Energy and Buildings 43 (2011) 393–399

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental study on thermal behavior of a building structure using rubberized exterior-walls

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ARTICLE INFO

Article history:
Received 29 April 2010
Received in revised form
20 September 2010
Accepted 30 September 2010

Keywords:
Scrap-tire
Waste-recovery
Thermal insulation
Energy efficient building
Time-lag

ABSTRACT

Addition of scrap-tire pieces into cementitious composites improves their thermal insulation performance. Development of such construction materials with lower thermal transmittance reusing these wastes is a challenging issue since it provides a combined solution for today's energy saving and environmental pollution concerns. In favor of this, recent European Union directives have brought quiet strict limits to reduce energy consumption and landfill disposal of solid wastes. A model room whose exteriors are fully made with scrap-tire added concrete is built here to increase its thermal protection. A standard/conventional room at identical dimensions but surrounded by ordinary concretes is also built to examine influence of scrap tire addition on room's thermal protection. Long-term thermal behaviors of these two rooms are investigated and compared under real atmospheric environments. Their indoor temperatures reveal that addition of scrap tire pieces lowers both indoor temperature variations and the effect of outdoor conditions. As an example, mean values of yearly thermal time lag are found to be 3.28 and 2.96 h, respectively for the rooms built with and without using scrap tire pieces, corresponding to nearly 11% improvement in thermal protection. Results in overall verify that scrap tire addition improves thermal protection of the room and it is a cost effective solution for people with low income and/or individuals living in rural areas.

1. Introduction

Energy use in buildings is a significant factor in world's overall energy consumption and a major contributor to greenhouse gases. Nowadays, approximately 25–30% of the total energy consumed in world is used in buildings. About 80% of the energy consumed in the commercial and residential buildings is used for space heating and cooling. Enhanced thermal protection is a therefore pre-requisite to construct or rehabilitate buildings to reach a reasonable energy consumption, satisfactory thermal comfort conditions and low operational costs. Energy saving can be obtained by insulation since significant part of heat losses or heat gains occurs through walls and ceilings [1].

The new European energy regulation (EPBD: energy performance of buildings directive) considers a high standard of thermal protection in order to advance more sophisticated energy saving measures and to stricter energy performance limits [2]. The EPBD is indeed the main community legal tool that provides for a holistic approach towards efficient energy use in the buildings sector. The EPBD's main objective is to promote the cost effective improvement of the overall energy performance of buildings. Its provisions cover energy needs for space and hot water heating, cooling, ventilation and lighting for new and existing, residential and non-residential buildings. Most of the existing provisions apply to all buildings, regardless of their size and their use (residential or non-residential). The energy efficiency requirements of the building shell or envelope have always been an essential part of nearly all regulations since the improvement of these parts represent a major saving potential [3].

Requirements for energy efficiency in a building envelope surrounding the heated and cooled parts of the building is generally set based on resistance or contribution to heat transparency through a unit of the construction, respectively *R*-value or *U*-value. In heating season, low *U*-values or high *R*-values prevent heat from escaping from buildings, and in cooling season they prevent heat from entering buildings. The typical *U*-values required by the national regulations in most European countries have been sharply dropped in the last two decades. This has caused in increasing thermal insulation thicknesses in conventional building shells. Many advanced insulation materials exist in the market to fulfill these requirements. Nevertheless, their high investment costs have always been a significant burden to some low income households and to people living in rural areas [4].

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doi:10.1016/j.enbuild.2010.09.031

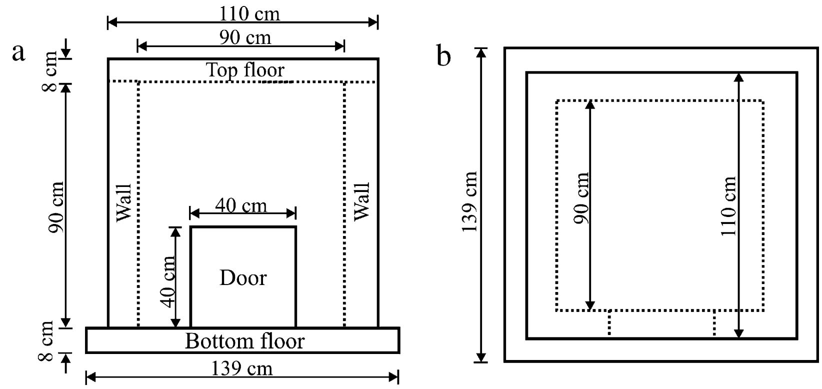

Fig. 1. Dimensions of the constructed model rooms; (a) front-view, (b) top-view.

