%.

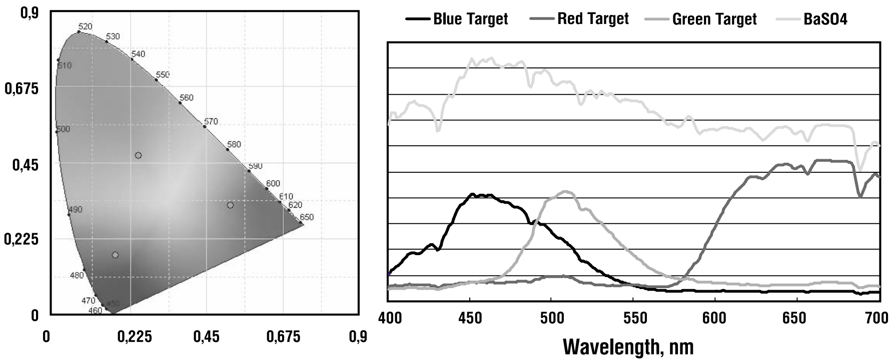
The measurements were made using spectroradiometer CS-2000 and imaging luminance photometer LMK Mobile Advanced.

3. VISIBILITY EXPERIMENTS WITH ACHROMATIC AND COLOURED TARGETS

3.1. Experimental set-up

The relative visibility of two targets located on the road was used as the visual task in four different test series. Test series were defined by four different road lighting conditions; two light spectra (HPS/MH) and two luminance levels. The visibility experiments were made from two viewing distances, 50 m and 83 m. The targets were achromatic and coloured 20 cm x 20 cm flat square surfaces positioned perpendicular to the road surface. The size of the targets represents a critical object which is the most difficult to perceive but still dangerous for a normal-sized vehicle [Güler 2003, Narisada 2007]. In the American National Standard Practice for Roadway Lighting similar achromatic square targets are used for Small Target Visibility calculations [IESNA 2005]. Similar achromatic flat surface targets with different reflection factors were used as the basis of the present road lighting recommendations [De Boer 1967].

Fig. 4 represents the colour coordinates of the blue, red and green targets and their spectral distribution under daylight (6800 K). In each test series two targets; one achromatic and one coloured, were positioned on the central axis of the road. The targets were positioned close to each other at interval of 10 cm in the transverse direction. The task of the



a) *b)*

Fig. 4. a) The colour coordinates of the blue, red and green targets in the CIE chromaticity diagram. b) Reflected spectrum of a white reference surface (barium sulphate, ρ=0.97) and coloured targets. The targets were measured under daylight (6800 K) with spectroradiometer CS-2000

Fig. 5. Experimental set-up in the underground tunnel and two road lighting installations used in the experiments. a) Two achromatic and three coloured targets illuminated with MH lamps. b) An achromatic and a green target illuminated with HPS lamps

subject was to define which target is more visible. Subjects used a simple five-option scale to define the targets relative visibility. The options were:

1. The left target is substantially more visible than the right target (SMV);
2. The left target is slightly more visible than the right target (MV);
3. No difference, do not know (S);
4. The right target is slightly more visible than the left target (MV);
5. The right target is substantially more visible than the left target (SMV).

The subject was always positioned at a distance of 50 m or 83 m from the targets. The subject viewed the targets with foveal vision and the angle of observation was approximately 1° in both cases. The reaction time of the subject was 2 s. The targets were covered between the measurements and thus the subject did not know which coloured and which achromatic targets will appear, and on which side the coloured target will appear. The experiments were done in random order for each subject. Randomized parameters were road lighting installation (MH/HPS), luminance level, targets and viewing distance.

Twelve young subjects (seven males, five females) of 20–29 age participated in the experiments. The subjects were not working in the lighting field and were not familiar with the theory of road lighting. They had normal colour vision (Ishihara test) and visual acuity. Before the experiments the subject had adapted to the tunnel lighting for 30 min. The subject was also adapted to each of the following lighting conditions used in the test series for 5 min. Before the experiments the subject was asked to imagine the situation as he/she were driving a vehicle at night-time.

Fig. 5 a shows the underground tunnel and five different targets illuminated with MH lamps (100 % lumen output). Fig. 5 b shows an example of the visual task in the experiments, where an achromatic

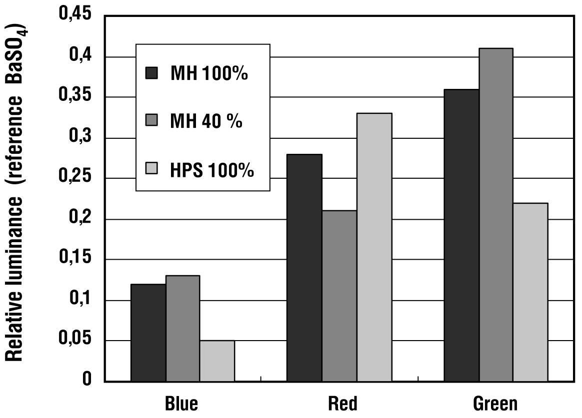


Fig. 6 Relative luminances (luminance of target/ luminance of reference) of coloured targets in different lighting conditions

and a green target are positioned on the road and illuminated with HPS lamps (100 % lumen output).

3.2. Results

Fig. 6 shows the variations in relative luminances of the coloured targets in different lighting conditions. White surface (barium sulphate) with reflectance of 0.97 was used as a reference. The relative luminances of the coloured targets were calculated in proportion to the luminance of the reference in every lighting condition.

The relative luminance of the blue target was significantly higher in the MH lamp illumination; both dimmed and not dimmed, compared to the HPS lamp illumination. The relative luminance of the red target, on the other hand, was higher in the HPS lamp illumination. The relative luminance of the red target decreased significantly when the MH installation was dimmed from 100 % to 40 % lumen output. The relative luminance of the green target increased when the MH installation was dimmed but decreased substantially when illuminated with HPS lamps. The variations in relative luminances of the coloured targets were due to differences in the lamp spectra in various conditions.

