MEASURED AND MODELLED CONTRIBUTIONS TO UV EXPOSURES BY THE ALBEDO OF SURFACES IN AN URBAN ENVIRONMENT

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Summary
The increases in the erythemal UV exposures to horizontal planes and to inclined planes over three surfaces that are found in an urban environment (water, concrete and sand) due to the albedo of these surfaces have been estimated. For the cloud free case, the additional daily estimated UV exposures to a horizontal plane have a maximum value of 222 $(J\ m^{-2})_{ER}$, where the index after the unit is there to indicate that it refers to a biologically effective exposure. In comparison, the daily erythemal UV exposures over a year to a horizontal plane ranged from 425 to 8,321 $(J\ m^{-2})_{ER}$. For a vertical receiving plane that is rotating about a vertical axis, the additional erythemal daily UV exposures for the sub-tropical latitude location of this research for the ranges of solar azimuth angles encountered over the days in each season ranged from 16 to 311 $(J\ m^{-2})_{ER}$, 29 to 566 $(J\ m^{-2})_{ER}$ and 46 to 905 $(J\ m^{-2})_{ER}$ for water, concrete and sand respectively. The estimated error is ±20% and the calculations are based on clear-sky conditions. The additional erythemal UV averaged over each of the seasons was higher for the receiving plane inclined at 45^{o} below the horizontal plane. In a similar fashion, the vertical surface has the higher additional erythemal UV exposures compared to the surfaces inclined at an angle above the horizontal.

Introduction

The albedo of ground covering, generally expressed as a ratio of the upwelling irradiance to the downwelling irradiance (McKenzie et al., 1996) contributes to the total ambient solar UV radiation. The UV irradiance to a receiving surface has a portion resulting from surface reflected radiation that is scattered back by the atmosphere to a receiver plane on the surface (McKenzie et al., 1996). The albedo in the UV waveband over different ground cover surfaces has been measured to range from 0.02 for grass to more than 0.8 for snow (Blumthaler and Ambach, 1988; McKenzie et al., 1996; Feister and Grewe, 1995). Additionally, the albedo of metallic roofing material has been found to range from approximately 0.04 to 0.3 (Lester and Parisi, 2002). Consequently, the albedo of the surfaces encountered during the occupational, non-occupational and recreational activities of humans contributes to the solar UV exposure of humans. The UV exposures are due to the direct and the diffuse component. The diffuse component is due to that scattered from the atmosphere, $Diffuse_{sky}$ and additionally that reflected from the ground surface, $Diffuse_{reflected}$. This diffuse component is higher in the UV waveband compared to the visible due to the higher degree of Rayleigh scattering at shorter wavelengths. Additionally, the presence of any cloud will increase the relative amount of this component compared to the direct.

The majority of the previous research on the effect of albedo has been for horizontal surfaces only. For example, the influences of snow covered surfaces on the UV irradiances to a horizontal plane have been investigated (Weihs et al., 1999; McKenzie et al., 1998; Kylling et al., 2000). However, in addition to horizontal surfaces, organisms also have surfaces orientated at any angle to the horizontal and at any azimuth angle. The influence of the ground topography on the UV exposures was investigated for inclined planes over high albedo ground surfaces (Weihs, 2002). The UV irradiances on vertical surfaces (Webb et al., 1999) and surfaces normal to the sun have been reported (Parisi and Kimlin, 1999; McKenzie et al., 1997; Parisi et al., 2001).

Surfaces normal to the sun were investigated by Philipona et al. (2001) who derived an empirical relationship relating solar UV on a horizontal plane to the solar UV on a surface normal to the sun as a function of the surface albedo and solar elevation. Non-horizontal surfaces at angles other than normal to the sun have been investigated for vertical, hemispherical, spherical, conical and pinnacle surfaces (Schauberger, 1990, 1992; Parisi and Wong, 1994, 1996, 1997; Parisi et al., 1996). Depending on the solar zenith angle (SZA), there can be significant differences in the irradiances to these non-horizontal surfaces compared to those received by a horizontal surface.

