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Thermal properties of interior decorative material and contacted sensory cold–warmth I: relation between skin temperature and contacted sensory cold–warmth

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Abstract The purpose of the study was to investigate the relation between the skin temperature of the palm and sensory cold–warmth after contact with some materials. Ten men and ten women were selected and introduced to 21 kinds of material for a contact test of 30 min without seeing the specimens in a climate-controlled room at 25° ± 1°C and 65% relative heemidity. The palm-contacted test materials and skin temperature of the palm, central fingertip, and back of the palm were measured during the experiment. A sensory evaluation test was applied to evaluate the contacted sensory cold–warmth. Results showed that the maximum temperature decrease of the fingertip (T_d) was positively related to the natural logarithm of the material's specific gravity ($\ln \rho_u$) and to the natural logarithm of the material's thermal conductivity ($\ln \lambda$). There were also negative linear relations between the contacted sensory cold–warmth (S) with $\ln \rho_u$ and $\ln \lambda$; and there was a negative linear relation between S with T_d and between S with the value of T_d by λ. The thermal osmotic coefficient (b) of wood and wood-based materials ranged from 3.63 to 3.97, and the materials were qualified as good thermal insulation materials. Furthermore, there was a negative linear relation between S and b. Accordingly, it is possible to evaluate the contacted sensory cold–warmth relying on the basic thermal properties of material.

Key words Interior decorative material · Change of skin temperature · Contacted sensory cold–warmth · Physiological value · Thermal osmotic coefficient

Introduction

Human tactile perception is influenced by the physical properties of materials when touched. The contacted sense affects the acceptability by the individual – whether they like or dislike it. Thus the contacted sense has a strong relation with the physical properties of the material, such as the temperature sense and the coarseness of the material.

Because the average human body temperature is about 37°C and the surface skin temperature is about 32°C, there is heat transfer from skin to the material at room temperature (18°–22°C). The contacted temperature sense is based on the temperature difference between the contacted part and the stimulation of temperature change. Sadoh and Nomata[1] simulated hand contact with floor material surface contacted with wax or paint. Owing to the temperature difference, heat transfer from hand to material reached a thermal balance during the contact period. Their results showed that there was a significant relation between the change in surface skin temperature and the heat flux of the material and thus with contacted thermal comfort. Sadoh[2] indicated that there were reversed relations between the thermal conductivities of wood-based and non-wood-based material (cross sections and longitudinal sections) and the contact temperature sense. For example, polyvinyl chloride (PVC) was warmer than wood owing to its lower thermal conductivity. Suzuki[3] compared concrete, wood, and PVC tile by placing human feet on these materials. They found that the surface temperature of the feet was reduced significantly when concrete floor was used as the specimen at both high and low temperatures. Okajima[4] indicated that the contact temperature sense of lauan was similar to that of towels and cotton clothes, being ranked as "warm"; aluminum and stainless steel were ranked as "cold" materials. Sakuragawa et al.[5] measured the initial heat flux (q_{max}) and the heat flux after 10 min (q_{10}) using a heat flux meter affixed to the palm while contacting the floor material. The results showed that q_{max} was about 100–150 kcal/m^2/h, and q_{10} was about 70–100 kcal/m^2/h. During a contact

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temperature sense test, individuals feel "comfort" if both heat flux values are close to those cited above. Because the values of wood-based material were about 85–134 kcal/m^2/h, the contact temperature sense was ranked as "excellent."

Okuma and Izumi[6] quantified the contacted temperature sense by applying Fechner's theory and proposed that the relation of "stimulus" and "response" could be expressed as $R = k \log S$, where R and S represent the quantities of reaction and stimulation, respectively. They indicated that the temperature sense of metal and other nonwood material could change to "warm" if these materials were covered or coated with a wood-based material. Their results also showed that the thicker the coating layer, the less was the heat flux; and the contact temperature sense was closer to a "not cold" category.