Addition of scrap-tire pieces into cementitious composites is known to improve thermal insulation performance with almost no extra material cost and can thus provide an alternative cost-effective solution for today's energy saving need, especially for low cost buildings. It also provides an alternative safe way of utilizing a waste material to help environmental protection [5]. A series of significant restrictions on the disposal of used tires in landfills, stockpiles, or illegal dumping grounds are also imposed in recent European Union Directives, since scrap-tires hold significant part of industrial solid wastes [6]. The development of composite construction materials with lower thermal transmittance reusing these wastes is thus a challenging issue and subject of the present study.

Accumulation of a large amount of used tires annually generated is a major environmental concern for all countries. It is roughly estimated that more than 10,000,000 tires are discarded each year in Turkey, and less than 10% of these tires are currently recovered, leaving the rest to the environment. Reusing these tires in building sector would create dual benefits of reducing both the energy consumption and the environmental pollution [7,8]. Scrap tires have long been investigated as an additive to concrete to form 'Rubcrete' for various applications and have shown promising results. Addition of rubber particles has a disadvantage of leading degradation of mechanical properties, especially lowering compressive strength of the concrete. Most studies [9–12] have therefore focused on measuring physico-mechanical properties of rubberized specimens at different shapes (i.e. flat, cylindrical). They have collectively [9–14] indicated that the rubberized concrete mixtures possess lower density, increased toughness and ductility, more efficient heat and sound insulations but lower compressive and tensile strengths, which make them suitable mostly for non-load-bearing walls. Its potential thermal protection ability has therefore been disregarded for long-time, with the exception of few recent works [4,7,8,10,15–17]. These studies have mostly attempted to characterize thermal performance of rubber-added cementitious products. Up to now no work has dealt with the investigation of an end-use whole structure with rubberized concretes, such as the one presented here.

A room whose exterior walls are fully made with scrap-tire added concrete is constructed here for obtaining better thermal protection. Whole part of a scrap tire is distinctively utilized in the concrete products, without any need for removing the steel belts. This approach eliminates extra cost of removing steel belts in the whole tire, which is pre-required operation for grinding process to reach the form of crumb rubber. Thermal behavior of this rubber-added room is examined and compared with a conventional reference room at identical dimensions but surrounded by ordinary concretes.

Table 1
Mixture proportions for the concretes used in bottom and top walls.

Cement (kg/m^3)	Water (kg/m^3)	W/C	Sand (kg/m^3)
573	242	0.45	2293

2. Materials and methods

2.1. Construction of the rooms

A rubberized room (RR), whose envelope is fully made with scrap-tire added concrete, is built here to increase its thermal protection. A standard room (SR) at identical dimensions but surrounded by ordinary concretes is also built to examine influence of scrap tire addition on indoor thermal behavior. The interior dimensions of the both rooms are $90 \times 90 \times 90$ (in cm) as schematically illustrated in Fig. 1.

Two types of rubberized concretes, slabs with shredded tire rubber (as bottom and top walls) and slabs with crumb tire rubber (as side walls), are used in construction of the RR. The mixture proportions of concrete used in the bottom and top walls are given in Table 1. In processing of a scrap tire before reusing it in concrete, an original approach is applied here to benefit from all parts of a scrap tire without removing the steel belts. According to this approach; the whole tire is first splitted into three pieces by a simple cutting process: a single piece of a planar front wall and two pieces of annular side wall. Planar front wall include treads and steel belts whereas annular pieces have no metal inclusion at al. The planar surface is shredded in perpendicular by a simple mechanical process into the desired lengths without removing steel wires. These planar tire pieces are set into fresh concrete with desired distance and arrangements before pouring the top layer. The possible use of this composite material is to enhance heat insulation performance of non-loaded concrete blocks, such as floor, roof and precast concretes. The annular side sections of a scrap tire are directly grinded into crumb rubber of desired size by a simple cracker mill process. No additional separation process to remove steel fibers is necessary since this part of the tire already has no steel fragments at all. These crumb rubbers as aggregates are then used in manufacturing of side walls of the RR.