In an urban environment, the effect of surface reflectivity on non-horizontal receiving surfaces was investigated over roofing materials with polysulphone dosimeters attached to different sites on a model of a human face (Lester and Parisi, 2002). Schauberger (1990) provided the relative irradiances of the UV exposures on inclined surfaces over ground surfaces with albedos ranging from 0 to 0.8.

This present paper extends this previous research to consider the influence on the absolute UV irradiances of the UV exposures to receiving surfaces at different angles to the horizontal due to the albedo of common surfaces encountered in an urban environment, namely water, sand and concrete. This has been done by measuring the erythemal UV on a horizontal plane. If the receiving surface was inclined at different angles to the horizontal and over the different albedo surfaces, a semi-empirical model was employed to calculate the change in these irradiances.

Methods

Measurement of Erythemal UV

The ambient erythemal UV exposures on a horizontal plane were measured with a UV meter (model 501, Solar Light Co., Philadelphia, USA) in Toowoomba, (27.5°S, 151.9°E, 693 m above sea level), Australia. This meter was used to monitor the ambient UV exposures and is mounted on a horizontal unshaded plane on the edge of a building roof and records the erythemal exposures for every 15 minute interval of the day. The surface surrounding the instrument is a combination of surfaces found at a typical university campus, for example building roofs, concrete, grass. This data was measured for the period of a year from 1 January 2000 to 31 December 2000. The meter was calibrated in summer and winter, by measuring and weighting the solar spectrum with the erythemal action spectrum (CIE, 1987) between early morning and noon (SZA range 6^{o} to 66^{o}), against a calibrated dual grating spectroradiometer. During the calibrations the skies were relatively clear. The spectroradiometer was irradiance calibrated against an irradiance standard and wavelength calibrated against the UV spectral lines of a mercury lamp for each series of measurements. The error in the measured erythemal broadband exposures was at best ±10%.

UV on a Horizontal Plane

In clear sky conditions, the direct component of the UV on a horizontal plane is highly influenced by the SZA. Additionally, the diffuse component is affected by both the direct reflection from the ground surface and the multiple reflections between the surface and the atmosphere. The global solar UV spectral irradiances on a horizontal plane for clear sky days have been modelled using the Rundel (1986) formulation of the Green et al., (1980) and Schippnick and Green (1982) models. A full radiative transfer model was not used, as additional reductions in uncertainty were not significant compared to the uncertainty of the broadband equipment used in this project. Comparison of the equations of Green et al., (1980) and Schippnick and Green (1982) with a discrete ordinate method radiative transfer model has shown deviations of less than 10% for solar zenith angles less than 50^{o} and higher than 10% for higher zenith angles (Weihs and Webb, 1996).

The clear-sky model was run with an ozone column level of 300 DU and respective albedos of 0.02, 0.075, 0.12 and 0.18 for grass (Feister and Grewe, 1995), water (Madronich, 1993), concrete (Feister and Grewe, 1995) and sand (Feister and Grewe, 1995) for Toowoomba, (27.6^{o}S, 151.9^{o}E, 693 m above sea level) Australia. The model calculates, for each 15 minutes, the erythemal irradiances (CIE, 1987) and the broadband irradiances (Downs et al., 2000). These are summed using the trapezoidal rule to calculate the modelled daily erythemal and broadband UV exposures.

The erythemal exposures calculated by the model have been compared to those measured by the calibrated erythemal UV meter. The comparison was made for cloud free days in the middle month of each season. The slope of the fitted regression line to a plot of modelled versus measured exposures was higher than 1 by 5%. Based on the variations between the measured and modelled clear sky erythemal exposures, the error in the modelled clear sky erythemal exposure compared to the UV meter is of the order of ±10%.