In the experiments an achromatic and a coloured target were placed in the road close to each other and the effect of colour on the relative target visibility was studied. The first experiments were done with achromatic and coloured targets having approximately the same luminance contrasts against the background. The second experiments were made with achromatic targets having higher luminance contrast compared to the coloured targets. Due to luminance variations of coloured targets in different road lighting conditions, numerous achromatic targets with different reflection factors were used in the experiments. Target combinations and target positions were chosen separately for each viewing condition.

The target and the background luminances were measured for each target and for each visual task. Luminance contrast between the target and the background was calculated as follows:

$$C = \frac{L_t - L_b}{L_b}, \qquad (1)$$

where, C is contrast, L_t is luminance of the target and L_b is luminance of the background. The contrast value is negative when the target luminance is lower than the background luminance. In this case the target is seen darker than the background and the lower the contrast value the better the target visibility. On the other hand, if the target luminance is higher than the background luminance and the target is seen brighter than the background, its luminance contrast is positive. A contrast of zero corresponds to a situation in which $L_t = L_b$; the target with no colour contrast being invisible.

Tables 1 and 2 show results of two test series in the MH lamp installation; both, 100 % lumen output and 40 % lumen output. Table 1 shows results with achromatic and coloured targets having approximately the same luminance contrasts. Table 2 shows results with coloured targets having lower luminance contrast (luminance contrast closer to 0) than achromatic targets. The results are presented as a five-option scale for two viewing distances 50 m and 83 m.

The results show that at a viewing distance of 50 m all coloured targets were substantially or slightly more visible than the achromatic targets despite the fact that the luminance contrasts of both targets were approximately the same (Table 1 a). 50 % of the subjects rated the blue target, as substantially more visible than the achromatic target, and other 50 % of the subjects responded that the blue target was slightly more visible than the achromatic target. In the case of the red target, 67 % of the subjects responded that the red target was substantially more visible than the achromatic target. For the green target the differences in visibility ratings between achromatic and coloured target were the smallest.

TABLE 1. Experiment results with MH lamp installation:
a) 100 % lumen output, average road surface luminance 1.35 cd/m^2. b) 40 % lumen output, average road surface luminance 0.52 cd/m^2. The luminance contrasts of achromatic and coloured targets were approximately the same. AC = achromatic target contrast, BC = blue target contrast, RC = red target contrast, GC = green target contrast. The results are presented for two viewing distances 50 m and 83 m. SMV LEFT – the achromatic target is substantially more visible than the coloured target, MV LEFT – the achromatic target is slightly more visible than the coloured target, S = no difference, do not know, MV RIGHT – the coloured target is slightly more visible than the achromatic target, SMV RIGHT – the coloured target is substantially more visible than the achromatic target:

a) average road surface luminance 1.35 cd/m^2					
Achromatic		AC = –0.57		BC = –0.55	Blue
	SMV	MV	s	MV	SMV
50 м	0	0	0	6	6
83 м	0	0	1	9	2
Achromatic		AC = –0.64		RC = –0.61	Red
	SMV	MV	S	MV	SMV
50 м	0	0	0	4	8
83 м	0	0	1	7	4
Achromatic		AC = –0.53		GC = –0.51	Green
	SMV	MV	s	MV	SMV
50 м	0	0	0	10	2
83 м	0	0	4	8	0

b) average road surface luminance 0.52 cd/m^2					
Achromatic		AC = –0.56		BC = –0.52	Blue
	SMV	MV	S	MV	SMV
50 м	0	0	0	9	3
83 м	0	0	4	8	0
Achromatic		AC = –0.70		RC = –0.65	Red
	SMV	MV	S	MV	SMV
50 м	0	0	0	7	5
83 м	0	0	2	8	2
Achromatic		AC = –0.53	GC = –0.49		Green
	SMV	MV	S	MV	SMV
50 м	0	0	1	11	0
83 м	0	0	6	6	0

The effects of colour on targets visibility decreased when the viewing distance was increased to 83 m. For example in the case of the blue target, only 17 % of the subjects answered that the blue target was substantially more visible than the achromatic target, while at a viewing distance of 50 m the percentage was 50 %. Also in cases with the red and the green targets the differences in visibility ratings between achromatic and coloured target were lower compared to the results with the viewing distance of 50 m. Even so, the coloured targets were mostly rated as more visible than the achromatic targets despite the fact that the luminance contrasts of the targets were approximately the same. Also for the 83 m viewing distance the red colour had the highest effect on the relative visibility of the targets.

The effects of target colour on visibility decreased when the MH installation was dimmed to 40 % of the total lumen output (Table 1 b). The coloured targets were mainly rated as slightly more visible than the achromatic targets. For example at a viewing distance of 50 m, 25 % of the subjects rated the blue target and 42 % of the subjects the red target as substantially more visible than the achromatic target, whereas in the case with 100 % lumen output the same values were 50 % and 67 % of the subjects. The changes can mainly be explained by different light spectra, decreased colour rendering index (Ra) and lower luminance level. Still, at a viewing distance of 50 m all coloured targets were mainly considered to be substantially or slightly more visible than the achromatic targets. At a viewing distance of 83 m, the effect of target colours on visibility were significantly lower compared to the case with 100 % light output and viewing distance of 50 m.

The luminance contrasts of the targets varied between C = –0.70…-0.49. Such luminance contrast values can be considered to be relatively common for small targets positioned on the road in road lighting environments [Hansen 1979, Smith 1938].