The dimensions of planar tire pieces with steel-belt used in bottom and top walls are $1.5 \times 15 \times 35$ (in cm). Their placements into half-thickness of the walls are schematically shown in Fig. 2. These planar tire pieces are smoothly arranged on the fresh poured in half-thickness of 3.25 cm into a mould. The other half of fresh concrete in thickness of 3.25 cm is then poured over the surface with rubbers. The fresh concrete is compacted and its surface is then finished.

The concrete mixture proportions of the crumb rubber added concrete used in side walls of the RR are given in Table 2. The phys-

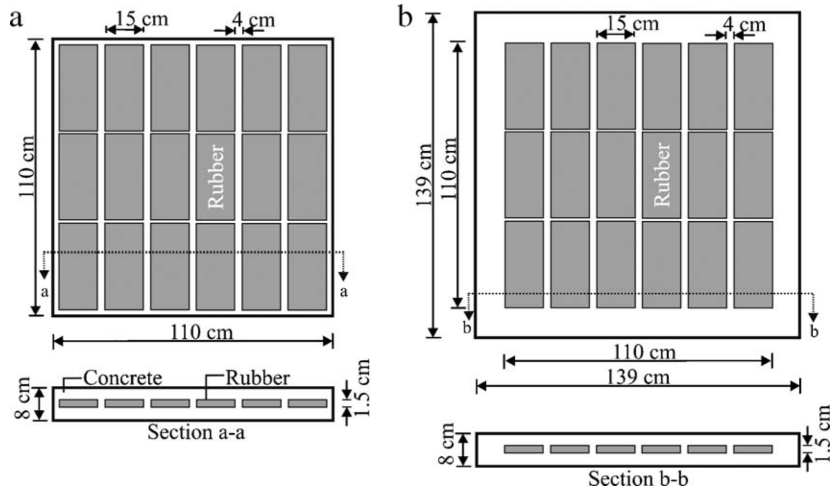

Fig. 2. Arrangement of planar scrap-tire pieces in concretes; (a) top-wall, (b) bottom-wall.

ical and mechanical properties of the crumb rubber added concrete used here are well-studied earlier by Turgut and Yesilata [10]. Its mechanical and physical properties have satisfied with the requirements of load-bearing units described in the corresponding Turkish Standard (TS 705) until crumb rubber inclusions volumetrically reach up to 60%. The concretes with 60% crumb rubber inclusions are preferred here in construction of the side walls to reach the best available thermal performance while pertaining required physico-mechanical limit. Comprehensive information on mechanical and physical test results of these crumb rubber added concretes can be found in [10].

Exterior walls of the standard room (SR) are simultaneously constructed in a similar manner without adding any rubber. Formworks are stripped after 24-h and both rooms are cured for 28-day by spraying water on exteriors. The rooms are dried by heater placed interiors for one week prior to that the thermal tests are performed.

2.2. Thermal measurements and statistical analysis

Both rooms are left unconditioned and unventilated. Their interior temperatures at five different locations along with the ambient temperature and global radiation on horizontal plane are measured and stored in a data-acquisition system with multi-channels. Instantaneous values of all thermal data are taken in 10 min interval during one year (between February 2007 and 2008). Temperature measurements taken at five different points of each room were averaged to obtain the mean interior temperature at any time. A quartile-wise approach, by splitting the distribution into four equal parts, was applied to select typical days for each month, instead of random selection of days. According to this approach a month is divided into four equal parts such as that the first, second, third and fourth quartiles correspond respectively to 4th, 12th, 20th and 28th days of a month. These days are analyzed with a special attention to describe thermal behaviors of the room for each month of a year.

In statistical analysis of instantaneous thermal data, three parameters; the range, the coefficient of variation, and the time-lag, are considered. The range is based entirely on the extreme values of the distribution. It is the simplest way of measuring the variability of spread of a distribution. The range Y for a X variable can be calculated easily by.

$$Y\_X = X_{\max} - X_{\min} \tag{1}$$

where $X_{\max}$ and $X_{\min}$ are the highest and the lowest values in the distribution.