The UV exposures received by a horizontal plane for the respective albedos have been calculated with the model and summed to provide the daily exposures. The exposures over the water, concrete and sand have been compared to those over the grass surface in order to calculate the percentage differences in the exposures received by a horizontal plane over each of the surfaces compared to those over grass. These exposures are for a cloud free day. On a cloudy or partially cloudy day, the component scattered back to ground level by the atmosphere is higher. Consequently, the calculated percentage differences represent the lower limit. These percentages have been applied to the measured daily UV exposures to calculate the additional daily erythemal UV exposures received by a horizontal plane over these surfaces. This calculation has the assumption that the erythemal UV exposure measurements with the UV meter are over a grass surface. As mentioned previously, there are a number of surfaces where the instrument is located. However, the aim is to determine an indication of the absolute values of the differences in exposures between objects over grass, water, concrete and sand and the error introduced by assuming that the measured horizontal plane erythemal exposures are over grass is approximately 1 to 3% as seen in the Results section where the effect of ground surface on horizontal plane exposures is considered.

UV on a Non-Horizontal Plane

The erythemal UV exposures to surfaces at inclinations other than horizontal have been calculated using the model of Schauberger (1990). These calculations assume isotropic reflection from the surfaces and isotropic scattering from the atmosphere. In this model a surface at fixed angles of inclination and rotating around a vertical axis are considered. This allows the approximation of a surface moving at random. For an inclined receiver plane the relative erythemal UV irradiance compared to that on a horizontal plane is (Schauberger, 1990):

$$UV_{rel}(\beta,r) = 0.5*(1+\sin\beta) + 0.5*r*(1-\sin\beta) - 0.18*(1-r)*\cos^2\beta \qquad (1)$$

where β is the angle between the horizontal and the normal to the receiving surface and r is the albedo of the surface between 0 and 1. Schauberger (1990) developed this model by measuring the UV irradiances to 26 differently orientated planes at 33 different measuring sites for a variety of albedo, cloud cover and cloud intensity. The differences over each of the surfaces are calculated as a percentage and the difference in percentages between the surfaces are calculated and multiplied by the exposures on a horizontal plane to calculate the absolute differences in exposures over the surfaces for the different inclinations.

Results

Daily Erythemal UV

The erythemal UV measured on a horizontal plane for each 15 minute interval of the day has been summed to provide the daily totals of the erythemal UV for the year 2000 in Figure 1. Day 1 is the 1st January, 2000. The daily erythemal UV ranges from 1,745 to 8,321 $(J\ m^{-2})_{ER}$ in summer (December to February) and 425 to 3,723 $(J\ m^{-2})_{ER}$ in winter (June to August).

Horizontal Plane

The modelled daily erythemal UV exposures, received by a horizontal plane for clear skies employing the albedo of grass, water, concrete and sand, have been calculated. For each of the latter three surfaces, the percentage of the additional UV over each surface for clear skies, compared to the grass surface, was calculated. These percentages have been applied to the measured daily UV exposures to calculate the additional daily erythemal UV exposures received by a horizontal plane over these surfaces. This percentage was applied to the daily values of the measured erythemal UV and the calculated amount of additional daily erythemal UV is shown in Figure 2. These additional daily erythemal UV exposures range from a minimum of 3 $(J\ m^{-2})_{ER}$ in winter to a maximum of 222 $(J\ m^{-2})_{ER}$ in summer. These additional UV exposures are 0.7-0.9%, 1.4-1.6% and 2.2-2.7% of the daily erythemal UV for water, concrete and sand respectively. This additional UV exposure is due to the UV reflected from the surface and scattered back to the horizontal plane by the atmosphere and applies for cloud free cases. For cloudy conditions, this enhanced UV exposure has not been determined.

The minimum and maximum of the additional daily erythemal UV exposures to a horizontal plane over each of the surfaces are provided in Table 1 for summer (December to February), autumn (March to May), winter (June to August) and spring (September to November). In summer, the maximum additional UV exposures over concrete are approximately twice that over water. Similarly, for sand, they are approximately three times that over water. This is also the case in autumn, winter and spring.

The calculated additional daily UV exposures have been added to the respective measured UV exposures. The maximum erythemal UV daily totals in each season for each surface are shown in Table 2.