The purpose of this study was to investigate the relations among the basic physical properties (e.g., specific gravity, thermal conductivity, heat flux) of common interior decorating materials, the human physiological responses (e.g., changes of skin temperature), and human psychological feelings (e.g., contact sensory cold–warmth). We also quantified the physiological temperature sense and further investigated the relations among the senses, thermal properties of material, and physical reactions. The results provide some basic information on the selection of interior decorating material. This is the first report of a study regarding the relations among specific gravity, thermal conductivities of material, and changes in human skin temperature, as well as the contact sensory cold–warmth for each.

Testing materials and methods

Testing materials

Nine types of solid wood material were used as test specimens: taiwania (*Taiwania cryptomerioides*), China fir (*Cunninghamia lanceolata*), Taiwan red cypress (*Chamaecyparis formosensis*), Taiwan paulownia (*Paulownia fortunei*), hard maple (*Acer saccharum*), red oak (*Quercus rubra*), red meranti (*Shorea negrosensis*), red cypress solid wood floor with polyurethane resin (PU) coating, and teak solid wood floor with PU coating. Another five types of wood-based material were used in the experiment, including fancy plywood of red oak with PU coating, fancy plywood of red cypress with PU coating, particleboard, medium density fiberboard (MDF), and insulation fiberboard. Five types of inorganic material including gypsum board, polystyrene (PS) foam, and rabbit fur were included in the experiment.

All materials were cut in 30 cm (length) × 20 cm (width) thin plates. The thickness of the solid wood and the wood-based material specimens were 1 cm, and the thickness of the other materials were their original thickness (0.8–1.7 cm). The properties of these 21 test materials are shown in Table 1. All specimens were conditioned in a climate-controlled room at 25° ± 1°C and 65% relative humidity until the moisture content reach equilibrium.

Twenty 20- to 30-year-old students in the Department of Forestry, National Taiwan University (10 men, 10 women) volunteered for this study. Each testee was tested only once.

Table 1. Physical properties of 21 interior decorative materials

Specimen	h Thickness (cm)	ρ Specific gravity	λ Thermal conductivity (kcal/mh°C)	C Specific heat[a] (kcal/kg°C)	B Thermal osmotic coefficient
Solid wood					
Taiwania	1.0	0.36	0.202	0.379	5.24
China fir	1.0	0.31	0.149	0.379	5.05
Taiwan red cypress	1.0	0.39	0.196	0.379	5.59
Taiwan paulownia	1.0	0.22	0.122	0.379	4.77
Hard maple	1.0	0.56	0.222	0.379	6.86
Red oak	1.0	0.62	0.236	0.379	7.97
Red meranti	1.0	0.52	0.209	0.379	6.42
Teak floor (PU coating)	1.0	0.66	0.201	0.379	5.13
Red cypress floor (PU coating)	1.0	0.45	0.128	0.379	3.63
Wood-based materials					
Fancy plywood (red oak)	1.0	0.65	0.141	0.379	4.68
Fancy plywood (red cypress)	1.0	0.55	0.115	0.379	4.46
Particleboard	1.0	0.62	0.233	0.379	6.03
Fiberboard	1.0	0.59	0.172	0.379	6.20
Absorption board	0.9	0.15	0.245	0.379	5.34
Inorganic material					
Gypsum	0.9	0.89	0.245	0.230	11.50
Tile	0.8	2.14	0.998	0.220	20.50
Marble	1.0	2.64	2.396	0.209	33.84
Terrazzo floor	1.7	2.50	0.650	0.220	18.97
Others					
Glass	1.0	2.32	0.872	0.937	16.40
PS foam	1.2	0.08	0.190	–	–
Rabbit fur	0.1	0.25	0.243	–	–

[a] Specific heat was from Okajima et al.[13]

Testing methods

Measurement of thermal conductivity

Thermal conductivities of all experimental material were measured with the hot-wire method. Magnetic wire was used to supply electric power that emitted a constant amount of heat per second in the surrounding material (specimen). The two-dimensional thermal conductivity of these materials were then calculated from the temperature change in the heat source plotted against the logarithm of time. A thermal conductivity-measuring apparatus (TCR-01; Kyoto Electric, Japan) was used in this study. The dimensions of the specimens were 10 cm (length) × 7 cm (width) with a minimum thickness of 4 cm. To attain the required thickness some specimens had to be overlapped.