The coefficient of variation (CV) is a dimensionless quantity that measures the amount of variability relative to the mean value. It is a useful statistic parameter for comparing the degree of variation from one data series to another, even if the mean values are drastically different from each other. The main advantage of using CV is that it allows the comparison of the scatter of each variable. It is a common approach to report CV as a percentage; such as

$$\mathrm{CV} = \frac{Std}{\overline{X}} 100 \tag{2}$$

where Std is standard deviation and $\overline{X}$ is the mean of data under consideration.

The other thermal parameter examined here for the constructed-rooms is the time lag, φ. The time lag is known as the required time for a periodic heat wave to propagate through a wall from the outer to the inner surface. The variation and swing of the external environmental temperatures result to a heat propagation process by a periodic thermal wave (thermal excitation or thermal vibration) from the outside to the inside, as schematically shown in Fig. 3. During this transient process, a heat wave flows through the wall from outside to inside, and the amplitude of these waves shows the temperature magnitudes while their wavelength shows the time. The amplitude of the heat wave on the outer surface of the wall is based on solar radiation and convection between the outer surface of the wall and the ambient air. The thermal wave, which propagates from the external to the internal surfaces of the wall, is delayed and diminished due to thermal inertia factors of the wall (the thicker and more resistive the material, the longer it will take for heat waves to pass through).

The time lag is responsible from time-delay of the thermal wave whereas the decrement ratio results in damping in amplitude of the wave shown in interior side of the wall given in Fig. 3. Thermal inertia of a wall is thus mainly represented by two factors of the time lag (φ) and the decrement ratio (f).

Mathematical descriptions of thermal inertia factors of these two are given with relatively simple equations. The time lag factor φ is calculated by considering time difference between external

Table 2
Mixture proportions for the concretes used in side walls.

Mixture	Cement (kg/m^3)	Water (kg/m^3)	W/C	Sand (kg/m^3)	Rubber (kg/m^3)
SR	537	242	0.45	1478	–
RR	537	242	0.45	591	341

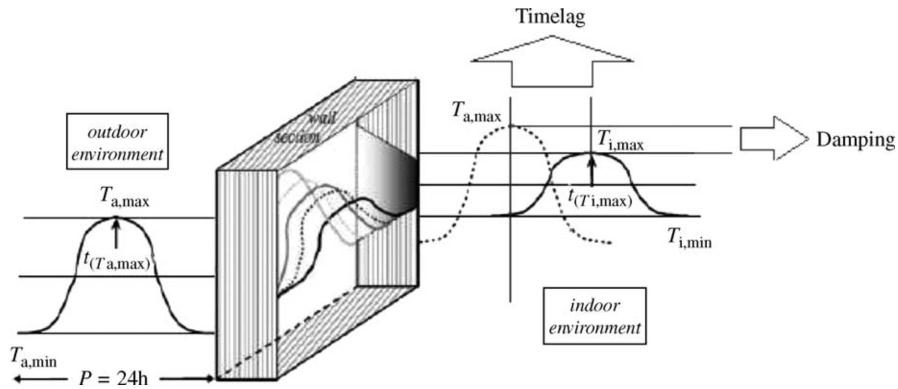

Fig. 3. Propagation of a periodic heat wave from the exterior to the interior surface of a wall.

Adapted from [18].