TABLE 2. Experiment results in the MH lamp installation:
a) 100 % lumen output, average road surface luminance 1.35 cd/m^2;
b) 40 % lumen output, average road surface luminance 0.52 cd/m^2. The luminance contrasts of the coloured targets were lower than those of the achromatic targets:

a) average road surface luminance 1.35 cd/m^2					
Achromatic		AC = –0.72		RC = –0.61	Red
	SMV	MV	S	MV	SMV
50 м	0	0	0	5	7
83 м	0	0	3	6	3
Achromatic		AC = –0.52		RC = –0.10	Red
	SMV	MV	S	MV	SMV
50 м	0	1	1	0	10
83 м	0	1	3	1	7
Achromatic		AC = –0.59		GC = –0.51	Green
	SMV	MV	S	MV	SMV
50 м	0	0	3	7	2
83 м	0	0	7	5	0
Achromatic		AC = –0.32		GC = –0.03	Green
	SMV	MV	S	MV	SMV
50 м	0	0	0	8	4
83 м	0	0	2	6	4

b) average road surface luminance 0.52 cd/m^2					
Achromatic		AC = –0.75	RC = –0.85		Red
	SMV	MV	S	MV	SMV
50 м	0	0	1	8	3
83 м	0	0	5	7	0
Achromatic		AC = –0.53		RC = –0.32	Red
	SMV	MV	S	MV	SMV
50 м	0	0	0	4	8
83 м	0	0	4	4	4
Achromatic		AC = –0.60	GC = –0.45		Green
	SMV	MV	S	MV	SMV
50 м	0	0	5	7	0
83 м	0	0	8	4	0
Achromatic		AC = –0.31		GC = 0.04	Green
	SMV	MV	S	MV	SMV
50 м	0	0	0	9	3
83 м	0	1	1	9	1

Table 2 shows experiment results for the same MH lighting conditions and with the same coloured targets as in Table 1. However, in these experiments the luminance contrasts of the achromatic targets were higher compared to the luminance contrasts of the coloured targets.

When the luminance contrasts of the achromatic and the red target were set to C = –0.72 and C = –0.61, and the lumen output of the MH lamps was 100 %, the red target was rated as substantially more visible by 58 % of the subjects (Table 2 a). None of the subjects considered the achromatic target to be as visible as the red target, not to mention rating the achromatic target as more visible than the red target. When the viewing distance was increased from 50 m to 83 m the visibility differences between the targets were not as high as in the case of 50 m viewing distance.

When the absolute luminance contrast values of the targets were decreased closer to 0 by changing the targets position in relation to the luminaires, the red target still remained substantially more visible than the achromatic target despite the large difference in luminance contrasts. 83 % of the subjects rated the red target as substantially more visible than the achromatic target though the luminance contrast of the red target was C = –0.10 and the luminance contrast of the achromatic target C = –0.52. 8 % of the subjects rated the achromatic target as slightly more visible than the red target. Although the luminance contrast of the red target was very low, the target luminance was high and the red colour was clearly visible. Hence, the red target resulted mostly in better relative visibility compared to the achromatic target.

Similar results were found with the green target. When the luminance contrast value of the green target was close to 0 and the target was visible only because of the colour contrast, the green target was rated as substantially more visible or as slightly

TABLE 3. Experiment results with HPS installation (100 % lumen output, average road surface luminance 1.71 cd/m^2) for the red and the green target.
The Table also shows which road lighting installation the subjects preferred more when asked after the experiments

Achromatic		AC = –0.65		GC = –0.60	Green
	SMV	MV	S	MV	SMV
50 м	0	2	9	1	0
83 м	0	2	9	1	0
Achromatic		AC = –0.73		GC = –0.60	Green
	SMV	MV	s	MV	SMV
50 м	0	7	5	0	0
83 м	0	6	6	0	0
Achromatic		AC = –0.42		GC = –0.21	Green
	SMV	MV	S	MV	SMV
50 м	1	6	5	0	0
83 м	0	7	5	0	0

Achromatic		AC = –0.64		RC = –0.59	Red
	SMV	MV	S	MV	SMV
50 м	0	0	0	10	2
83 м	0	0	1	11	0
Achromatic		AC = –0.69		RC = –0.59	Red
	SMV	MV	S	MV	SMV
50 м	0	3	2	7	0
83 м	0	2	3	7	0
Which road lighting installation do you piefet more?					
	MH	S	HPS		
	8	2	2		

more visible than the achromatic target though the luminance contrast of the achromatic target was C = –0.32 (Table 2 a). In all cases the increase of the viewing distance decreased the effects of colour on the relative visibility of targets.

As expected, the effects of colour on target visibility decreased when the MH installation was dimmed to 40 % of the lumen output (Table 2 b). The colour temperature increased and the light colour changed from natural white towards greenish, which negatively affected the visibility of the green target. Nevertheless, the red and the green target resulted mostly as being more visible than the achromatic targets despite the fact that the luminance contrasts of the achromatic targets were higher.

Table 3 shows the relative visibility evaluation results in the HPS installation (100 % lumen output) for the green and the red target. The green colour was hardly visible when illuminated with HPS lamps. When the green target and the achromatic target had similar luminance contrasts, 75 % of the subjects could not tell which one of these targets was more visible. 17 % of the subjects answered that the achromatic target was slightly more visible than the green target. This was due to slightly higher luminance contrast of the achromatic target. Only one subject out of twelve rated the green target as slightly more visible that the achromatic target. The viewing distance had no effect on the results. When the luminance contrast of the achromatic target was changed from C = –0.65 to C = –0.73, 58 % of the subjects rated the achromatic target as slightly more visible than the green target. The increase of the viewing distance to 83 m lowered the percentage to 50 %.

Increasing the targets luminances and decreasing the luminance contrasts of the targets did not increase the effect of green colour on relative visibility of the green target. 50 % of the subjects answered that the achromatic target (C= –0.42) was slightly more visible than the green target (C = –0.21). 42 % of the subjects could not tell which one of these targets was more visible and 8 % of the subjects thought that the achromatic target was substantially more visible than the green target.

The results suggest that in the HPS lamp illumination green targets are mostly seen as achromatic, and that green colour does not have a significant effect on target visibility under HPS lamps.

Due to the light spectra and low colour rendering index of HPS lamps the blue target was seen as achromatic when illuminated by HPS lamps. The blue target resulted in the same relative target visibility as the achromatic target with the same luminance contrast.