Non-Horizontal Plane

The human form, when placed over a surface, intercepts a portion of the diffuse UV, $Diffuse_{sky}$ and the UV reflected from the surface, $Diffuse_{reflected}$. Additionally, the portion of the direct component that is intercepted depends on the relationship of the azimuth angles of the sun and surface, the SZA and the angle of the intercepting surface. The $Diffuse_{sky}$ and $Diffuse_{reflected}$ are influenced by the albedo of the surface and the inclination angle of the plane. The additional daily erythemal UV enhancements for each of the surfaces compared to that over grass for a vertical plane have been calculated using Equation (1) and are provided in Figure 3. These are 3.7%, 6.8% and 10.9% of the daily erythemal UV for water, concrete and sand respectively.

The estimated additional erythemal UV exposures, averaged over each season, to receiving planes at angles of inclination of 30^o, 45^o, 60^o and 90^o above the horizontal and 45^o below the horizontal for summer, autumn, winter and spring have been calculated using Equation (1) and are provided in Figure 4. In this Figure, the angle of inclination refers to the angle above the horizontal plane (positive) or below the horizontal plane (negative). The error bars represent one standard deviation. The effect of the surface albedo on a non-horizontal plane at angles of 30^o, 45^o, 60^o and 90^o above the horizontal and 45^o below the horizontal has been determined by calculating the relative exposure for each surface. Multiplying this relative exposure with the measured erythemal UV for a horizontal plane provides the erythemal UV received by that inclined surface. This additional erythemal UV for each inclination in Figure 4 has been expressed as a percentage of mean daily erythemal UV for the respective season and provided in Table 3. The percentages are the same for each season.

Discussion

This paper shows that significant additional UV exposures may be received in an urban environment. This paper has estimated the increases in the erythemal UV exposures to horizontal planes and to inclined planes over three surfaces due to the albedo of these surfaces using a model when inclined at an angle. It has been found that the amount of increased UV exposures to the face and eyes is dependent on the type of reflecting surface.

The additional erythemal UV exposures have been calculated for the erythemal exposures that were measured during the year 2000. For the cloud free case, the additional daily estimated UV exposures to a horizontal plane have a maximum value of 222 $(J\ m^{-2})_{ER}$. This is an additional exposure of the order of 1 MED (minimum erythemal dose). The increases in the UV exposures to the horizontal receiving planes over each of the surfaces that have been calculated with the model are higher on cloudy days. However, the data presented in this paper provides the lower limit of the increases that would be expected.

The additional erythemal UV exposures to receiving surfaces on inclined planes have been presented. The error in these exposures is estimated to be of the order of ±20%. This has been estimated as ±10% due to errors in the model for calculation of UV exposures, ±3% due to the assumption that the UV meter is over grass when it is over a number of surfaces and ±7% due to errors in employing the Schauberger (1990) model. This latter figure has been estimated from the standard deviation of the residuals of the calculated values and the measured values (Schauberger, 1990).

For the vertical receiving plane that is rotating about a vertical axis, the additional erythemal daily UV exposures for the sub-tropical latitude location of this research ranged from 16 to 311 $(J\ m^{-2})_{ER}$, 29 to 566 $(J\ m^{-2})_{ER}$ and 46 to 905 $(J\ m^{-2})_{ER}$ (Figure 3) for water, concrete and sand respectively. The largest difference in the additional erythemal

UV between each of the surfaces occurs in the summer months. This is further illustrated in Figure 4 where the additional erythemal UV is presented for the five differently inclined planes. The additional erythemal UV averaged over each of the seasons is higher for the receiving plane inclined at 45^o below the horizontal plane. In a similar fashion, the vertical surface has the higher additional erythemal UV exposures compared to the surfaces inclined at an angle above the horizontal. These are additional UV exposures compared to a plane inclined at the same angle over a lower albedo surface. Specifically, in the case of the plane inclined at -45^o, although there is an increase over the higher albedo surface, it is necessary to note that there is a decrease in the UV exposures to all of the planes inclined at this angle as they face downwards.