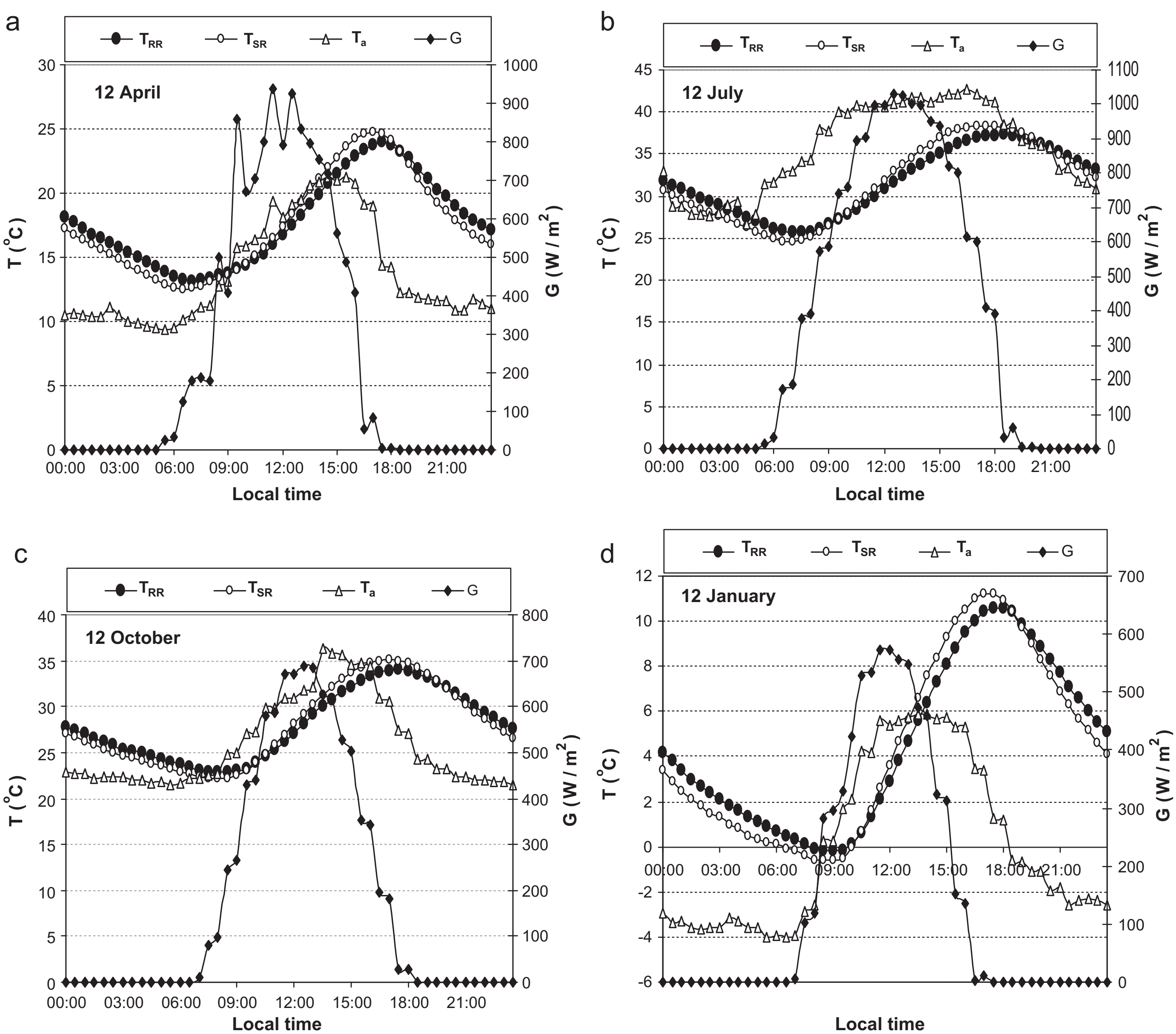

Fig. 4. Variation of indoor and ambient temperatures and solar radiation throughout the selected typical days representing various seasons of the year; (a) 1st transition season, (b) cooling season, (c) 2nd transition season, (d) heating season.

maximum (or minimum) temperature and internal maximum (or minimum) temperature, as given below:

$$\varphi(T_{\max}) = t_{(\mathrm{Ta,max})} - t_{(\mathrm{Ti,max})} \tag{3}$$

$$\varphi(T_{\min}) = t_{(\mathrm{Ta,min})} - t(_{\mathrm{Ti,min}}) \tag{4}$$

The decrement factor f on the other hand is generally described based on decreasing ratio of the temperature amplitude during the transient process of the thermal wave penetrating through the wall

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{\mathrm{a},\max} - T_{\mathrm{a},\min}}. \tag{5}$$

In Eqs. (3)–(5); t and T respectively shows time and temperature whereas subscripts 'a, i, max and min' correspond to abbreviations of 'ambient, internal, maximum and minimum'. It is important to note that f described in Eq. (5) is indeed a dimensionless measure of the statistical range parameter given in Eq. (1) (i.e. $Y\_T_i = T_{i,\max} - T_{i,\min}$).

