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Thermal conductivity of strawbale – a review of published results meeting ISO 10456 requirements, analysed to provide robust straw lambda values

Headline figure: strawbale design λ value – **0.08 W/mK**

Introduction

This paper reviews published test data on the thermal conductivity (lambda λ) of strawbale to determine a reliable design value to use in energy assessments and heatflow calculations for strawbale building, compliant with international and European standards for insulation products.

Different studies have identified different lambda values, obtained using different testing methods. Some have tested only small samples of straw assembled by hand; others have tested larger specimens made from strawbales. The latter most-closely resembles the reality of straw in a strawbale wall, so this review considers only data from such tests. Additionally, in order to investigate only the λ value of straw it excludes tests where timber is present within the straw, or where test specimens have been plastered.

Commercial insulation products are held to high standards of consistency and testing – to be used with confidence the same standards should be applied to bio-based insulation materials such as strawbale. ISO 10456 defines the standards by which the λ value may be determined: ISO 8302 (guarded hot plate method), ISO 8301 (heat flow meter), calibrated or guarded hotbox (ISO 8990), or equivalent national methods (e.g. EN 12667: 2001 and EN 12939: 2001). Guarded hotbox is generally used to test smaller samples, so this paper focuses on results from tests according to ISO 8302 and 8301 and EN 12667/12939.

The results of published strawbale λ results meeting the above criteria are analysed to arrive at reliable figures to use with statistical confidence – that is a figure that 90 % of tested samples would meet with a 90 % statistical confidence level, via the procedure defined in ISO 10456.

Bale fibre orientation

There is some suggestion that λ can be lower when bales are placed on edge, with the assumption that straw fibres are primarily aligned perpendicular to heatflow in this case (DIBt, 2006, 2017; Douzane *et al.*, 2016). Others have found bale/fibre orientation made little difference to λ values (Louis *et al.*, 2013a). Shea *et al.*, (2013) (figure 1) and Costes *et al.*, (2017) both note that slices through bales indicate random orientation of straw fibres, though the latter suggest a slight majority may be aligned in one direction. ModCell and Bath University carried out a CT scan of a strawbale (ModCell, 2015) which indicated random fibre orientation whichever way the bale was 'sliced' (figure 1). Throughout this paper, where fibre orientation is reported in the source literature, it is recorded here as orientation *primarily* in the stated direction.

