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The Effect of Vibrations on the Density of Loose-Fill Insulations

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Part of
The National Program
for
Building Thermal Envelope Systems
and Insulating Materials

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Insulating Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

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Summary

The three major loose-fill insulation products marketed in this country have been subjected to a variety of vibrations and impacts in a laboratory setting to determine the magnitude of the resultant density increases. Repeated drops of 19 mm (.75 inch) and 152 mm (6 inch) produced density increases of up to 75% for fiberglass, 45% for rock wool and 27% for cellulosic materials. The three insulation products were also subjected to vibrations ranging from 0.1 mm (.004 inch) to 6.35 mm (.25 inch) to obtain ratios of final density over initial density. Under the test conditions studied it was observed that the lighter materials settled more percentagewise than the dense materials.

The Effect of Vibrations on the Density of Loose-Fill Insulations

Introduction

The thermal resistance, R , of a layer of loose-fill insulating material depends on the thickness, L , and the apparent thermal conductivity, k_{app} , of the material. The R -value defined mathematically in Equation (1) is used by the insulation industry as an index of thermal performance.

$$R = L/k_{app} \quad (1)$$

$$k_{app} = (Q/A)/((T_h - T_c)/L) \quad (2)$$

$$L/L_{ref} = \rho_{ref}/\rho \quad (3)$$

The thickness term in Equation (1) is related to density, ρ , as shown in Equation (3). A reduction in thickness from the reference value, L_{ref} , results in a corresponding increase in the density. The k_{app} in Equation (1) is commonly measured using devices such as the guarded hot plate or the heat flux meter. In both cases a heat flux, Q/A , and a temperature gradient, $(T_h - T_c)/L$, are determined experimentally. The magnitude of k_{app} decreases with increased density in the range of densities normally encountered with loose-fill materials.

The thickness of a layer of insulation varies inversely with density while the relationship between k_{app} and density is relatively weak. As a first approximation, therefore, R -values vary directly with thickness or inversely with density.

The specification of the density to be used in calculating the coverage obtainable from a given mass of loose-fill insulation (design density) is of primary interest to the consumer. An understanding of changes in the density with time is important for correct evaluation of long-term thermal performance and economic evaluation. The present study documents density increases in loose-fill insulations resulting from low frequency - low amplitude vibrations. Laboratory results will be given in terms of the density ratio, ρ/ρ_0 , where ρ_0 is the blown density. The ratio will be referred to as the settling factor.

Vibrations in buildings occur as a result of activity within the building as well as external factors. This includes, for example, machines, processing equipment and occupant movements. A recent study by Medearis⁽¹⁾ of characteristic house dynamics showed that houses exhibit fundamental vibration frequencies in the range 5 - 15 Hz. Medearis used seismometers in 63 residences to detect vibrations resulting from selected routine actions like the slamming of doors. A similar study completed by the National Association of Home Builders Research Foundation, Inc.⁽²⁾, NAHBRF, used strain gauges to detect occupant induced vibrations. The NAHBRF study of a single structure detected frequencies in the 7 - 45 Hz range with amplitudes up to 0.13 mm (0.005 inch). Smith and Scanlan⁽³⁾ used an accelerometer to measure vibration frequencies and amplitudes in a single residence. A typical output of their analysis is shown in Figure 1. Low frequency-small amplitude vibrations were observed. In addition, however, the data in Figure 1 show high frequency, 1000 - 2000 Hz, vibrations at low amplitudes. The results of all three vibration studies indicate the presence of low frequency-low amplitude disturbances in residential structures. The laboratory results in this paper are restricted to low frequency vibrations and impact tests. The effects of high frequency vibrations will be the subject of a future study.

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Figure 1. Accelerometer Record Resulting From Kitchen Work

Experimental Procedure

Specimens of blown loose-fill mineral fiber insulation were prepared using a truck mounted insulation blowing machine manufactured by Unisul, Inc.⁽⁴⁾ Plywood boxes approximately 457 mm (18 inches) in length, 368 mm (14.5 inches) in width and 305 mm (12 inches) in depth were filled with loose-fill insulation using the mock attic shown in Figure 2. The insulation around the boxes after a blowing operation was removed manually and the insulation in the specimen box was leveled. The insulation-filled specimen boxes were then transported to one of four test stations.