Careful evaluations of both φ and f are important since they play a central role in several fields of the thermal analysis of building envelope schemes [18,19]. Thermophysical properties, thickness and position of wall materials have a very profound effect on both thermal inertia factors of φ and f [20–23]. Depending on thermophysical properties and thickness of the wall material, different φ and f values can be obtained. By designing special walls with a very low decrement factor and a large time lag, the propagation of the large fluctuations of outside temperatures to inside can be prevented and almost constant indoor temperatures can be obtained, which results in a good comfort level [19]. For example in winter season, the stored energy during the day can be used during night period when the outside temperature is low. Conversely, in summer, especially in some dry regions, inside temperature becomes too high for normal comfort level and walls with high thermal inertia give comfortable interior temperature even if the outside is very hot.

Because of its critical role in describing thermal performance of building envelope material, time-lag parameters of RR and SR are analyzed in this work. In the analysis; $\varphi(T_{\max})$ values given in Eq. (3) are experimentally determined from thermal measurements during a year-long. Due to extensive thermal data obtained during these measurements, results of the quartile-wise approach mentioned above are only presented here. On the other hand, instead of direct calculating the dimensionless 'f' factor, collective use of the statistical parameters of the range (dimensional measure of the 'f' factor) and CV value given respectively in Eqs. (1) and (2) are preferred here. This type of statistical approach is indeed observed to be quiet appropriate when analyzing such complicated long-term thermal data taken in unconditioned and unventilated rooms [17]. It is because of the fact that the damping effect may disappear in some consecutive days under mentioned conditions and dimensionless f values alone could sometimes be misleading. Besides, the combined approach used here allows satisfactory statistical observations on both extreme limits and stability of temperatures in the rooms under consideration.

3. Results and discussion

The variations of temperatures and global solar radiation for the selected days which represent heating, transition and cooling seasons are shown in Fig. 4(a)–(d). As seen from the graphs, although the interior temperatures of the RR and the SR show qualitatively similar trends, the differences between the ambient and indoor temperatures are generally higher for RR. This feature of RR represents an advantage for thermal comfort when there is a significant diurnal temperature swing.

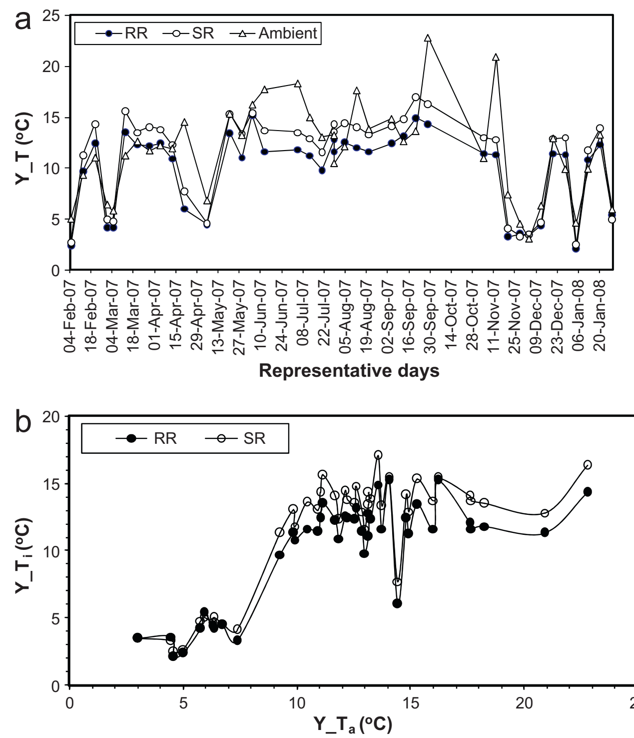

Fig. 5. Statistical range values of temperatures, as a function of (a) representative days, (b) range of ambient temperatures.

With the purpose of a quantitative comparison, variations of the indoor temperature ranges for both rooms (Y_T_i) along with outdoor temperature ranges (Y_T_a) are illustrated in Fig. 5. Results are first presented on yearly basis, in terms of representative days correspond to the typical days of each month selected by quartile-wise approach (see Fig. 5(a)). The temperature range of the RR is always smaller than that of the SR and the ambient, indicating that the indoor temperature of the RR has more uniform variation and it is less affected from outdoor conditions. It can be seen from Fig. 5(b) that both rooms indeed act qualitatively similar but the RR is less affected from outside temperature changes. In both cases, increasing outdoor temperature range results in a monotonic increase in the indoor temperature range, until a critical value of about 11 °C is reached. The indoor temperatures construct a plateau, swinging in a narrow band with nearly constant width after this critical point. It is also noticeable that the indoor temperature variations in RR remain distinctively lower at quite large values of the outdoor temperature range (>18 °C). The yearly mean difference between the ranges of the SR and the RR is calculated as 1.33 °C, confirming that RR provide better thermal comfort on yearly basis. This much of difference may seem small but it corresponds to nearly 12% improvement in thermal comfort conditions of the room.