Measurement of human skin temperature

The sense of warmth and the sense of coldness are defined here as temperature sense. Stimulation of temperature sense was from the temperature change of air or the objects that came into contact with the skin. A sense of warmth was present when the exterior temperature was 0.4°C higher than that of human skin, whereas a sense of coldness was present when the exterior temperature was 0.15°C lower than that of human skin. "Chilly" was defined as physiological zero, which was about 32°C. Human body temperature was about 37°C. A skin thermometer, Data Collector AM-7001 (Yasutate Keiki, Japan) was used to measure skin temperature. This system is equipped with six data-logging channels and is capable of recording the input directly into a personal computer using an RC-232C interface.

The experiment measured the temperature of both hands on the central fingertip, palm, and back of the palm by affixing the sensor of the thermometer on these positions for 30 min, as shown in Fig. 1. The change in skin temperature was recorded every 30 s.

Contact cold–warmth sensation

A test method originating from the paired comparison method and the rating method was applied for the contact cold–warmth sense experiment on the human hand because it is simple and its objectivity helps make a clear judgment. The method was designed to compare m kinds of materials that could not be sorted easily. Two materials were chosen for a comparison test. After mC_2 times of testing, all materials could be sorted for the final results.

First, testees stood quietly in a climate-controlled room for 5 min. Then skin thermometers were affixed to the central fingertip, palm, and back of the palm. Both hands were required for placement on the surface of two tested specimens separately for 30 min, as shown in Fig. 1. For the experiment to be unbiased, tested specimens were placed in a covered box. Sensory sensitivity was reduced after long durations of stimulation, a phenomenon called sensory adaptation. The contacted cold–warmth sense was determined by oral inquiry after the testee had made a contact with the specimens for 10 s. They were assigned one to five points for their cold–warmth sense as follows: very cold, 1 point; cold, 2 points; chilly, 3 points; cool, 4 points; warm, 5 points. For example, 2 points may be recorded for the right palm and 3 points for the left palm. After all the specimens were tested, the cold–warmth sense and its standard deviation were calculated. In other words, if there were m specimens and N testees, the psychological material-contacted sensory perception was based on $N(m - 1)$ averages and standard deviations of the test values. Changes in skin temperature were also measured during the experiment.

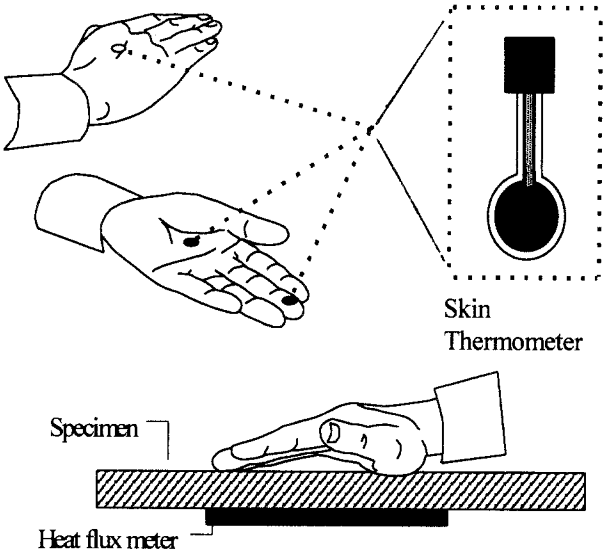

Fig. 1. Locations for the skin thermometer and experimental setup

Results and discussion

Thermal conductivity

The thermal conductivities and specific gravities (ρ_u) of all 21 test materials are shown in Table 1. Generally, thermal conductivity (λ) influenced the contacted cold–warmth sense of the material. The more porous the material, the more the air quantity and the lower the λ were; that is, λ increased with ρ_u. The linear relation between λ with ρ_u was expressed as follows:

$$\lambda = 0.521\, \rho_u - 0.058, \quad R^2 = 0.627, \quad F = 37.5^{**}$$

The F-test was significant at the 0.01 level, which is consistent with the results of previous studies.[7–9]