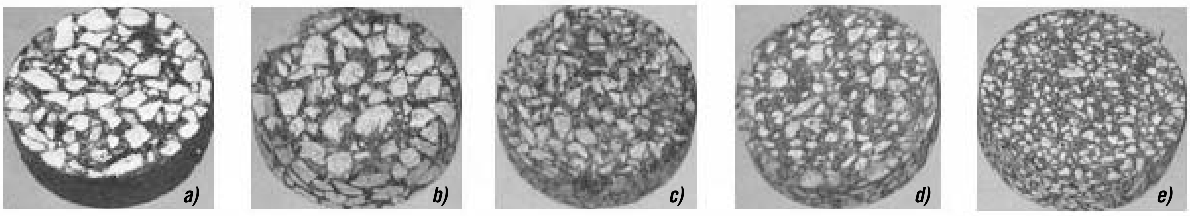


Fig. 7. Samples (D = 100 mm) of five different pavements used in the measurements; a) SMA 16 White with white aggregate; b) SMA 16 with slightly reddish aggregate; c) SMA 8 Grey, quiet asphalt with greyish aggregate; d) SMA 8 Hiltti, quiet asphalt; e) SMA 6

The results with the red target indicate that red colour, unlike green and blue, does have an effect on the relative visibility of targets in HPS illumination. When the luminance contrasts of the achromatic and the red target were almost the same, the red target was rated as slightly more visible than the achromatic target by 83 % of the subjects. 17 % of the subjects were of the opinion that the red target was substantially more visible than the achromatic target. At the viewing distance of 83 m, the effect of red colour on target visibility decreased slightly. When the luminance contrast of the achromatic target was lowered from C = –0.64 to C = –0.69, the subjects found it hard to define which target was more visible than the other and there seemed to be large variation in the views. The results in the HPS installation indicate that red colour partly loses its efficiency in making the targets visible when illuminated with HPS lamps.

When the HPS installation was dimmed to 15 % of the maximum light output, the effects of colours on target visibility were unsubstantial and all coloured targets were basically seen as achromatic having certain luminance contrasts against the background.

After the visibility experiments subjects were asked which road lighting installation they preferred better (100 % lumen output). 67 % of the subjects preferred the MH lamp illumination more than the HPS lamp illumination. The main reason was the light colour temperature which for MH installation was rated as more natural and pleasant. 17 % of the subjects preferred lighting conditions caused by HPS installation because the HPS lamp illumination was familiar and the light was warmer compared to the MH lamp illumination. 17 % of the subjects could not justify which road lighting installation they preferred better.

The results of visibility experiments show that colours have a major effect on target visibility if the road is illuminated with a light source with adequate colour rendering properties. The results indicate that in MH lighting conditions the target visibility is not only defined by luminance contrast but rather by the combination of colour contrast and luminance contrast. It can also be argued that the combination of colour and luminance contrast seems to be a good way of revealing targets on a road surface.

Under MH lamp illumination, at a viewing distance of 50 m, all coloured targets were substantially or slightly more visible than the achromatic targets despite the fact that the luminance contrasts of both targets were approximately the same. Dimming and the increase of the viewing distance decreased the effects of colours on target visibility. When the luminance contrasts of the achromatic targets were higher compared to the luminance contrasts of the coloured targets, the coloured targets were still rated as more visible than the achromatic targets. Under HPS lamp illumination only red colour had an influence on the visibility of the target.

Generally, colour discrimination is best in the fovea and decreases toward the periphery, where there are fewer cones. However, colour discrimination for very small fields (1/3 º or less) presented to the fovea is not so good, because there are very few short wavelength cones in the middle of the fovea [IESNA 1993]. When the viewing distance increases, the size of the target presented to the fovea decreases and this might be one possible explanation why the increase of the viewing distance decreased the effects of colours (especially blue colour) on visibility of target.

The results of this paper suggest that especially red colour has a significant effect on target visibility. One explanation for this might be that the red colour is usually experienced as a strong stimulus and also because the red colour is commonly used as a negative colour for traffic signs and traffic lights. Green colour had the lowest effect on target relative visibility, which might be partly due to the use of green colour as a positive colour for traffic lights.

As expected, colours had more significant effect on target visibility when illuminated with MH lamps compared to the HPS lamps.

4. EFFECTS OF AGGREGATE TYPE ON PAVEMENT REFLECTANCE PROPERTIES

4.1. Measurements

In this paper eight, different pavements were measured to study the effects of aggregate lightness and aggregate colour on spectral reflectance properties of the pavements. Also relative luminances of the pavement samples were investigated and two different light sources and four different lighting conditions were used in the measurements: two light spectra HPS/MH and two dimming levels of the lamps. The Prall method, which follows the European standard EN 12697–16, was used for the wearing of the pavement samples [EN 2004]. The pavements used in the measurements were stone mastic asphalt (SMA) pavements. SMA pavement has a high coarse aggregate content that interlocks to form a stone skeleton that resists permanent deformation. The stone skeleton is filled with mastic of bitumen and filler to which fibres are added to provide adequate stability of bitumen and to prevent drainage of binder during transport and placement. Typical SMA composition consists of 70−80% coarse aggregate, 8−12% filler, 6.0−7.0% binder, and 0.3% fibre [Troutbeck 2005]. The main purpose of the SMA pavement is to provide a deformation resistant, durable surfacing material, suitable for residential streets and highways.

For each pavement two samples (100 mm in diameter) were measured. Fig. 7 shows five different pavements used in the measurements. The measured pavements varied in aggregate lightness, colour and size.

The measurements were made using spectroradiometer CS-2000. The measurement angle between the sample and the spectroradiometer was set to 30° (α= angle of observation) and the measurement area covered most of the sample area [Gibbons 1997]. The spectroradiometer was placed on the same longitudinal axis as the pavement samples. The measurements were made using different values of β=90 °, 55 °, 35 °, 25 °, 20 °, 13 ° (angle between vertical plane of incidence and vertical plane of observation) and γ=50 °, 46 °, 40 °, 35 °, 30 °, 25 °, 20 °, 13 ° (angle of incidence from the upward vertical) [CIE 1984, Crabb 2005].