It has been quantitatively verified by Turgut and Yesilata [8] that the introduction of the scrap-tire pieces into concrete products cause an increasing thermal resistance, reducing the heat transfer through the wall. By applying a comparative thermal performance measurement technique of the adiabatic-box (see [10], for the technique), they have found that inclusions of shredded and crumb tire rubbers separately into concrete slabs improve thermal performance respectively by 13.3% and 10.8%. These results have been obtained with similar content and configurations of the tire-rubbers used in exterior walls of the RR considered here. Higher thermal resistance of the RR envelope is known to be very important for keeping the temperature changes of indoor air at a minimum level of thermal comfort.

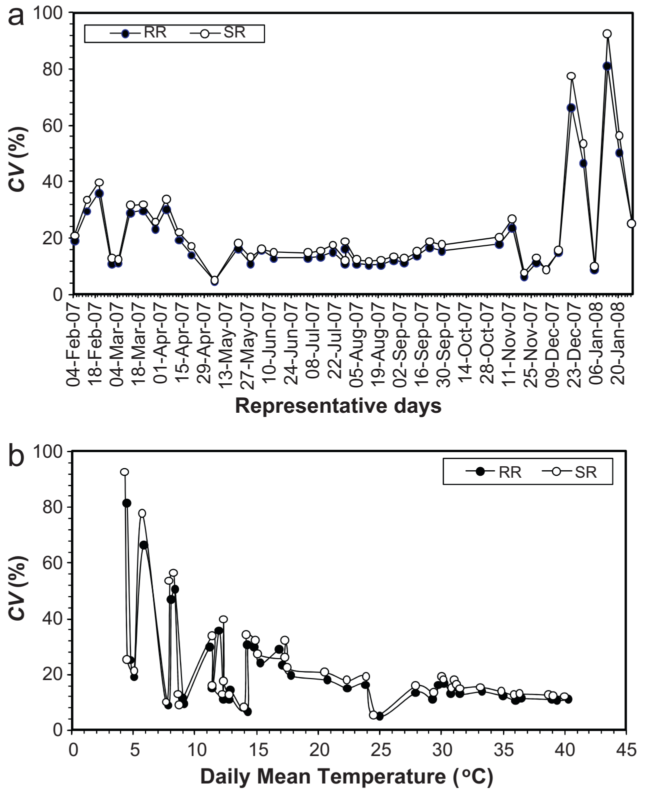

Fig. 6. Statistical CV values of interior and ambient temperatures, as a function of (a) representative days, (b) mean ambient temperatures.

The coefficient of variation (CV) is also examined here for both rooms in order to compare the stability of indoor temperatures around their mean values. The mean, standard deviation and CV values of indoor temperatures are calculated for this purpose by considering typical days selected from the quartile-wise approach. Major output of this analysis is based on CV values and results are presented in terms of representative days and daily mean temperatures in Fig. 6(a) and (b), respectively. From both plots, it is clear that CV values for the SR are always greater than those of the RR. This means that the RR has less indoor temperature fluctuations or more stable temperature swings around their means. Regardless of this comparison, interior temperatures behave more stable in summer months, gradually getting the worst through the coldest months. Expressed in percentage, the interior temperature stabilities of the RR are better respectively by 14% and 9% in summer and winter months. Improvement on yearly basis is nearly 13%.

The last thermal parameter statistically examined here is the time lag, φ. Because of the time lag effect, the interior temperatures of the rooms will be a function of the outside/ambient temperatures over some previous hours. In order to illustrate such an influence, indoor temperature profiles of both rooms along with ambient temperatures for five consecutive days in two different seasons are given in Fig. 7. Temperature profiles of the rooms are only for indicative purpose to show that $\varphi(T_{max})$ values for the presented consecutive days are relatively higher for the RR. Having larger thermal lag delays and prevents the majority of undesired outdoor heating and cooling effects reaching from the outside air to the inside.