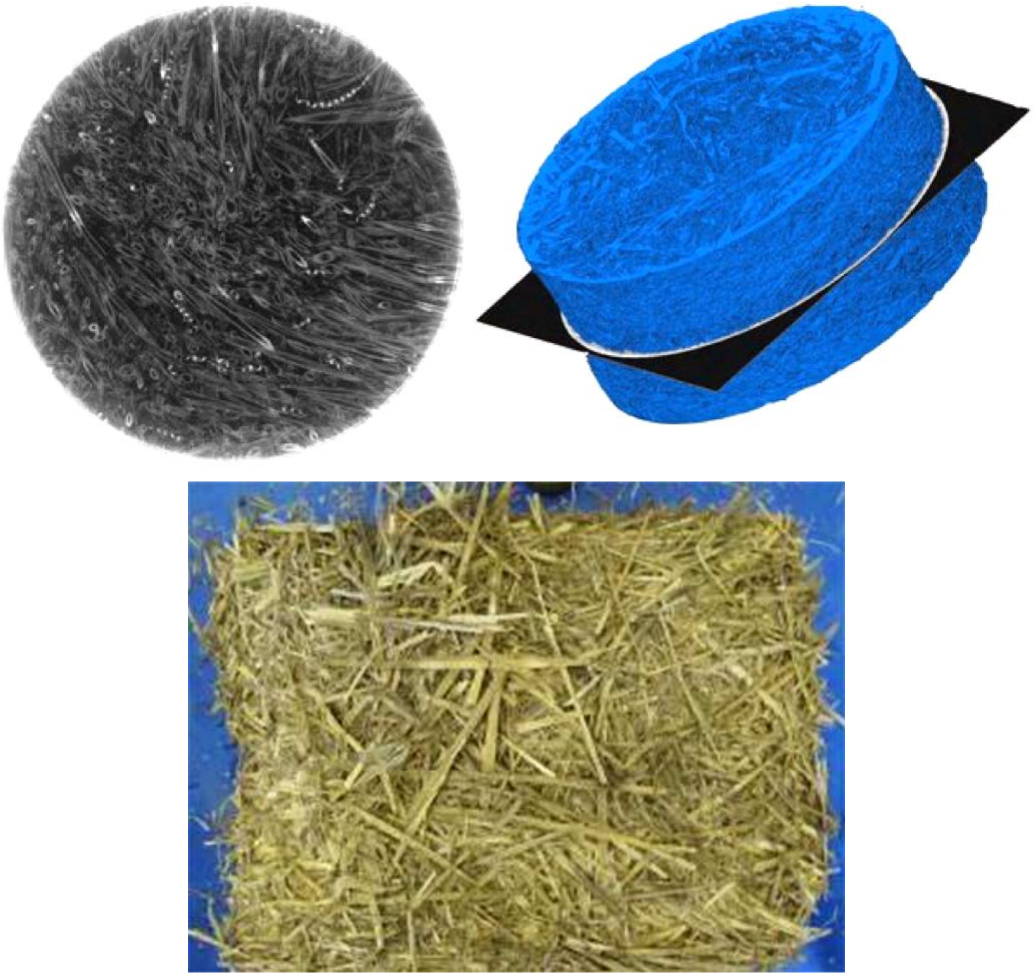

Figure 1 - Top: virtual slices through a strawbale from CT scan data (Modcell, 2015).
Bottom: Cross section across width of a two-string bale, suggesting random fibre orientation (Shea et al., 2013).

Summary of test data from the literature

DIBt (2006) tested strawbale samples with straw orientation primarily parallel and perpendicular to heatflow, to EN 12667, with a density of 100 kg/m_3. Samples were tested dry, with given design values adjusted for moisture according to German standard DIN 4108. Dry values were 0.067 W/mK for straw primarily parallel to heatflow and 0.044 W/mK for straw primarily perpendicular to heatflow, adjusted to 0.08 W/mK and 0.052 W/mK respectively.

DIBt (DIBt, 2017) revised the 2006 figure for straw primarily perpendicular to heatflow to bring it in line with European Technical Assessment (ETA) rules and calculated design λ according to ISO 10456. At 23 °C and 50% RH the revised design λ value is 0.048 W/mK. The figures for straw primarily parallel to heatflow were not revised. The moisture conversion factor used in the design value calculation is given as F_m 1.10. If the same factor is applied to the dry λ value for straw primarily parallel to heatflow, it gives 0.074 W/mK. These revised values are used in this review as they better reflect practice throughout the EU and ensure the same criteria are applied to all data here.

The technical reports for the above tests do not state sample dimensions. The use of EN 12667 suggest a sample of reasonable size, but its thickness remains unknown as does how accurately the assembled sample resembles the physical reality of a strawbale. Without a more detailed test report it is only possible to speculate. The data from DIBt tests have remained part of this review.

Shea *et al.* (2013) tested according to ISO 8301 and EN 12667 at a British Board of Agrément (BBA) site. λ ranged from 0.0594 W/mK at 63 kg/m3 density, to 0.0636 W/mK at 123 kg/m3 density. The straw was conditioned at 50% relative humidity (RH) at 23 °C.

Louis *et al.*, (2013a, 2013b) tested according to ISO 8302, a test sample constructed from bales with primarily vertical straw-orientation when lain flat. They found λ of 0.0651 W/mK with heatflow perpendicular to primary straw orientation, and 0.0682 W/mK with heatflow parallel. They note general randomness of straw orientation. RH was not stated.

SPSC (2013) tested the straw insulation layer of EcoCocon panels according to ISO EN 12667 and 12939, finding an adjusted design λ of 0.06 W/mK.

Douzane *et al.*, (2016) carried out ISO 8302 test of strawbale panel, with bales laid flat, and with bales on edge. With fibres primarily parallel to heatflow λ was measured at 0.067 W/mK. With fibres primarily perpendicular to heatflow λ was measured at 0.046 W/mK. Test samples were dried, and figures were not adjusted. Sample thickness was 100 mm – cut down from full bales. For this review these figures were adjusted according to ISO 10456 using the moisture conversion factor in DIBt (2017) of F_m 1.10 – this gives 0.074 W/mK and 0.051 W/mK respectively.

Costes *et al.*, (2017) conducted ISO 8302 tests. The found a range of thermal conductivities from 0.063 W/mK to 0.082 W/mK. Test samples were conditioned to 50% RH.

D'Alessandro *et al.*, (2017) completed EN 12667 tests at 50% RH. λ was measured at 0.05 W/mK and 0.06 W/mK (bales laid flat, but primary straw orientation not indicated). Test panels 125 mm thick, cut down from full bales.

SPSC (2019) tested the straw insulation layer of EcoCocon panels according to ISO EN 12667 and 12939, finding a design thermal conductivity of 0.06 W/mK.