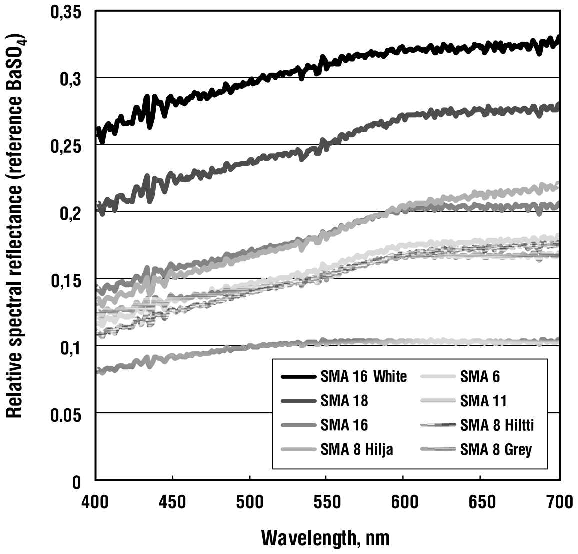


Fig. 8. Relative spectral reflectances of eight different pavements measured under the MH lamp spectrum (Fig. 1 a). White barium sulphate surface (ρ = 0.97) with homogeneous spectral reflectance was used as a reference. The angles β and γ were set to 90 ° and 25 °

During the measurements only one luminaire was on. White barium sulphate surface (ρ= 0.97) with homogeneous spectral reflectance was used as a reference. The measurement accuracy of the spectroradiometer CS-2000 is ± 2 % [Konica 2008].

4.2. Results

Fig. 8 shows the measured spectral reflectances of the pavements. For the most of the measured pavements the relative reflectances were higher for the long wavelength region. The results suggest that light sources with high output in the long wavelength region (for example HPS lamps) are more effective compared to ones with high output in the short wavelength region.

As shown in Fig. 8 *SMA 16 White* with white aggregate resulted in highest relative spectral reflectance. For *SMA 16 White* the reflectance values were higher for the long wavelength region, partly because of the fact that fine aggregate used for the pavement was reddish. When compared to the *SMA 16* with the same aggregate size, *SMA 16 White* resulted in significantly higher spectral reflectance due to differences in the aggregate lightness. *SMA*

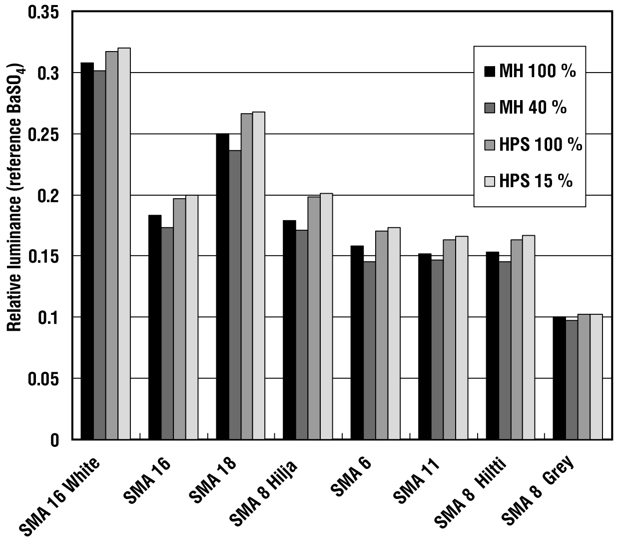


Fig. 9. Relative luminances of eight different pavements. White surface (barium sulphate) with reflectance of 0.97 was used as a reference. Relative luminances were measured in four different lighting conditions. MH – metal halide lamp, HPS – high pressure sodium lamp. The angles β and γ were set to 90 º and 25 º

16 represent quite common aggregate type (lightness and colour) used for road pavements in Finland. Thus the results suggest that by using the white aggregate instead of conventionally used aggregate types, significantly higher road surface luminances could be achieved with the same road lighting energy consumption.

SMA 18 with light aggregate resulted in the second highest spectral reflectance. Also for *SMA 18* the relative reflectance values of the long wavelength region were higher compared to those of the short wavelength region. For the noise reducing quiet asphalt *SMA 8 Hilja* the relative reflectance was similar to the *SMA 16*. However, for *SMA 8 Hilja* the shape of the relative spectral reflectance curve was different compared to the *SMA 16* due to differences in the aggregate colour. *SMA 6, SMA 11* and quiet asphalt *SMA 8 Hiltti* all had very similar spectral reflectances. The noise reducing quiet asphalt *SMA 8 Grey* had very low relative spectral reflectance values. Because of the grey aggregate the *SMA 8 Grey* also resulted in somewhat uniform spectral reflectance over all wavelengths.

Fig. 9 shows relative luminances of the pavements measured in four different lighting conditions. The results show that the same pavement can result in different road surface luminance values under various light sources with various light spectra. As expected, for the most of the measured pavements relative luminances were higher when illuminated with HPS lamp compared to the MH lamp. When the MH lamp was dimmed to 40 % of the lumen output, the relative luminances of the pavements decreased but when the HPS lamp was dimmed to 15 % of the lumen output, the relative luminances increased. This was due to the changes in light spectra (Fig. 1) and due to the spectral reflectance properties of the pavements.

No significant variations were found in the shapes of the relative spectral reflectance curves between samples of the same pavement type. However, there were some minor variations in the reflectance values of these samples. In calculating the pavement relative luminances one sample was used for each pavement type (Fig. 9).