Change in skin temperature

Temperature of fingertip

Once the human hand is in contact with the material, the temperature of the central fingertip starts to decrease

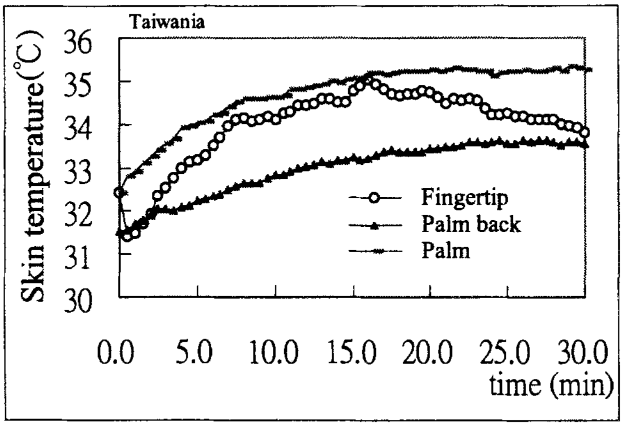

Fig. 2. Change in variously positioned skin temperatures on the palms of female testees in contact with Taiwania

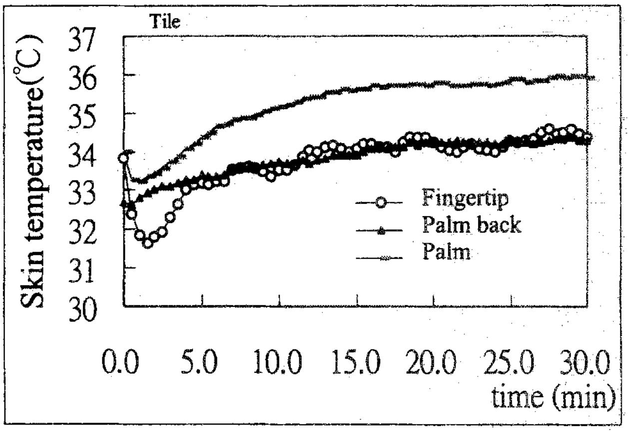

Fig. 3. Change in variously positioned skin temperatures on the palms of male testees in contact with tile

significantly, although it increases gradually later. Typical changes in fingertip temperature are shown in Figs. 2 and 3. Obviously, changes in the fingertip temperature were more sensitive than those of the palm and the front and back of the hand. The maximum temperature of the fingertips can be lowered depending on the material contacted. For example, the temperature of the fingertips decreased 0.5°–1.6°C within 0.5–1.0 min using solid wood and wood-based material. With gypsum board and marble, it took about 0.5–1.0 min to decrease the temperature of the fingertip by 1.0°–1.4°C. Tiles, terrazzo floor, and glass took 1.0–1.5 min to lower the temperature by 2.0°–3.8°C. Rabbit fur and PS foam took a shorter time (0.5 min) to lower the maximum temperature 0.4°C–0.5°C. These results are summarized in Table 1.

In regard to a gender difference, the maximum fingertip temperature decrease was significantly larger in men than in women using red cypress, red oak, red cypress fancy plywood, and terrazzo floor; but the difference was not significant with other materials. The maximum fingertip temperature decrease was defined as the difference between the initial temperature and the lowest temperature of the fingertip. The relations among the maximum drop in fingertip temperature (T_d), the specific gravity of the material (ρ_u), and thermal conductivities (λ) showed that T_d increased linearly with an increasing natural logarithm of ρ_u and λ. The regressive equations were significant at the 0.01 level and can be summarized as follows:

$$T_d = 0.606 \ln \rho_u + 1.494, \quad R^2 = 0.508, \quad F = 41.2^{**}$$

$$T_d = 0.539 \ln \lambda + 1.929, \quad R^2 = 0.323, \quad F = 19.0^{**}$$

Palm temperature

Palm temperature increased gradually after making contact with an object until 35°C was reached, after which the temperature stabilized. Typical changes in palm temperature are shown in Figs. 2 and 3. The temperature of the back of the palm dropped slightly immediately after the hand contacted a material; later it gradually increased to 34°C. Typical changes of the temperature are also shown in Figs. 2 and 3.