Specimens of loose-fill cellulosic insulation were also prepared in the attic shown in Figure 2 using a hand-held Cadillac⁽⁵⁾ blower. In this case the insulation was moved to the suction side of the blower by gravity feed. The same vibration and impact tests were used for the loose-fill cellulosic material that were used with the mineral fiber insulations.

The vibration devices used in this study are pictured in Figures 3 and 4. Figure 3 shows a modified Syntron polishing machine⁽⁶⁾ that was used to subject specimens to 60 Hz vibrations with a vertical displacement component of 0.1 mm (.004 inches). The polisher was fitted with a plywood platform to facilitate the firm attachment of specimen boxes. Well defined vertical vibrations were obtained using the vibration testing machines shown in Figure 4.⁽⁴⁾ The vibration testing machine can be used to produce displacements up to 6.35 mm (.25 inch) at 10 - 60 Hz.

A 19 mm (0.75 inch) drop test was conducted using the device pictured in Figure 5. This apparatus uses a notched cam to drop the specimen platform a measured distance. The shaft connected to the cam was equipped with an electronic counter to record the number of drops completed. The

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Figure 2.

Mock Attic For Specimen Preparation

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Figure 3. (a) Modified Polishing Machine (a) Side View
Showing Specimen Platform (b) Polisher
With Specimen Box attached

(b)

Figure 4. Vibration Testing Machine With Specimen
Box In Place

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Figure 5. Apparatus For 19mm Drop Test

apparatus was operated manually.

A 152 mm (6.0 inch) drop test described by Bomberg and Shirtliffe⁽⁷⁾ was accomplished using a pulley system and a 152 mm spacer. This drop test was done using boxes 914 mm (36 inches) in length. In all cases a specimen was subjected to repeated drops with density determined as a function of the number of drops.

Insulation depths in the specimen boxes as blown and after specific vibration times or number of drops were measured to within ± 6 mm (.25 inch) using a tapered steel welding rod. Average depth was determined from five measurements. One measurement was made at the center of the specimen while the other four were centered in each of the four quadrants of the specimen surface. At the completion of a series of tests the mass of the insulation in the specimen box was determined to within ± 1.0 gram.

As a result of the procedures described above it was possible to determine the density of a loose-fill specimen after measured amounts of vibration or number of drops. The density measurements are accurate to within $\pm 2\%$. Results will be discussed in terms of a settling ratio which is the ratio of the density after vibration to the blown density, ρ/ρ_0 .

Discussion of Results

Experimental values for ρ/ρ_0 as a function of vibration time on the modified polisher are shown in Figure 6 for loose-fill fiberglass, LFFG, and loose-fill rock wool, LFRW, insulations. The results obtained at displacements of 0.1 mm (.004 inches) and 60 Hz showed very small thickness changes and, consequently, the test was not used exhaustively. The settlement ratios for vibration times up to 10,000 s were 1.02 or less. One specimen of LFFG showed sufficient settlement, $\rho/\rho_0 > 1.04$, for the points to fall outside the band of experimental uncertainty. It was concluded that

Figure 6. Settling Factors Obtained With The Modified Polishing Machine

the low amplitude-low frequency vibration tests of reasonable durations do not have sufficient effect on the loose-fill material to make laboratory evaluations practical.

The 152 mm (6.0 inches) drop test was applied to LFFG, LFRW, and loose-fill cellulosic insulation, LFC. Typical curves of ρ/ρ_0 versus number of drops which were obtained from a Least Squares analysis are shown in Figure 7. Equation (4) was used to obtain a mathematical representation of the experimental data. Values for the parameters a and b in Equation (4) are given in Table 1. Equation (4) is valid for interpolations within the data set but not extrapolations.

$$\rho/\rho_0 = 1 + aN + b\sqrt{N} \quad (4)$$

where N is either the number of drops or
the total vibration time in seconds.

The curves in Figure 7 are the result of curve fitting the data without regard to initial density. The fact that the resulting equations describe the experimental data to better than $\pm 3\%$ supports the observation that blown density is not a strong factor within the density ranges tested.