The pavement samples of *SMA 16 White* had 3 % higher relative luminances when illuminated with HPS lamp compared to the MH lamp. When the MH lamp and HPS lamp were dimmed, the relative luminances were 6 % higher for the HPS illumination. As shown in Fig. 9 *SMA 16 White* had significantly higher relative luminances than the other pavements. The relative luminance of *SMA 16 White* was 68 % higher than the relative luminance of *SMA 16* when illuminated with MH lamp, and 61 % higher when illuminated with HPS lamp. When compared to the *SMA 8 Grey, SMA 16 White* resulted in three times higher relative luminances (Figs. 7 a, 7 c). This means that if *SMA 8 Grey* is used for road pavement, luminaires would have to produce three times more light to achieve the same luminance levels on the road surface as in the case with *SMA 16 White* pavement.

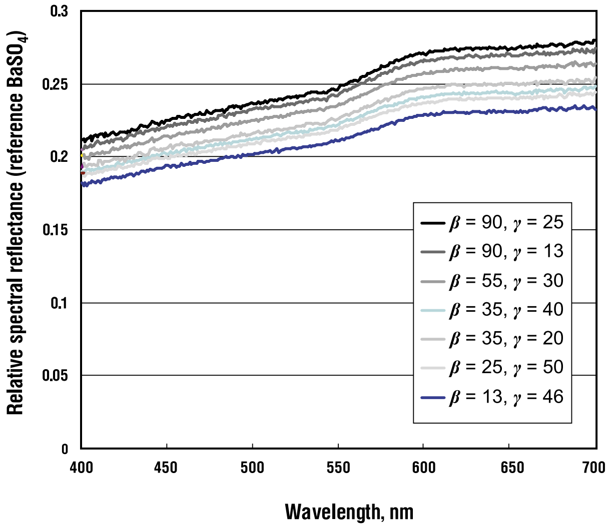


Fig. 10. Relative spectral reflectances of SMA 18 sample measured with different β and γ values. White barium sulphate surface with reflectance of 0.97 was used as a reference

In the case of *SMA 16* the relative luminance was 8 % higher when illuminated with HPS lamp compared to the MH lamp. When the light sources were dimmed the relative luminance was 16 % higher when illuminated with HPS lamp (15 % lumen output) compared to the MH lamp (40 % lumen output). For *SMA 18*, the corresponding values were 6 % and 14 %. The relative luminances of the *SMA 8 Hilja* varied the most and the relative luminances of the sample were 11 % and 18 % higher when illuminated with HPS lamp compared to the MH lamp. The relative luminances of *SMA 8 Grey* did not change significantly in various lighting conditions.

The pavement samples were measured using different β and γ values. Fig. 10 shows an example of relative spectral reflectance variations of SMA 18 sample in relation to the parameters β and γ. As shown in Fig. 10 there were no significant changes in the shapes of the relative spectral reflectance curves of the pavement samples. However, the reflectance values and the total reflectances of the pavement samples varied significantly depending on the β and γ values. This means that the spectral reflectance properties of the pavement remain relatively the same but the total reflectance of the pavement changes in relation to the position of the light source relative to the road surface point under consideration.

The pavement measurements in this paper indicate that the aggregate lightness and the lightness of the pavement are very important factors in road lighting design. Also, the aggregate colour seems to have a major effect on road lighting performance. It can be argued that road pavement is a very important parameter in optimization and development of road lighting energy efficiency. Thus more extensive cooperation between road administration authorities and road lighting experts is needed in order to be able to efficiently optimise road lighting performance.

5. SPECTRAL TRANSMITTANCE OF VEHICLE WINDSHIELD

One important factor, which is usually not considered in the road lighting design and practice, is the spectral transmittance of the vehicle windshield. In driving, most of the visual information is gained through a windshield of a vehicle. Thus the spectral transmittance of vehicle windshield affects the visibility conditions of the driver. Fig. 11 shows the spectral transmittance curves for four different windshield types used in Europe. Windshields A, B & C are green tinted windshields while IRR Windshield is an infrared reflective (IRR) type windshield with a metallic coating [Bolton 2008]. As shown in Fig. 11 spectral transmittances of different windshields are not homogeneous for various wavelengths. For all four windshields types the transmittance values are the highest for the green and the yellow wavelength regions. For the green tinted windshields (Windshields A, B & C) the transmittance value decreases significantly in the long wavelength region, while for the IRR Windshield the change in the transmittance value is lower. It can be argued that such variations in the transmittance values for

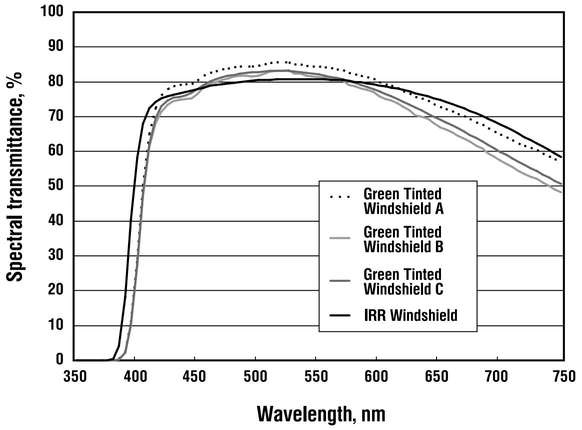


Fig. 11. Spectral transmittances of four different vehicle windshield types [Bolton 2008]

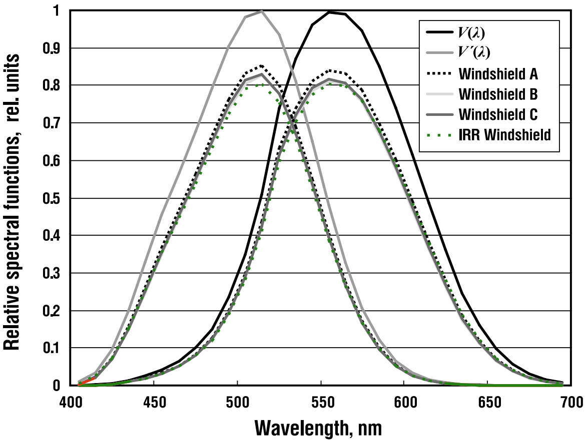


Fig. 12. Spectral sensitivities of the eye V (*λ*) and V' (*λ*) (photopic and scotopic vision) and spectral transmittances of four different vehicle windshield types multiplied by the V (*λ*) and V' (*λ*) functions

different wavelengths have a significant effect on driver's visibility in different road lighting conditions. In reality, also such factors as the cleanliness of the windshield and the inclination of the windshield in relation to the driver affect the transmittance properties of the vehicle windshield.