The temperature of the back of the palm remained stable, and there were almost no changes during the test perhaps because it was exposed only to air, without contacting the material. Originally, the temperature of the palm was highest, and it contacted the material over a larger area; therefore, the palm was the major heat source for the material. The temperature difference was largest in the central fingertip because it is located at the end of the vein and it makes direct contact with the material. After the test period all hand temperatures stabilized, and the highest and lowest temperatures were found on the palm and the back of the palm, respectively.

Cold–warmth sensation

When the human body comes into contact with materials, heat is transferred from the higher-temperature object to the lower-temperature one through the skin–material interface. The cold–warmth sense would be felt depending on the amount of heat flux. The cold–warmth sense was registered when the testees contacted the material for 10 s. Data from 10 male and 10 female testees were analyzed statistically based on a point system. The averages, standard deviations, and coefficients of variation (CV) are shown in Table 2.

The cold–warmth sense for solid wood, wood-based material, and gypsum board was described as "chilly" by both genders, with the average points ranging from 2.5 to 3.2, whereas there were 1.3–1.7 points for tiles, marble, terrazzo floor, and glass, which were ranked as "cold." For the PS foam and the rabbit fur the average points ranged from 3.0 to 3.8, and these materials were ranked as "cool." However, the wide and irregular spread of the CVs may indicate that the psychological value was easily influenced by personal subjectivity.

Analyzing the cold–warmth sense of the gender difference by *t*-test found that only rabbit fur showed a significant difference between the male and female testees. Thus, the

Table 2. Difference of maximum drop in temperature of testees' fingertip and the evaluated cold–warmth sensory for 21 interior decorative materials

Specimen	Maximum drop in temperature (°C) (Td)		Time of max. drop in temperature (min)		Conspicuous difference	Contacted sensory cold–warmth		Coefficient of variation (%)		Conspicuous difference
	Male	Female	Male	Female		Male	Female	Male	Female	
Solid wood										
Taiwania	1.4	1.0	0.5	0.5	–	2.7	2.8	23	40	–
China fir	0.7	0.6	0.5	0.5	–	3.2	2.9	17	10	–
Taiwan red cypress	1.0	0.8	0.5	1.0	*	2.9	2.7	10	10	–
Taiwan paulownia	0.6	0.9	0.5	0.5	–	2.9	3.0	10	22	–
Hard maple	1.2	1.6	0.5	0.5	–	2.7	2.7	23	23	–
Red oak	1.2	0.6	0.5	0.5	*	2.5	2.5	27	27	–
Red meranti	0.9	0.5	1.0	0.5	–	2.9	3.0	10	1	–
Teak floor (PU coating)	0.6	1.1	1.0	0.5	–	2.5	2.4	27	26	–
Red cypress floor (PU coating)	1.2	1.4	0.5	0.5	–	2.8	2.7	17	23	–
Wood-based materials										
Fancy plywood (red oak)	1.2	1.0	0.5	0.5	–	2.8	2.5	40	27	–
Fancy plywood (red cypress)	1.5	1.0	0.5	0.5	*	2.6	2.5	26	27	–
Particleboard	1.0	1.1	0.5	0.5	–	2.7	2.5	23	50	–
Fiberboard	1.3	1.1	0.5	0.5	–	2.6	2.9	26	10	–
Absorption board	1.7	0.5	0.5	0.5	–	3.0	3.2	0	17	–
Inorganic material										
Gypsum	1.0	1.1	1.0	0.5	–	3.0	2.3	0	23	–
Tile	2.2	2.0	1.5	1.5	–	1.3	1.4	23	26	–
Marble	1.3	1.4	1.0	1.0	–	1.4	1.4	26	26	–
Terrazzo floor	3.8	2.9	1.0	1.5	*	1.7	1.7	23	23	–
Others										
Glass	2.7	2.6	1.5	1.0	–	1.3	1.3	23	23	–
PS foam	0.4	0.5	0.5	0.5	–	3.2	3.8	62	40	–
Rabbit fur	0.5	0.4	0.5	0.5	–	3.0	3.6	44	26	*

