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Bamboo lumber: An innovative sustainable raw material and an accelerated weathering study for establishing its durability

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Abstract

Bamboo lumber was prepared using *Bambusa bamboos* species and its weathering performance was evaluated under natural and accelerated weathering. Specimens of bamboo lumber were exposed to natural weathering for 150 days. Another set of specimens were exposed to UV light source (UVA 360) in accelerated weathering tester up to 250 hours. A comparative study on the level of degradation in natural and accelerated weathering was made by evaluating CIEL*a*b* colour changes measured using a Hunter lab spectro-colorimeter. Rate of color change due to photodegradation were evaluated. Results showed that all three-color axes, viz. L*, a* and b* changed linearly with respect to time under natural exposure, but only L* was changed under accelerated weathering, keeping a* and b* values to be almost constant. Photodegradation of bamboo was mainly due to UV light absorption by chromophores present in the lignin, which constitutes about 32.2% of total bamboo.

Keywords *Bambusa bamboos*; CIELAB color system; photodegradation; sustainable raw material; durability; bamboo lumber; spectro-colorimeter; chromophores

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1. Introduction

Bamboo is a perennial woody grass belongs to the family Poaceae, which is characterized by a jointed stem called a culm. Bamboo is commonly used as a substitute building material in tropical and subtropical regions of the world because of its fast growth rate, high mechanical strength, short rotation age, easy machinability. Bamboo can be made into its composite form, which can act as an alternative to wood and plywood. The process involves several steps like the splitting of bamboo along its vertical axis, extracting the middle layer of its wall, impregnating them into conventional resin and then converting them into laminated bamboo lumber, bamboo mat board or any kind of composites by hydraulic pressing.

Several bamboo-based materials such as bamboo plywood, particle board, bamboo-laminated strand board, bamboo scrimber etc. have been developed (Matsumoto et al. 2001, Nugroho & Ando 2001 and Qin et al. 2012). The process of manufacturing these products has been successfully developed in Asia. However, the certain value of all these kinds of bamboo products is not very high; e.g. - Bamboo Plywood of size 8×4 feet, thickness 6 to 25 mm costs around Rs. 40/ square feet at Wood Mall, Ernakulam, Kerala. So, the improvement of the utilization ratio of bamboo is very necessary. Bamboo is excellent natural composite material; but poor in durability and requires special coating to enhance the life in exterior condition.

There are many potential indoor and outdoor applications in which the bamboo composites can be used. For example, bamboo lumber/bamboo laminate composites can be used for outdoor and indoor flooring, wooden plank road, container flooring, garden landscaping, wind turbine blade, furniture etc.

Yu and his team 2014 studied the method of producing bamboo fiber reinforced composite (BFRC) with high yield and investigated the mechanical properties of BFRC comparing with those of commercial bamboo scrimber (BS) and laminated bamboo lumber (LBL). However, the application of Bamboo composite in exterior environments has been greatly limited due to its susceptibility against weathering. It has been found that the wood composites made of bamboo are also prone to weathering. Failure to recognize the effects of weathering can lead to catastrophic failure of wood and bamboo composites.

This study is intended to investigate the accelerated weathering study of bamboo composites (bamboo lumber or bamboo laminate). Accelerated weathering for finished bamboo lumber composite samples were tested according to US standard (ASTM-G154 2006). Test specimens were exposed to repetitive cycles of UV light and moisture under controlled environmental conditions in a weatherometer and the CIE L*a*b* readings are noted down before exposure, outdoor exposure and under UV exposure.

2. Literature Survey

The application of bamboo composite in exterior environments has been greatly limited due to its durability against weathering. Weathering is the general term, used to define the slow degradation of materials when exposed to weather. Weathering of a material is the change in its physical, chemical, aesthetic, compositional or molecular structure, when it is subjected in the external parameters such as temperature, pH value etc. of the environment. This degradation mechanism depends on the type of material; but the cause is a combination of factors such as moisture, sunlight, heat/cold, chemicals, abrasion by windblown materials and biological agents.