Conclusion

The additional erythemal UV exposures over water, concrete and sand increase the cumulative UV exposures to humans over these surfaces compared to a surface with a lower UV albedo. Additionally, it may contribute to cases when sunburn may occur. For each of the surfaces (water, concrete and sand), the maximum daily additional UV exposures for a vertical plane at the sub-tropical site of this research correspond to approximately 1.6, 2.8 and 4.5 MED respectively. The estimated error is ±20% and the calculations are based on clear-sky conditions. This has implications for increasing the skin cancer risk. There are also implications for sun-related eye disorders. The field of view angles for the eye of an upright subject have been reported as 50^o above the horizon to 70-80^o below the horizon (Sliney, 1999). Receiving planes in this field of view will receive additional UV exposures due to the albedo of the urban surfaces considered in this paper. Consequently, these surfaces also contribute to the risks of sun-related disorders such as cataracts, age-related macular degeneration and pterygium.

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Table 1 – The minimums and maximums for each season of the additional daily erythemal UV to a horizontal plane over each of the surfaces.

	Seasonal minimum and maximum additional UV (J $m^{-2})_{ER}$		
	Water	Concrete	Sand
Summer	15-73	28-135	46-222
Autumn	4-55	8-103	12-168
Winter	3-30	6-56	9-91
Spring	16-66	29-122	47-199

Table 2 – The maximum daily erythemal UV to a horizontal plane in each season for each surface.

	Maximum Erythemal daily UV (J m^{-2})$_{ER}$		
	Water	Concrete	Sand
Summer	8394	8457	8543
Autumn	6581	6628	6694
Winter	3754	3779	3815
Spring	7537	7593	7671

Table 3 – The mean additional UV_{ery} from Figure 4 as percentage of the mean daily erythemal UV for the respective season for planes inclined at different angles to the horizontal.

Angle with respect to the horizontal	Additional UV (%)		
	Water	Concrete	Sand
30^o	0.6	1.1	1.8
45^o	1.3	2.4	3.8
60^o	2.1	3.9	6.2
90^o	3.7	6.8	10.9
-45^o	5.2	9.4	15.1

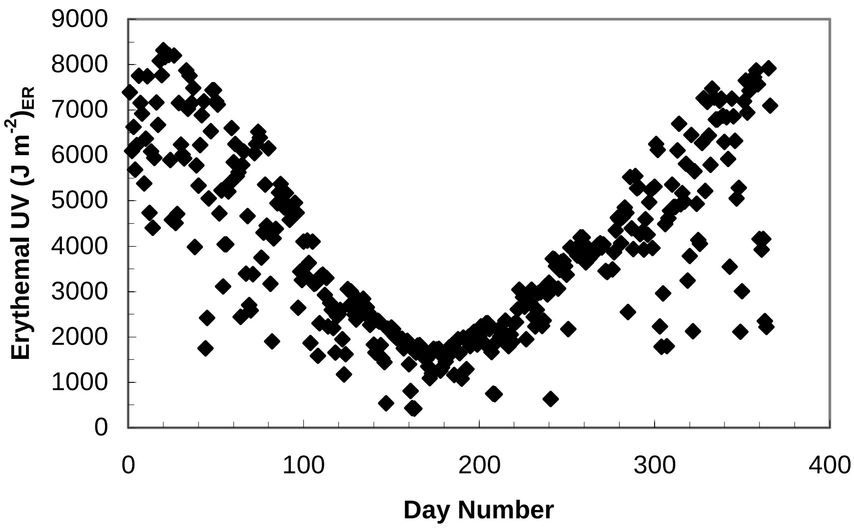
Figure Captions

Figure 1 – The measured daily totals of erythemal UV on a horizontal plane for the year 2000 at a sub-tropical site. Day 1 is the 1st January, 2000.

Figure 2 – The calculated additional daily erythemal UV exposures to a horizontal plane over each of the surfaces based on calculations for clear-sky conditions.