* Significant difference at the 0.05 level by *t*-test

–, no significant difference at the 0.05 level by *t*-test

Sensory cold–warmth was evaluated by the average points according to the five-point scale (see text)

Maximum drop in temperature (Td) was defined as the difference between the initial temperature and the lowest temperature of the material during the experiment purpose of quantifying the cold–warmth sense was to find the relation between the physical properties of materials and the psychological responses of humans.

According to Fechner's law, the stimulus-sense (R–S) relation could be expressed as $S = k \log(R)$, where R refers to the physical properties of the material such as specific gravity (ρ_u), thermal conductivity (λ), and heat flux (Q); S is quantified at given points as described in the following section; and k is the coefficient of the material.

Relation between cold–warmth sense and specific gravity of the material

The larger the specific gravity of the material, the lower is the porosity ratio. Because of the many thermal contact points of the materials, heat flux increased and the cold–warmth sense tended to be "cold." Results of the analysis showed the cold–warmth sense (S) decreased linearly with an increasing natural logarithm of specific gravity ($\ln \rho_u$). The regression was significant at the 0.01 level and can be summarized as follows:

$$S = -0.630 \ln \rho_u + 2.257, \quad R^2 = 0.473, \quad F = 374.5^{**}$$

The results were consistent with those previously reported.[9,10]

Relation between cold–warmth sense and thermal conductivity

Because the temperature of the object (25°C) is lower than that of the human hand, heat is transferred from the heat source (human hand) to the contacted object. The larger the thermal conductivity of the material (λ), the more was the heat flux, which induced the cold–warmth sense of being "cold." It was found that the cold–warmth sense (S) of all testees decreased linearly with an increasing natural logarithm of thermal conductivity ($\ln \lambda$). The regressive equation was significant at the 0.01 level and can be summarized as follows:

$$S = -0.657 \ln \lambda + 1.673, \quad R^2 = 0.414, \quad F = 259.1^{**}$$

Harada et al.[11] investigated the cold–warmth sense of the hand at room temperature (25°C) and indicated that the cold–warmth sense (psychological value) was significantly related to specific heat (C), thermal capacity ($C\rho$), thermal conductivity (λ), and thermal diffusivity (α). The characteristic of heat transfer was from the palm to the surface of the material. They also applied a paired-comparison method and found that the psychological value has a significant negative relation with the natural logarithm of the thermal conductivity. Thus, the larger the thermal conductivity of the material, the more was the motion of thermal energy on the contacted surface, inducing a "cold" sense.

Kawamura et al.[10] studied floor material and indicated that the feeling induced by PVC tile characteristic of thermal conductivity was "cold," whereas the feeling engendered by plywood, hard fiberboard, and cork tile was warm. Moreover, there was a negative relation between the cold–warmth sense and thermal conductivity. Wang and Kuo[8] indicated that there is a negative relation between the cold–warmth sense of feet and thermal conductivity at 20°C and 25°C room temperatures. All of the above results are consistent with those of the present study.