Fig. 12 shows the spectral transmittances of the same vehicle windshield types, shown in Fig. 11, multiplied by the V (*λ*) function (spectral sensitivity of the eye, photopic vision) and the V' (*λ*) function (spectral sensitivity of the eye, scotopic vision). The results represent the total spectral transmittances of the windshields as perceived by the driver. The results show that in photopic vision the Windshield B, Windshield C and IRR Windshield result in very similar transmittance curves despite the differences in the transmittance values shown in Fig. 11. The Windshield A results in slightly higher transmittance values for the green and the yellow wavelength regions compared to the other windshield types. In scotopic vision, some variations between different windshield types occur for the bluish and the green wavelength regions.

In photopic vision, if compared to the V (*λ*) curve, the total spectral transmittance curves of the windshields are slightly shifted towards the short wavelength region (Fig. 12). In scotopic vision similar but reversed effects appear and the spectral transmittance curves of the windshields are slightly shifted towards the long wavelength region. According to these results, it can be argued that spectral transmittances of the windshields are well optimized for the mesopic light levels, which lie between the photopic light levels and the scotopic light levels [Viikari 2008].

The effect of vehicle windshield transmittance was not included in the experiments for this paper because of the limited dimensions of the underground tunnel entrance. This can be defined as a major lack of the experiments and measurements. The spectral transmittance of vehicle windshield affects the visibility of coloured targets, the visibility conditions of the driver in different lamp type and road surface conditions, and finally also the mesopic visual performance. Thus the effect of vehicle windshield and possible variations of windshield spectral transmittance values should also be considered in evaluating the visibility conditions for drivers.

6. DISCUSSION

The visibility experiments indicate that colours have a high impact on target visibility if the road is illuminated by light sources with good colour rendering properties. It is, however, very difficult to determine how these effects relate to the safety of the driver in various traffic conditions. It is not known whether the use of light sources with good colour rendering properties can actually reduce traffic accident rates by improving the visibility of coloured targets. A number of extended field measurements and traffic statistics are needed in order to determine the overall effects of colours and colour contrasts on target visibility in road lighting environments. However, it is obvious that with the further development of road lighting it cannot be assumed anymore that targets located in the road are always achromatic and visible to the driver only because of the adequate luminance contrast.

One major problem of these kinds of visibility experiments is that it is not precisely known what targets are likely to appear in the road and which targets are critical for the safety of the driver. In driving, luminance and colour contrasts of targets are changing constantly and the target cannot be expected to be stationary. Visual targets may also have non-uniform luminance and colour contrasts against the background.

The road lighting conditions used in the visibility experiments are partly different from actual road lighting conditions. The geometry of both road lighting installations was limited by the dimensions of the underground tunnel and thus the pole spacing and the pole height were smaller compared to the commonly used values in road lighting design. However, road surface average luminances and luminance uniformities were adjusted to represent quite common road lighting conditions (MH: average luminance 1.35 cd/m^2, overall luminance uniformity 0.40, longitudinal luminance uniformity 0.61, HPS: average luminance 1,71 cd/m^2, overall luminance uniformity 0.38, longitudinal luminance uniformity 0.59) [EN 2003]. The road surface of the tunnel consisted of coarse sand, which differs from the commonly used road surface pavements in colour and reflection properties (Fig. 5).

Small Target Visibility design described in the American National Standard for Roadway Lighting is based on visibility of 18 cm x 18 cm achromatic small targets with reflection factor 0.50 [IESNA 2005]. Similar achromatic flat surface targets with different reflection factors were also used as the basis of the present road lighting recommendations [De Boer 1967]. However, the experimental results of this paper indicate that when a coloured target is placed in the road, the visibility of such target is not necessarily the same compared to the similar achromatic target with the same luminance contrast. The question is whether it can be assumed that colours have only positive effect on target visibility and that coloured targets are always more visible compared to achromatic targets if the luminance contrasts of the targets are the same? If this is true, it can be concluded that if the road lighting conditions are adequate for the driver to see an achromatic target, they will also be able to see a coloured target.

In Finland the use of white aggregate for road pavements is rather expensive and may result in triple aggregate costs. This is mostly due to the fact that white aggregate has to be imported from other countries, for example Norway. In assuming that aggregate costs are about 15 % of the total pavement and paving costs, the white pavement would result in about 30 % higher total expenses compared to the conventional pavements. However, at the same time it may be possible to save more than 50 % of road lighting energy consumption by using white pavement instead of conventional pavements. In addition, such energy savings could be achieved basically for the whole lifetime of the pavement.

Yet, despite the high energy saving potential of light pavements, there are two major problems concerning the use of pavements with white aggregate in Finland. First of all, in Finland, white aggregates with suitable quality properties for pavement use are very rare. Secondly, the use of studded types at winter time sets very high wearing requirements on the pavements and thus not all white aggregates are suitable for the pavement use.

One potential extension scenario for pavement measurements presented in this work would be to study the reflectance properties of wet pavement surfaces. The pavement samples used in the measurements were also quite clean, while in reality such factors as dirt, gravel and rubber affect the reflectance properties of the road surface. Thus the pavement measurements should be made on real roads, which are used by traffic. Pavement measurements should also be made in different seasons to be able to study the actual effects of studded tyres on the reflectance properties of pavements. Also the effect of vehicle windshield on drivers' visibility should be considered in the measurements.

7. CONCLUSIONS

The results of visibility experiments show that in road lighting environments colours have a major effect on target visibility in road lighting with lamps of adequate colour rendering properties. Thus in road lighting design it cannot always be assumed that targets on the road are visible to the driver only because of the adequate luminance contrast but colour contrasts should also be considered in the development of road lighting design criteria.