Method

ISO 10456 states that design λ values must be either measured values where RH of the material tested at 23 °C is 50% (23/50 measurement) – or if measured dry the design value should be determined statistically. The method applied in each case is indicated in the text above, and in the tables below, with reported results all being equivalent of 23/50 measurements with the exception of those in Louis *et al.*, (2013b) where temperature and humidity conditions are not reported (it is assumed that tests were at ambient RH).

The statistical inner and outer fences are identified (derived from the quartiles of the results) and used to indicate statistical outliers, if present (none are found). The λ value is calculated, along with the sample standard deviation of the reported results.

Ultimately λ 90/90 values are calculated, as defined in ISO 10456 and required for all insulation products under EU regulations. The 90/90 figure is derived by multiplying the sample standard deviation by a coefficient for a 90 % statistical confidence interval (k_2) for a specific sample size (given in ISO 10456) and adding the result to the mean value. If the number of samples is smaller, the coefficient is larger – accounting for the increased statistical uncertainty resulting from a smaller number of samples. For λ values below 0.08 this is rounded up to the nearest 0.001 W/mK and for results above 0.08 to the nearest 0.005 W/mK.

One the λ 90/90 figure is established, the U value is calculated of a strawbale wall with 450mm straw, and 30mm of lime plaster each side.

This procedure is carried out on all results together; separately for results where primary straw orientation is reported as random or parallel to heatflow; and for results where primary straw orientation is reported as perpendicular to heatflow.

Results

Table 1 lists all the results which meet the criteria of this review: compliance with ISO 10456 and tests of large samples constructed from strawbales.

No strong outliers are identified, indicating a statistically reliable data set without unexpected extreme variance (although the distribution of results is not quite Gaussian, given the variety of sources).

The mean λ value from all results is 0.065 W/mK. Sample standard deviation of results is 0.00875. The k_2 value from ISO 10456 for the sample size of 22 is 1.74, resulting in a λ 90/90 value of 0.08 W/mK. The resulting U value for a strawbale wall is 0.171 W/m_2K.

Table 2 gives results for straw orientated primarily randomly or parallel to heatflow. The mean λ value in this case is 0.066 W/mK. Sample standard deviation of results is 0.00782. The k_2 value from ISO 10456 for the sample size of 19 is 1.78, resulting in a λ 90/90 value of 0.085 W/mK. Although the standard deviation is lower with these results analysed separately, the 90/90 tolerance limit and λ 90/90 value is higher than for all results analysed together – this is due to the combination of a higher mean λ value and the higher k_2 value to reflect decreased certainty in the smaller sample size. The resulting U value for a strawbale wall is 0.181 W/m_2K.

Table 1. Larger specimen tests of straw thermal conductivity, results compliant with ISO 10456, and calculation of Lambda 90/90 - all results.

Source	λ W/mK	Density, kg/m_3 (median density used where a range is stated in source data)	RH (or Design value adjusted from dry test according to ISO 10456)	thickness of test specimen in direction of heatflow	primary fibre orientation relative to heatflow	Test standard

DIBt (2006)	0.074	100	Adjusted*		parallel	EN 12667
DIBt (2017)	0.048	100	Adjusted		perpendicular	EN 12667
Shea *et al.,* (2013):	0.0594	63	50%	300 mm	random	ISO 8301 and EN 12667
	0.0621	76.3	50%	300 mm	random	ISO 8301 and EN 12667
	0.0619	87.4	50%	300 mm	random	ISO 8301 and EN 12667
	0.0642	107	50%	300 mm	random	ISO 8301 and EN 12667
	0.0642	114	50%	300 mm	random	ISO 8301 and EN 12667
	0.0636	123	50%	300 mm	random	ISO 8301 and EN 12667
Louis *et al.,* (2013)	0.0651	100	unknown	460 mm	perpendicular	ISO 8302
	0.0682	100	unknown	360 mm	parallel	ISO 8302
SPSC (2013)	0.06	112.5	Adjusted	400 mm	unknown	EN 12667
Douzane *et al.,* (2016):	0.074	80	Adjusted*	100 mm	parallel	ISO 8302
	0.051	80	Adjusted*	100 mm	perpendicular	ISO 8302
Costes *et al.,* (2017):	0.063	69.4	50%	460 mm	random	ISO 8302
	0.067	83.3	50%	460 mm	random	ISO 8302
	0.071	97.2	50%	460 mm	random	ISO 8302
	0.075	111.1	50%	460 mm	random	ISO 8302
	0.078	125	50%	460 mm	random	ISO 8302
	0.082	138.9	50%	460 mm	random	ISO 8302
D'Alessandro *et al. (*2017)	0.05	80	50%	125 mm	unknown	EN 12667
	0.06	80	50%	125 mm	unknown	EN 12667
SPSC, (2019)	0.06	112.5	50%	400 mm	unknown	EN 12667
1st quartile	0.06					
median quartile	0.0639					
3rd quartile	0.0703					
Interquartile range	0.0103					
Statistical Lower Inner fence	0.0446					
Statistical Lower Outer fence	0.0291					
Statistical Upper Inner fence	0.0858					
Statistical Upper Outer fence	0.1012					
Statistical lower strong outlier	none					
Statistical Upper strong outlier	none					
Statistical lower weak outlier	none					
Statistical upper weak outlier	none					
No. of results	22					
Mean	**0.06462**	**97.3**				
SD, Sample standard deviation of λ results	0.00875					
k_2 tolerance interval coefficient from ISO 10456 (for 90% confidence)	1.74					
90/90 tolerance limit	0.07985					
λ 90/90 (rounded according to ISO 10456)	**0.080**					
Horizontal U Value with 450mm straw and 30mm lime/sand plaster on each face, W/m^2K						**0.171**
* Adjusted according to ISO 10456 using moisture conversion factor from DIBt (2017)						