Experimental results for ρ/ρ_0 after repeated 19 mm (.75 inch) drops have been correlated using Equation (4) and are shown in Figure 8. The parameters a and b for this test are given in Table 1.

The order in which the loose-fill products settle due to 19 mm drops is consistent with the 152 mm drop test data, i.e.: LFRW > LFFG > LFC. The observation that the settlement factor curves for 152 mm drops fall above the corresponding 19 mm drop curves is consistent with the fact that the velocity on impact varies with the square root of the drop distance.

Vibration tests at 10 Hz and 2.54 mm (0.10 inch) vertical displacement

Figure 7. Settling Factors For Repeated 152 mm (6 inch)
Drops of LFRW, LFFG and LFC Specimens

Figure 8. Settling Factors For Repeated 19 mm (.75 inch)
Drops of LFRW, LFFG, and LFC Specimens

TABLE 1

Values for a and b in Equation (4)

Test	Material	Average ρ kg/m^3	a	b	Number of Specimens	Number of Data Points	Average Deviation (a) %
152 mm drop	LFFG	8.8	1.55690×10^{-2}	4.66114×10^{-2}	7	81	3.0
152 mm drop	LFRW	37.6	2.54201×10^{-2}	8.83639×10^{-2}	2	25	0.6
152 mm drop	LFC	35.4	0.49355×10^{-2}	2.55624×10^{-2}	1	11	0.4
19 mm drop	LFFG	8.5	-0.13008×10^{-2}	4.96579×10^{-2}	5	49	3.3
19 mm drop	LFRW	37.6	-0.21167×10^{-2}	8.16912×10^{-2}	2	21	2.8
19 mm drop	LFC	34.6	-0.08763×10^{-2}	3.05608×10^{-2}	1	13	0.3
2.54 mm, 10 Hz vibra- tion	LFFG	11.0	-0.020422×10^{-2}	1.27915×10^{-2}	6	54	3.3
2.54 mm, 10 Hz vibra- tion	LFRW	28.6	-0.010869×10^{-2}	0.71254×10^{-2}	9	79	1.4

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(a) Average of the absolute values
of $((\rho/\rho_o)_{\text{calc}} - (\rho/\rho_o)_{\text{exp}})100/(\rho/\rho_o)_{\text{exp}}$

were completed for three specimens of LFC, nine LFRW specimens and six LFFG specimens using the vibration test machine. The constants a and b in Equation (4) were obtained for LFRW and LFFG for the entire data set. Figures 9 and 10 summarize much of the test data obtained at 10 Hz and 2.54 mm.

Figure 9 gives ρ/ρ_0 as a function of ρ_0 for 1800 s of vibration at 10 Hz and 2.54 mm. The data for each of the three insulations show the variation of settling factor observed at different blown densities with a given material. The mineral fiber insulations show a trend toward decreased settlement with increased blown density. The number of cellulose samples, three, was too small to determine a ρ_0 variation. The trend line in Figure 9 ties together the data for the three types of insulation tested and shows that settling decreases sharply with increased densities.

Average values of the settling factor for LFC, LFRW, and LFFG are shown in Figure 10 as a function of vibration time. These data which are for 10 Hz and 2.54 mm of displacement clearly show the settlement ordering among the three products, i.e., $LFC < LFRW < LFFG$. The curves shown in Figure 10 result from calculation of the average value of ρ/ρ_0 after four periods of vibration. There is a small difference between the curves in Figure 1 and the least square results summarized in Table 1.

The variations of ρ/ρ_0 with frequency and displacement have also been determined for the three loose-fill products tested. Test series were completed at displacements from 1.27 mm (.05 inch) to 6.35 mm (0.25 inch) and from 10 Hz to 30 Hz. Selected numerical results are given in Table 1. For each of the products tested results are also given for the variation of ρ/ρ_0 with displacement at a fixed vibration frequency of 10 Hz. Frequency variation results are given for a constant displacement of 3.81 mm (.15 inches).