Sahin and George (2011) noted that the color changes in wood surfaces of European pine, fir, Bosnian pine, chestnut and cherry had been modified by a new nano particulate treatment. Color values (CIE L*, a*, b*) for both control and modified wood samples had been studied for each of the five different species. They showed that anti-UV treatment of wood was effective in discoloration of wood. They were obscure with the reason for wood discoloration; however, they reported that this could be due to the chemical modification, which would not itself affect all of the color properties of wood.

Rosu and team (2016) investigated the reason for wood discoloration using FTIR and CIELAB techniques. They investigated the effect of UV-visible light irradiation on the changes in the color and chemical composition of the surfaces of non-modified and chemically modified *Abies alba L.* (fir, a softwood), where the chemical modification was done by esterification of wood with succinic anhydride in xylene in different concentration. FTIR had confirmed the relation between color changes and structural modifications on the surface of samples as a function of irradiation time. Their result found that the decrease in photo-degradation of chemically modified wood might be due to the light stability of lignin to the polychromatic light action. This action was given by high reactivity of poly-conjugated lignin systems, which were capable of trapping and immobilizing of free radical states, such as phenoxyl radicals.

Nagarajappa and Pandey (2016) included the process of modification of wood using Isopropenyl Acetate (IPA) in the presence of anhydrous Aluminium Chloride as a catalyst.

Modification of wood using the trans-esterification with IPA was effective in suppressing photo-yellowing and UV degradation of wood polymers along with achieving hygroscopicity and good dimensional stability. Hence, the color darkening in modified wood was suppressed.

Feist and Hon (1984) studied the chemistry of weathering and protection and found that UV light interacts with lignin to initiate discoloration and deterioration. Deterioration of wood in the natural weathering process involves a very complex, free radical reaction sequence. Light does not penetrate wood past 200 μm; therefore, degradation reactions are a surface phenomenon. The free radicals generated in wood by light rapidly interact with oxygen to produce hydroperoxides which in turn are easily decomposed to produce chromophoric groups.

Okubo and team (2004) reported the development of composites for ecological purposes (Eco-composites) using bamboo fibers and their basic mechanical properties. The tensile strength and modulus of PP based composites using steam-exploded fibers found to be increased about 15 and 30%, due to well impregnation and the reduction of the number of voids.

Patil and Talekar (2017) studied the composite material, their applications and market trend. They found that, from the last thirty to thirty-five years composite materials, plastics and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials have grown steadily. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications. While composites have already proven their worth as weight-saving materials, the current challenge is to make them cost effective. Bamboo plants are giant, fast-growing grasses that have woody stems. The characteristics of each vary in size, growth habit, sun tolerance, soil moisture needs and heat/ cold temperature tolerance. The study of anatomy of bamboo, extraction of bamboo fibers, bamboo fiber composites with different matrix materials becomes necessary.

Li and team (2018) evaluated the influence of media treatments on color changes, dimensional stability, and cracking behavior of bamboo scrimber, which has many applications in construction. Bamboo scrimber specimens were tested under ten different conditions to determine the color changes, dimensional stability, and cracking behavior. The results showed that the bamboo scrimber specimens became darker after all treatment conditions, especially the oil treatments and infrared drying. The color of the oil-treated bamboo scrimbers was found to be more homogenous than the others. The dimensional stability of the bamboo scrimbers was more or less influenced by the water treatments, air drying, and infrared drying, and the oil-treated bamboo scrimbers were relatively stable. Moreover, during the 4-hour treatments, cracks were found in the bamboo scrimbers after air drying at 150 ˚C or infrared drying at 100 ˚C or 150 ˚C.

Sahin and George (2011) stated that fabricated bamboo lumber is sensitive to degradation when it is exposed under ultra-violet radiation, resulting in rapid colour changes. These rays affect the chromophores present in lignin. Hence a study on color changes of bamboo lumber was made to determine the extent of degradation, due to its exposure in both natural and accelerated weathering conditions.

CIELAB color space (also known as CIE L*a*b* or sometimes abbreviated as simply "Lab" color space) is a color space defined by the International Commission on Illumination (CIE) in 1976. It expresses color as three values: L* for the lightness from black (0) to white (100), a* from green (−) to red (+), and b* from blue (−) to yellow (+). CIELAB was designed so that the same amount of numerical change in these values corresponds to roughly the same amount of visually perceived change.