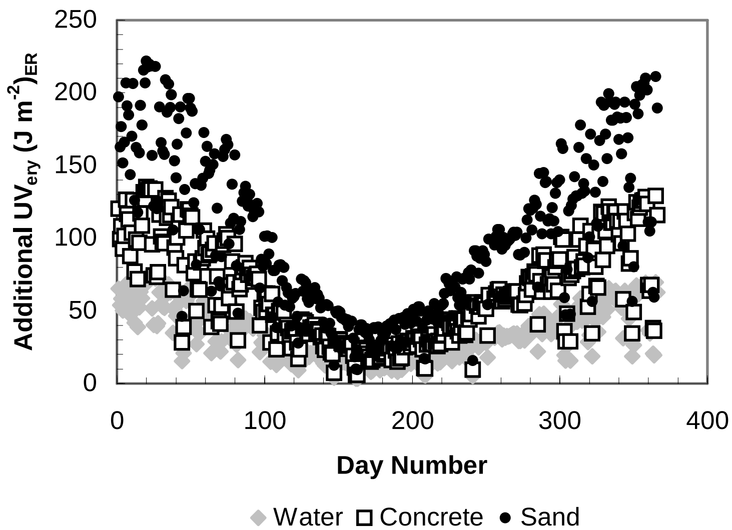
Figure 3 – The calculated additional daily erythemal UV for each of the surfaces compared to that over grass for a vertical plane based on calculations for clear-sky conditions.

Figure 4 - The average of the calculated additional erythemal UV exposures to receiving planes at different angles of inclination (using the model) for (a) summer, (b) autumn, (c) winter and (d) spring. The angle of inclination refers to the angle above the horizontal plane (positive) or below the horizontal plane (negative). The data is for the ranges of solar azimuth angles encountered over the days in each season and based on calculations for clear-sky conditions.



9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Erythemal UV (J m-2)ER
0
100
200
300
400
Day Number

Figure 1


250
200
150
100
50
0
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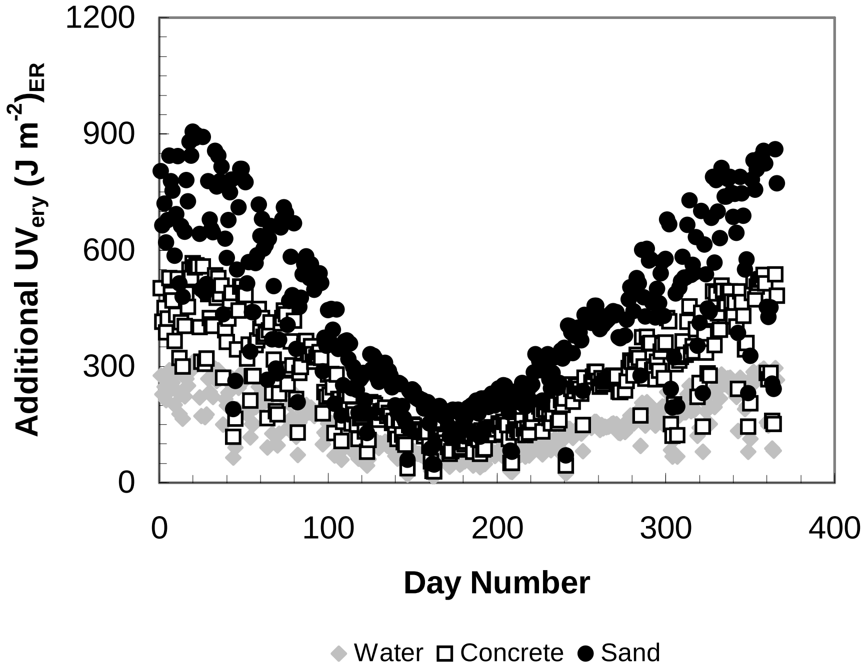
200
300
400
Additional UVery (J m-2)ER
Day Number
Water
Concrete
Sand

Figure 2


1200
900
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400
Additional UV$_{ery}$ (J m^{-2})$_{ER}$
Day Number
Water
Concrete
Sand