Table 2. Larger specimen tests of straw thermal conductivity, results compliant with ISO 10456, and calculation of Lambda 90/90 - straw orientation primarily random or perpendicular to heat flow.

Source	**λ W/mK**	**Density, kg/m^3** (median density used where a range is stated in source data)	**RH (or Design value adjusted from dry test according to ISO 10456)**	**thickness of test specimen in direction of heatflow**	**primary fibre orientation relative to heatflow**	**Test standard**
DIBt (2006)	0.074	100	Adjusted		parallel	EN 12667: 2001

Shea *et al.,* (2013):	0.0594	63	50%	300 mm	random	ISO 8301 and EN 12667
	0.0621	76.3	50%	300 mm	random	ISO 8301 and EN 12667
	0.0619	87.4	50%	300 mm	random	ISO 8301 and EN 12667
	0.0642	107	50%	300 mm	random	ISO 8301 and EN 12667
	0.0642	114	50%	300 mm	random	ISO 8301 and EN 12667
	0.0636	123	50%	300 mm	random	ISO 8301 and EN 12667
Louis *et al.,* (2013)	0.0682	100	unknown		parallel	ISO 8302
SPSC (2013)	0.06	112.5	Adjusted		unknown	ISO 8302
Douzane *et al.,* (2016):	0.074	80	Adjusted*		parallel	ISO 8302
Costes *et al.,* (2017):	0.063	69.4	50%	460 mm	random	ISO 8302
	0.067	83.3	50%	460 mm	random	ISO 8302
	0.071	97.2	50%	460 mm	random	ISO 8302
	0.075	111.1	50%	460 mm	random	ISO 8302
	0.078	125	50%	460 mm	random	ISO 8302
	0.082	138.9	50%	460 mm	random	ISO 8302
D'Alessandro *et al.* (2017)	0.05	80	50%	125 mm	unknown	EN 12667
	0.06	80	50%	125 mm	unknown	EN 12667
SPSC, (2019)	0.06	112.5				
1st quartile	0.06095					
Median quartile	0.0642					
3rd quartile	0.0725					
Interquartile range	0.01155					
Statistical Lower Inner fence	0.0436					
Statistical Lower Outer fence	0.0263					
Statistical Upper Inner fence	0.0898					
Statistical Upper Outer fence	0.1072					
Statistical lower strong outlier	none					
Statistical Upper strong outlier	none					
Statistical lower weak outlier	none					
Statistical upper weak outlier	none					
No. of results	19					
Mean	**0.06619**	**97.9**				
SD, Sample standard deviation of λ results	0.00782					
k_2 tolerance interval coefficient from ISO 10456 (for 90% confidence)	1.78					
90/90 tolerance limit	0.08010					
λ 90/90 (rounded according to ISO 10456)	**0.085**					
Horizontal U Value with 450mm straw and 30mm lime/sand plaster on each face, W/m_2K						**0.181**
* Adjusted according to ISO 10456 using moisture conversion factor from DIBt (2017)						

Table 3 gives the results where straw fibre orientation is stated as primarily perpendicular to heatflow. In this case the sample standard deviation is 0.00913, with a k_2 value of 4.26. The mean λ value is 0.055 W/mK. Despite the lower mean, the 90/90 tolerance level and resulting λ 90/90 figure are much higher. This is a function of the high k_2 value, indicating the level of statistical uncertainty inherent in a result based on such a small sample size. The resulting U value for a strawbale wall is 0.201 W/m_2K.