Chawla and team (2016) investigated the production of an engineered bamboo lumber product. The properties (physical and mechanical) were evaluated as per IS: 1734 and found that Bamboo Strand Lumber can be used as an alternative to timber for different application.

3. Scope and Objectives

Weathering study helps to predict the life of bamboo lumber, when it is exposed to natural weather under different radiation of electromagnetic spectrum. The main objective of accelerated study on bamboo lumber is to determine its photodegradation property (in outdoor weathering and through Xenon weatherometer) according to US Standard ASTM G154 (2006).

4. Materials and methods

Bambusa bambos species of bamboo and phenol formaldehyde resin were used to prepare bamboo lumber.

4.1. Preparation of Bamboo Lumber

Bamboo lumbers were prepared using the procedure described below.

- **<u>Cross Cutting:</u>** A raw bamboo culm is cut for the 4'1" length, transverse to the bamboo fibers. After cross cutting, the culm is now ready for primary processing and conversion into splits and slivers.

- **<u>Outer Nodes Removal:</u>** After cross cutting of the bamboo, the outer nodes (protrusions) are removed in order to have a smooth surface over the culm.

- **<u>Bamboo Splitting:</u>** Splitting process involves the splitting of bamboo culm of desired width through radial-bladed circular splitter which contains 4 or 6 or 8 blades, using a mallet over the vertically positioned bamboo section.

- **<u>Inner Nodes Removal:</u>** After the splitting of bamboo, the nodes and other protrusions are seen in the split pieces. The knots are simply the internal projections of the node. In most cases, the knot would need to be removed for smoother surface for further processes.

- **<u>Bamboo Sliver/Slat Making:</u>** Split bamboos, whose internal knots and outer protrusions are removed, are slivered or made into slats, depending on the required thickness. The objective of slivering is to remove the outer and inner layers of bamboo, due to their low adhesion property.

- **<u>Grooving and Sampling:</u>** All the slivered pieces of bamboo are grooved using a grooving machine. The objective of grooving is to have the penetration of the resin inside the strips, which can provide more strength to bamboo products. Each slivered pieces of bamboo are then cut into a desired length (generally 12 or 13 inches) and this process is called as "Sampling".

- **<u>Resin Application:</u>** Conventional Phenol Formaldehyde resin is poured in a container and the same amount of water (1:1) is added to reduce its viscosity. All the treated, untreated and boiled bamboo split samples (B1 to B10) are now dipped separately into this Phenol Formaldehyde resin for about 8 minutes.

- **<u>Air Drying:</u>** Resin-dipped crushed bamboo strips are kept in atmospheric condition for air drying by placing the strips vertically with support in a container for 3-4 hours to drain out excess resin from strips. After air drying, strips are kept in an industrial oven at 50º-60ºC until the moisture content of strips reach 10-12%. But oven dry of the strips can lead to poor adhesion of the bamboo lumber. Therefore, these strips can also be dried at the atmospheric conditions for 24-48 hours.

- **Assembling and Hot Pressing:** In this process, resin-dipped crushed strips are stacked in such a way that all crushed strips are aligned in same direction. Then assembly was loaded in a Hydraulic hot press, whose temperature is maintained at 145°±15°C, with the Gauge Pressure of 40-45 kg/cm^2 and Specific Pressure of 120-130 kg/cm^2 for 15 minutes. Hence the obtained product is a "Bamboo Lumber". This product is supposed to be placed under a heavy load unless it cools down, to avoid any deformation and is trimmed to a required size for the testing of its mechanical properties.

4.2. Evaluation of photo-degradation of bamboo lumber

Three samples were made from each lumber, meant for (a) no-exposure, (b) outdoor weathering condition [60 days and 150 days] with (dimensions 150×30×10 mm^3) and (c) accelerated weathering (dimensions 150×40×4 mm^3) under UV light for 250 hours, respectively. UV rays were incident normal to the surface of the samples, so as to increase the cross-sectional area of radiation absorption. Color changes in unexposed (freshly prepared) bamboo lumber was recorded through CIEL*a*b* technique in a Hunter lab Spectrocolorimeter, where the lightness (L*), redness (a*) and yellowness (b*) coordinates were measured for each sample, at different positions. A shift in color toward red signifies Δa^* positive while the shift in color from blue toward yellow signifies Δb^* positive. Similar set of values were recorded after 60 days and 150 days of lumber exposure in outdoor or natural condition. Third sample of lumber was kept in a weatherometer (Qlab QUV accelerated weathering tester) under UV rays exposure for a period of 250 hours, at the chamber temperature maintained at 60ºC and the CIEL*a*b* readings were recorded.