The variations of ρ/ρ_0 with displacement are shown in Figure 11a for LFFG, Figure 11b for LFRW, and Figure 11c for LFC. In each case data for

Figure 9. Settling Factors as a Function of Blown Density for Loose-Fill Insulations Vibrated for 1800 s at 10 Hz and 2.54 mm (.1 inch) of Displacement

Figure 10. Settling Factors as a Function of Time for Loose-Fill Insulations Vibrated at 10 Hz and 2.54 mm (.1 inch) of Displacement

Figure 11a. Settling Factors for LFFG Resulting from 10 Hz Vibrations

Figure 11b. Settling Factors for LFRW Resulting from 10 Hz Vibrations

Figure 11c. Settling Factors for LFC Resulting from
10 Hz Vibrations

Figure 12. Settling Factors for Loose-Fill Insulations as a Function of Vibration Displacement for 600 Seconds at 10 Hz

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Figure 13a. Settling Factors as a Function of Vibration Frequency for LFFG Tested at 3.81 mm (.15 inch) Displacement

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Figure 13b. Settling Factors as a Function of Vibration Frequency
for LFRW Tested at 3.81 mm (.15 inch) Displacement

ORNL-DWG 81-9439

Figure 13c. Settling Factors as a Function of Vibration Frequency for LFC Tested at 3.81 mm (.15 inch) Displacement

ORNL-DWG 81-9438

Figure 14. A Comparison of Settling Factors for LFFG, LFRW, and LFC for 600 s Tests at 3.81 mm (.15 inch) Displacement

four vibration times and a fixed frequency of 10 Hz show that a large fraction of the settling takes place during the early increments of vibration. The data also exhibit a "leveling-off" at the upper end of the displacement scale. A single graphical comparison of the three products appears in Figure 12. Figure 12 demonstrates that the settlement factor decreases with increase in product density.

Variation of ρ/ρ_0 with vibration frequency at a fixed displacement of 3.81 mm (0.15 inches) is given in Figure 13a for LFFG, Figure 13b for LFRW and Figure 13c for LFC. In each case the ρ/ρ_0 values generally increase with frequency. There are two cases where the ρ/ρ_0 values versus frequency appear to be out of order. The scatter is postulated to be the result of a limited number of measurements at the frequencies in question. No adjustments have been made for variations in blown density.

The 600 second data shown in Figure 13a-c are compared in Figure 14. In this case the results for LFRW and LFFG are superimposed while the LFC tests show smaller ρ/ρ_0 values and an apparent saturation effect between 10 and 20 Hz.

Conclusions

The following conclusions are based on the laboratory data collected in this study. Quantitative results must be read with the understanding that the sample of products tested was not nationwide but rather was restricted to insulation materials purchased from local outlets.

- The three loose-fill insulations; LFFG, LFRW and LFC; show settling as a result of laboratory vibration or drop tests. Repeated 19mm drops resulted in maximum ρ/ρ_0 values of about 1.75 for LFFG, 1.45 for LFRW and 1.27 for LFC.

- The settling factor, ρ/ρ_0 , for a given product type is not strongly dependent on initial density within the range of densities tested.
- The settling factors due to 2.54 mm 10 Hz vibrations showed a dramatic decrease with initial density increase when data from all products are considered together. The magnitudes for ρ/ρ_0 are ordered LFFG > LFRW > LFC for this test.
- Settling factors due to vibration tests increase with the duration of the test. Increases of ρ/ρ_0 after 1800 s of testing, however, are negligible.
- Relatively brief, 10,000-20,000 s, vibration periods at 0.1 mm displacement and 60 Hz showed density increases equal to or less than the measurement uncertainty.
- Settling factors increase with vibration frequency or displacement in the ranges tested but appear to level-off between 4 and 5 mm of displacement at 10 Hz for the mineral fiber products.

The results of this study show that all three of the loose-fill insulations tested settle as a result of impacts or vibrations. It is recommended that the degree of settling for the three materials be determined by one test method. Determinations of design density using data from a precision vibration testing machine at specified test conditions of displacement, frequency and duration represents the best defined test and

could be combined with an environmental test. Specification of the vibration test conditions should be consistent with observations of installed loose-fill products.

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