Figure 3

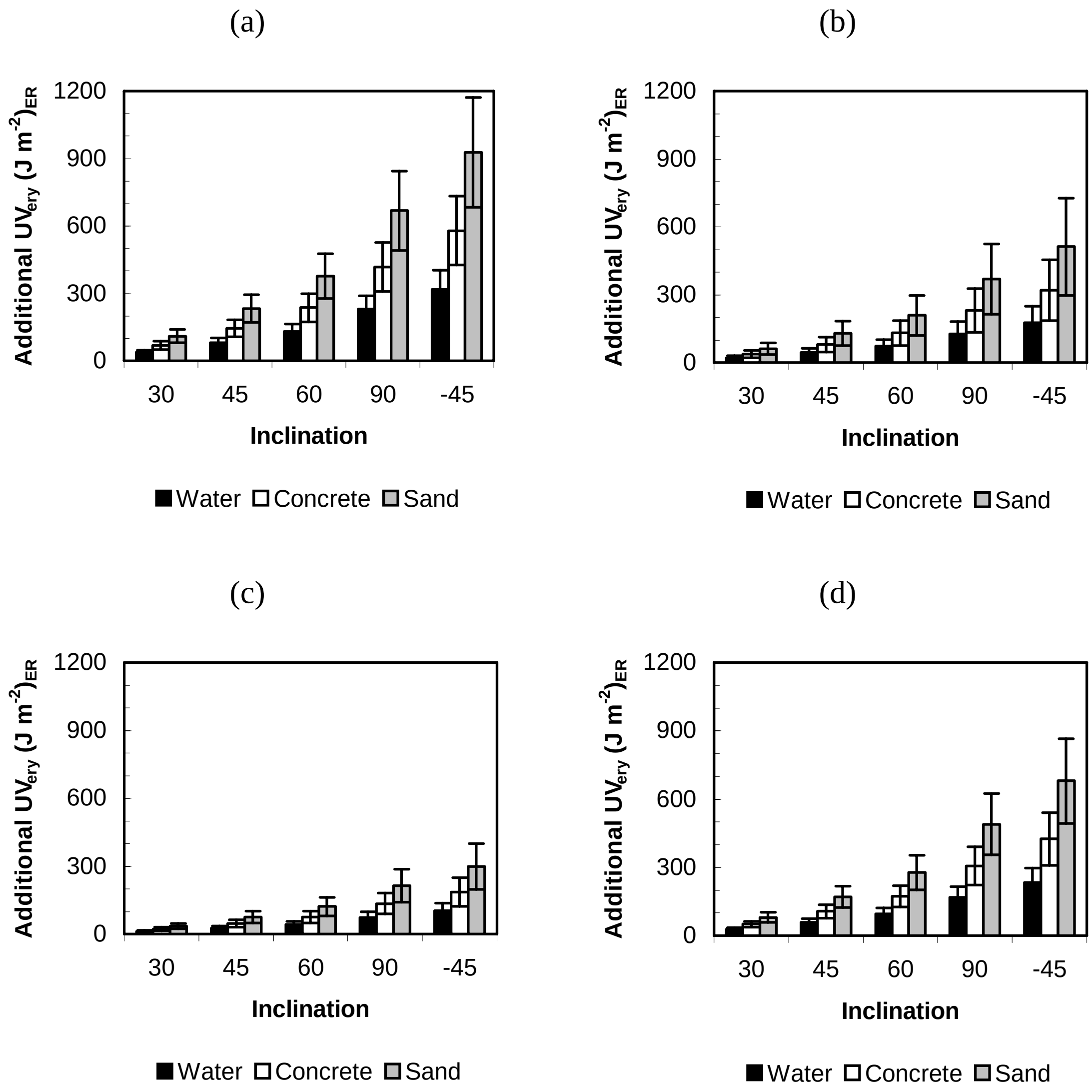
(a)
(b)
(c)
(d)
Additional UV_{ery} (J m^{-2})$_{ER}$
1200
900
600
300
0
30
45
60
90
-45
Inclination
Water
Concrete
Sand

Figure 4