Considering ΔE_1 and ΔE_2 to be the color difference values of before exposure to 150 days outdoor and before exposure to weatherometer respectively, ΔE_1 and ΔE_2 can be calculated using the formula: $\mathbf{\Delta E = [(\Delta L)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}}$

4.3. Evaluation of Testing: The physical and mechanical properties viz. hardness under static indentation (IS 1708 Part 10 1986) [25], Water absorption (IS 2380 Part 16 1981) [26], Density (IS 1708 Part 2 1986) [25], modulus of rupture in bending, modulus of elasticity in bending (IS 1708 Part 5) [25], flammability, flame penetration, rate of burning (IS 1734 Part 3 1983) [1], thermal conductivity (IS 9490 – 1980) [27], moisture content, bulk density, compressive strength parallel to the grain, screw withdrawal strength in face and edge were conducted as per IS 1734 [1].

5. Results and discussions

Samples of Bamboo lumber were subjected to natural weathering and exposed to UV light source in an accelerated weathering tester or chamber and the extent of discoloration due to exposure were monitored using a spectrocolorimeter.

5.1. Natural outdoor weathering

Figures 1 (a), (b) and (c) describe the lightness, redness and yellowness value, respectively before exposure and followed by the exposure of 60 and 120 days. All three figures show that there were drastic decrease in L*, a* and b* values from initial day to 60th day and then their L*, a* and b* values attain constancy. Most of the changes were observed during first few days.