Table 3. Larger specimen tests of straw thermal conductivity, results compliant with ISO 10456, and calculation of Lambda 90/90 - straw orientation primarily perpendicular to heatflow.

Source	**λ W/mK**	**Density, kg/m3** (median density used where a range is stated in source data)	**RH (or Design value adjusted from dry test according to ISO 10456)**	**thickness of test specimen in direction of heatflow**	**primary fibre orientation relative to heatflow**	**Test standard**
DIBt (2006)	0.048	100	Adjusted		perpendicular	EN 12667
Louis *et al.,* (2013)	0.0651	100	unknown		perpendicular	ISO 8302
Douzane *et al.,* (2016):	0.051	80	Adjusted*		perpendicular	ISO 8302
1st quartile	0.0495					
median quartile	0.051					
3rd quartile	0.05805					
Interquartile range	0.00855					
Statistical Lower Inner fence	0.0367					
Statistical Lower Outer fence	0.0239					
Statistical Upper Inner fence	0.0709					
Statistical Upper Outer fence	0.0837					
Statistical lower strong outlier	none					
Statistical Upper strong outlier	none					
Statistical lower weak outlier	none					
Statistical upper weak outlier	none					
No. of results	3					
Mean	**0.05470**	**93.3**				
SD, Sample standard deviation of λ results	0.00913					
*k*2 tolerance interval coefficient from ISO 10456 (for 90% confidence)	4.26					
90/90 tolerance limit	0.09360					
λ 90/90 (rounded to nearest higher value, according to ISO 10456)	**0.095**					
Horizontal U Value with 450mm straw and 30mm lime/sand plaster on each face, W/m2K						**0.201**
* Adjusted according to ISO 10456 using moisture conversion factor from DIBt (2017)						

Table 4 provides the λ 90/90 figures for all cases and indicates the number of data points each value is derived from.

Table 4. Strawbale λ 90/90 design values, according to ISO 10456

Strawbale lambda 90/90 Design values (W/mK), according to ISO 10456		No. of data points value derived from
All orientations	**0.080**	22
With straw orientation primarily random or parallel to heatflow	**0.085**	19
With straw orientation primarily perpendicular heatflow	**0.095**	3

Conclusions

This report reviews test data that meet the requirements of ISO 10456 and by extension EU regulation for insulation products, and where test samples resemble the physical reality in constructed strawbale walls. It seeks to apply the same criteria to these results as for commercially produced insulation products, establishing a robust λ 90/90 figure for strawbale: a thermal conductivity value that 90% of tests will achieve with a 90 % statistical certainty. The calculation adjusts results to account for an appropriate level of statistical uncertainty for the number of samples in each case. Actual performance may be better in some cases, but it should only be worse in 10% of cases – reducing the risk of underestimating heat-flow during building design. The λ 90/90 figures established are approximately equivalent to design values at 23 °C and 50% RH, with results either from samples tested at these conditions or adjusted to reflect them.

The λ 90/90 value for straw where orientation is reported as either primarily random or parallel to heatflow is 0.085 W/mK; the sample standard deviation in this case is lowest, but the interquartile range is the largest. The value for straw reported as primarily perpendicular to heatflow is 0.095 W/mK; the sample standard deviation is highest in this case, but the interquartile range is the smallest. The opposite positions for the standard deviation and range figures between these two cases suggest some uncertainty in the results, possibly indicating unreliability of figures derived from separating the two sets.

When all results are analysed together the λ 90/90 figure is 0.08 W/mK.

There is further uncertainty over the degree to which bale orientation effects thermal conductivity, with only a small sample of results indicating a difference. More research is needed in this area, especially given the anecdotal and academic evidence that actual orientation in all bales is somewhat random. For this reason, it is suggested that that the most reliable λ value to use currently is that derived from all results: 0.08 W/mK.

Further research involving ISO 10456 compliant tests of strawbale would be useful. As mentioned above more extensive testing is needed to explore any difference in thermal conductivity between bales laid flat or on edge; such tests should include a slice through a bale of the type tested to demonstrate fibre orientation, ideally stating what type of baling machine manufactured the bales. For the UK specifically, important information could be obtained by identifying the type of baling machine most-frequently used to produce construction bales here. A number of samples of these bales should then be tested in identical conditions at a single test centre. A λ 90/90 value derived from such results is likely to be more representative of performance in UK strawbale construction.

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