Colours have clearly a more significant effect on target visibility when illuminated with MH lamps compared to HPS lamps. Dimming and the increase of the viewing distance decreased the effects of colour on target relative visibility.

The results of pavement measurements indicate that aggregate's colour, and especially, aggregate's lightness, have a significant effect on pavement reflection properties. Stone mastic asphalt sample with white aggregate resulted in significantly higher reflectance compared to the other pavement samples. Thus it can be argued that the aggregate lightness and the lightness of the pavement are very important factors in road lighting design. For the most of the measured pavements the relative reflectances were higher for the long wavelength region. When the MH lamp was dimmed the relative luminances of the pavements decreased but when the HPS lamp was dimmed the relative luminances increased. The results suggest that due to the higher content in the long wavelength region HPS lamps are more effective than MH lamps in terms of light reflected from the pavements.

Combining the results of this paper together leads to a very complex interaction between the visibility of coloured targets, the road surface reflection properties, the spectral transmittance of the vehicle windshield and the visual performance at mesopic light levels. All these factors have their own effects on road lighting performance. Overall, it can be concluded that MH lamps perform better in revealing coloured targets on the road compared to the HPS lamps. MH lamps are also more effective at mesopic light levels than the HPS lamps. However, it is worth noticing that mesopic vision is highly dependent on the viewing eccentricity (foveal and peripheral vision) and the prevailing lighting levels. HPS lamps, on the other hand, are usually more effective than the MH lamps due to the pavements' higher reflectance for the long wavelength region.

The spectral characteristics and the lightness of the road surface also have an effect on the visibility of coloured targets and mesopic vision. The colour and the lightness of the pavement affect luminance and colour contrasts of targets and thus play a role in defining the target visibility. At the same time, the reflectance properties of the pavement or the road surroundings define the light spectra of the light reflected from the surface and thus have effect on the mesopic calculations and visual performance at the mesopic light levels. Also the transmittance of the vehicle windshield and changes in spectrum of the transmitted light has an effect on the visual performance. Mesopic vision on the other hand affects the visibility of the coloured targets but not in foveal vision. Finally, all these factors are highly dependent on the prevailing weather conditions. Thus a large number of extended field measurements and experiments are needed in order to determine the overall effects of colour contrast and pavement aggregate type on road lighting performance.

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REFERENCES

1. Bolton, C., 2008, *Windshield spectral transmittance*, Pilkington Automotive, email correspondence [received 2.6.2008].
2. CIE Commission International de l'Éclairage, 1984, *Road surfaces and lighting*, Tecnical report CIE/PIARC, CIE Publication No 66, Paris, France.
3. CIE Commission International de l'Éclairage, 1982, *Calculation and measurement of luminance and illuminance in road lighting*, Technical report Pub. CIE N°. 30–2 (TC – 4–6), Paris, France.
4. Crabb, G.I., Beaumont, R.J., Steele, D.P., Darley, P., Burtwell, M.H., 2005, *Visual performance under CMH and HPS lighting systems,* NumeLiTe project final report, PPR043, TRL Limited.
5. De Boer, J.B., 1967, editor, *Public lighting*, Eindhoven, Philips Technical Library.
6. Eloholma, M., 2005, *Development of visual performance based mesopic photometry*, Doctoral Thesis, Helsinki University of Technology, Lighting Laboratory, Espoo, Finland.
7. European standard EN 12697–16, 2004, *Bituminous mixtures. Test methods for hot mix asphalt. Abrasion by studded tyres*, Standard. No EN 12697–16:2004.
8. European standard EN 13201–2, 2003, *Road lighting – Part 2: Performance requirements,* Publication 269–2003. Ref. No. EN 13201–2:2003 E. 16 p.

9. Gibbons, R.B., Adrian, W.K., 1997, *Influence of Observation Angle on Road Surface Reflection Characteristics*, Journal of the Illuminating Engineering Society, Vol. 26, No 2, pp. 139–149.

10. Güler, Ö., Onaygil, S., 2003, *The effect of luminance uniformity on visibility level in road lighting*, Lighting Res. Technol. 2003; 35: pp. 199–215.

11. Hansen, E., Larsen, J., 1979, *Reflection factors for pedestrian's clothing,* Lighting Res. Technol. 1979; 11: pp. 154–157.

12. Illuminating Engineering Society of North America (IESNA), 2005, *Roadway Lighting,* RP-8–00, American National Standard Practise for Roadway Lighting, New York, United States of America.

13. Illuminating Engineering Society of North America (IESNA), 1993, *Lighting Handbook. Reference & Application,* Eighth Edition, New York, United States of America.

14. Konica Minolta, 2008, *Spectroradiometer CS-2000*, Catalogue, http://www.konicaminolta.com/.

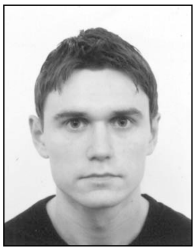
15. Narisada, K., Karasawa, Y., 2007, *New method of road lighting design based on revealing power*, 26 th Session of the CIE, July 4–11, 2007, 1 C-P7, Presented paper, D: 10–13, Beijing, China.

16. Smith, F., 1938, *Reflection factors and revealing power*, Trans. Illum. Eng. Soc. (London), *3,* pp. 196–206.

17. Troutbeck, R., Kennedy, C., 2005, *Review of the use of Stone Mastic Asphalt (SMA) surfacings by the Queensland Department of Main Roads,* Report, Australia.

18. Van Bommel, W.J.M., de Boer, J.B., 1980, *Road Lighting*, Eindhoven, Philips Technical Library.

19. Viikari M., Ekrias A., Eloholma M., Halonen L., 2008, *Modelling spectral sensitivity at low light levels based on mesopic visual performance,* Clinical Ophthalmology, Vol. 2, No 1, pp. 173–185.



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