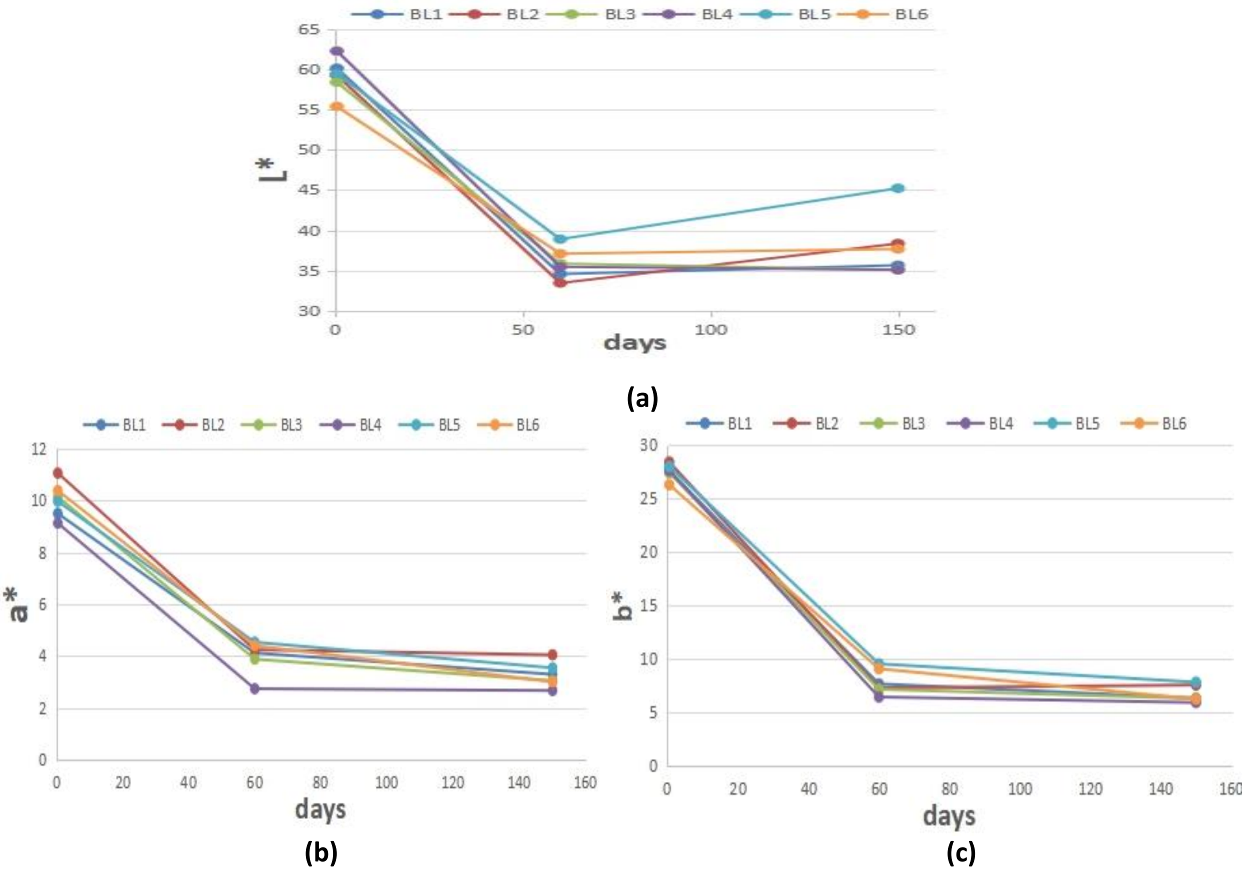

Fig. 1. Color change values of bamboo lumber due to natural weathering. (a) *L**, (b) *a**, (c) *b**

5.2. Accelerated weathering

CIE L*a*b* values were recorded for unexposed bamboo lumber samples and for those samples which were exposed to Xenon fluorescent UV light under weatherometer for 250 hours. Drastic color difference (ΔE) was observed. Which is due to the high intensity of UV light, emitted from Xenon lamp, and this can affect chromophores located on lignin

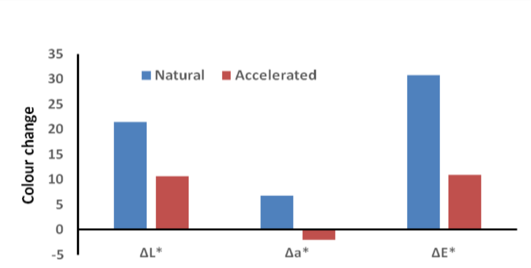

Fig. 2. Comparison of colour change in natural and accelerated weathering of bamboo lumber

Table 1. Change in color difference values (natural and accelerated weathering)

Sample	Natural weathering (ΔE_{sun})	Accelerated weathering (ΔE_{uv})
BL1	33.04	14.77
BL2	30.36	12.81
BL3	32.26	9.63
BL4	35.41	13.55
BL5	25.52	10.18
BL6	27.76	4.73

Table 2. Variation of L*, a* and b* values under accelerated weathering with time

Samples	**Natural weathering**			**Accelerated weathering**		
	ΔL*	Δa*	Δb*	ΔL*	Δa*	Δb*
BL1	24.53	6.19	21.25	14.52	-2.67	0.49
BL2	20.95	6.99	20.84	12.71	-0.54	1.53
BL3	23.36	7.07	21.09	9.34	-2.17	-0.85
BL4	27.25	6.44	21.68	13.16	-3.13	0.80
BL5	14.29	6.41	20.15	9.74	-2.90	-0.64
BL6	17.75	7.36	20.03	4.53	-0.80	-1.12

Table 3. Comparison of slope (ΔE/day) values of natural and accelerated weathering

Natural weathering (ΔE_{sun}) avg.	**Slope (ΔE_{sun}/day)**	**Accelerated weathering (ΔE_{uv}) avg.**	**Slope (ΔE_{uv}/day)**
30.72	0.20	12.19	1.17

Table 4. Properties of Bamboo strand lumber with respect to LVL

Sl. No	Parameter	Laminated veneer lumber (IS 14616 Specification)	BSL Value
1	Hardness under static indentation, N	--	9927
2	Water absorption, %	--	
	2 hrs		2.3
	24 hrs		5.1
3	Density, kg/m^3	--	1156.9
4	Modulus of Rupture, N/mm^2	50 Minimum	215.2
5	Modulus of Elasticity, N/mm^2	7500 Minimum	23216
6	Flammability, Min (Time taken for the second ignition)	Shall not be less than 30 min	5
7	Flame penetration (Time taken for flame penetration from bottom to top surface), Min	Shall not be less than 15t/6 min = 15x14/6=35	38
8	Rate of burning (Time taken to lose weight from 70% to 30%), Min	Shall not be less than 20 min	11
9	Moisture content, %	5 – 15%	9.68
10	Bulk Density, kg/m^3	--	1093.30
11	Compressive strength parallel to grain, N/mm^2	35 Minimum	38.4
13	Screw withdrawal strength, N		
	a) Edge	2300 Minimum	1245
	b) Face	2700Minimum	1985