Relation between cold–warmth sense and maximum temperature drop of the fingertip

When the fingertip touched the lower-temperature material, heat was transferred from the fingertip to the material. The amount of heat flux increased as the temperature difference of the fingertip–material interface, thermal conductivity, and specific gravity of the material increased. Because of the heat flux the temperature of the fingertip decreased after contact, although it recovered gradually afterward. The cold–warmth sense (S) of all testees after contacting the material depended on the maximum drop in fingertip temperature (T_d). This finding means that the larger the maximum temperature drop, the greater was the feeling that the material was "cold." The regression of the cold–warmth sense (S) on maximum temperature dropping (T_d) was significant at the 0.01 level and can be summarized as follows:

$$S = -0.667\, T_d + 3.358, \quad R^2 = 0.597, \quad F = 59.3^{**}$$

The result is consistent with previous results.[11]

In this section, T_d and λ refer to the physiological reaction of the human body and the physical thermal property of the material, respectively. From the above-mentioned results, S not only has negative linear relations with $\ln \lambda$ and T_d, there is a positive linear relation between $\ln \lambda$ and T_d. Because the R^2 values of these regressive equations are low, the cold–warmth sense (S) was analyzed statistically with the product ($T_d \cdot \lambda$). The regression was significant at the 0.01 level and can be summarized as follows:

$$S = -0.587(T_d \cdot \lambda) + 2.914, \quad R^2 = 0.763, \quad F = 129.0^{**}$$

Thus the R^2 and F values were greater than those of S and T_d in the regressive equation. Therefore, the relation of the psychological reaction to the physiological phenomena could be expressed more precisely if the property of the material was considered as a weight index. This could be explained as the product of $T_d \cdot \lambda$ having a synergistic effect on S.

Thermal insulation and cold property of material

One of the purposes of interior decorating material is to improve thermal insulation for protecting the human body. Thus, the ideal physical property of material is low thermal conductivity. The cold–warmth sense of floor material is another important factor. The physical value of the cold–warmth sense can be expressed by a thermal osmotic coefficient (b)[12] in the relation:

$$b = \sqrt{\lambda \cdot C \cdot \rho_u}$$

where λ is the thermal conductivity of material, C is the specific heat, and ρ_u is the specific gravity or density. Generally, humans feel "warmth" at the feet if the b value of the material is under 10. When the b value is above 20, the feet feel cold. Solid wood and wood-based material maintain the b value under 10, but concrete scored 20.[12] Note, however, that this is a general classification and can be influenced by individual physiological differences.

The b values for all 21 materials used in this study are listed in Table 1. The b value of solid wood and wood-based material was less than 10 (range 3.63–7.97), so they are good thermal insulating materials. On the other hand, tile, marble, and terrazzo floors had a b value of 18.97–33.84, and they are ranked as "very cold" material. The b values for gypsum board and glass are 11.53 and 16.42, respectively; and they are ranked as between "warm" and "cold." This trend is similar to that of general construction materials.[12]

The temperature sense of all testees decreased linearly with an increasing b value. The regression was significant at the 0.01 level and can be summarized as follows:

$$S = -0.066b + 3.108, \quad R^2 = 0.455, \quad F = 315.7^{**}$$

Based on the equations outlined above, temperature sense can be predicted by the physical properties of the material.

Conclusions

1. Thermal conductivity (λ) increased linearly and positively with the specific gravity (ρ_u) of solid wood.
2. The temperature of the fingertip decreased significantly after the palm came in contact with the testing material but later rose gradually. The fingertip maximum temperature drop with solid wood and wood-based materials ranged from 0.5°C to 1.6°C, whereas that with tiles, terrazzo floor, and glass ranged from 2.0°C to 3.8°C.
3. The fingertip maximum temperature drop (T_d) has a positive linear relation with the natural logarithm of the specific gravity ($\ln \rho_u$) and thermal conductivity ($\ln \lambda$), but the cold–warmth sense (S) has a negative relation with $\ln \rho_u$, $\ln \lambda$, and T_d. The cold–warmth sense (S) has a more marked linear relation with $T_d \cdot \lambda$. Therefore, evaluation of the cold–warmth sense is more persuasive when it considers the thermal property of the material and the physiological reaction of the human body together.
4. The thermal osmosis coefficients (b) of solid wood and wood-based material ranged from 3.63 to 7.97, and they were ranked as good insulating material. The relation between the cold–warmth sense (S) and the b-value was negative and linear; thus, the cold–warmth sense could be evaluated by both fingertip maximum temperature drop and the basic properties of the material.

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