Table 1. describes the changes in color difference values due to natural and accelerated weathering, which show the significant change in color with time under both the conditions. Table-2 describes the individual change in L*, a* and b* values under natural and accelerated weathering with reference to unexposed samples. All three values of L*, a* and b* for naturally exposed samples decreased with time, which means that the samples became lighter and attained reddish-yellow color. Accelerated (UV) exposed samples also became lighter, but their Δa* showed negative, which means that they tend to attain blue color; and Δb* value remained unaffected. Table-3 compares the slope values of natural weathering, exposed in sunlight and accelerated weathering, exposed in UV lamp. It can be clearly seen that slope value of ΔE per day under accelerated condition is 1.17 while that of natural condition is 0.20 per day, which means that the bamboo lumber is sensitive to UV radiation. Careful observation shows that the

lightness values had decreased with time, keeping the redness and yellowness value almost same as they were in unexposed samples as shown in table 2 Chemical composition of bamboo asserts that it contains lignin as a binding material, which is responsible for its color degradation through chromophore action.

Plate 1. Control sample of bamboo lumber.

Plate 2. Treated sample of bamboo lumber in outdoor weathering condition.

Plate 3. UV light treated sample of bamboo lumber in UV Chamber.

Table 4. describe the physical and mechanical properties viz. hardness under static indentation, water absorption, density, flammability, flame penetration, rate of burning, thermal conductivity, bulk density, moisture content, modulus of rupture in bending, modulus of elasticity in bending, compressive strength, screw withdrawal strength in face and edge were conducted as per IS 1734 [1]. Compressive strength parallel to grain value, modulus of rupture in bending, modulus of elasticity in bending, flame penetration is on the higher side but other mechanical property such as flammability, rate of burning, and screw withdrawal strength is slightly lower as compared to IS 14616 –Indian Standard -1999, Laminated veneer lumber specification [2]. Particularly flammability, flame penetration, rate of burning values are lower due to not given fire retardant chemical treatment to bamboo strands while screw withdrawal strength is 45% and 26.4 % lower at edge and face respectively this may be due to inherent properties of bamboo i.e. week adhesion of longitudinal fibre and non-availability of radial fibre so.

Conclusions

Bamboo lumber was prepared and extent of color change under natural and accelerated weathering conditions was evaluated. The amount of sunlight, as perceived in the atmosphere contains low intensity of ultra-violet radiation, due to which the colour difference rate was found to be 0.20 per day. Another set of similar samples of bamboo lumber were exposed to UV lamp in an accelerated weathering tester and the rate of color difference was recorded as 1.17 per day. The colour changes is attributed to the chromophores present in lignin which is 32.2% of the total chemical composition of bamboo. All three-color axes changed in accordance with time under natural exposure, but only L* decreased with time under accelerated UV exposure, keeping their* and b* values unaffected. Compressive strength parallel to grain value, modulus of rupture in bending, modulus of elasticity in bending, flame penetration is on the higher side but other mechanical property such as flammability, rate of burning, and screw withdrawal strength is slightly lower as compared to IS 14616 –Indian Standard -1999, Laminated veneer lumber specification [2]. Particularly flammability, flame penetration, rate of burning values are lower due to not given fire retardant chemical treatment to bamboo strands while screw withdrawal strength is 45% and 26.4 % lower at edge and face respectively this may be due to inherent properties of bamboo i.e. week adhesion of longitudinal fibre and non-availability of radial fibre so. This study was limited to examining the weathering effects on bamboo lumber, with physical and mechanical properties tested on control samples. A comparison with accelerated weathering exposed samples was not conducted due to constraints in the sample size of the weathering study.

Conflict of Interest

The authors declare there is no conflict of interest

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