Quantitative calculations of φ (based on T_{max}) values from experimental measurements are also performed here. The maximum temperatures and their occurring times are identified from the instantaneous temperatures measured for the representative typical days of the year under consideration. These extensive

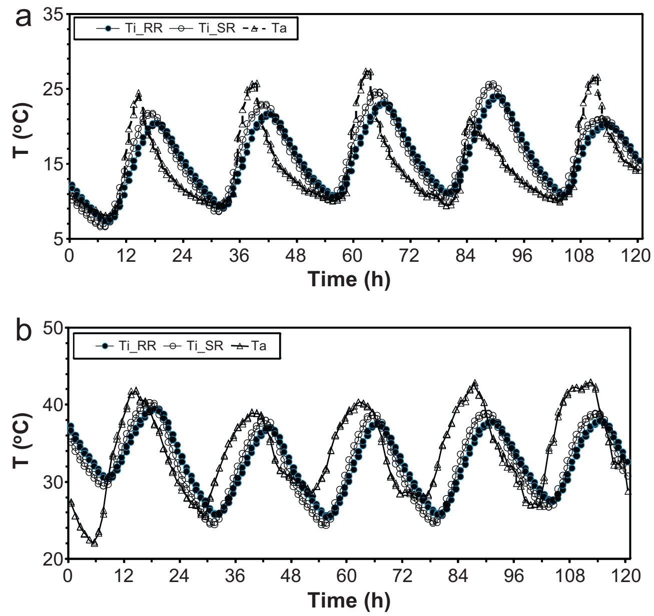

Fig. 7. Interior and exterior temperature profiles for five consecutive days in two different seasons: $t = 0$ on the horizontal axis corresponds to (a) 00:00 of March 07, (b) 00:00 of July 07, 00:00.

data-set are not tabulated here but available upon request. The measurements indicate that the ambient temperatures in general reach the highest values between 11:30 and 16:30 whereas the indoor temperatures reach the highest values between 16:00 and 19:00. The calculations have shown that there are many days for which the φ values of the rooms are not distinctively different, or the maximum ambient temperatures are lower than the interior ones, due to the nature of long term thermal measurements in uncontrolled room environments. When there is difference on φ_{RR} and φ_{SR} (time lag values for the RR and SR, respectively), φ_{RR} values are generally higher, shifting the peak to later hours. This feature of φ_{RR} is shown in Fig. 8 by using a dimensionless ratio of $\varphi_{RR}/\varphi_{SR}$. This ratio is generally equal or slightly more than unity. There are few exceptional points in where the ratio goes below unity or much higher than unity.

On yearly basis, the difference on the φ_{RR} and φ_{SR} is found to be only 0.32 h, which is relatively small in number-wise. This difference is mainly due to insulation improvement provided by tire-rubber addition since the rooms are empty and small in dimensions, minimizing possible thermal-mass contribution. Obtaining relatively small φ values for both rooms (3.28 h for RR and 2.96 h

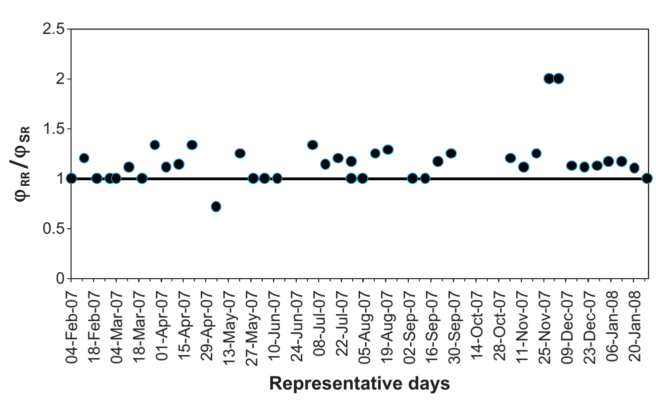

Fig. 8. Dimensionless ratio of time lag values for both rooms ($\varphi_{RR}/\varphi_{SR}$), as a function of representative days.

for SR) is thus not surprising. This small difference in numbers can gain a better meaning in percentagewise, corresponding to nearly 11%, improvement in the time-lag factor, just by adding tire rubber pieces into thin concrete walls with no extra material cost.

4. Conclusions

This paper presents an explorative study to investigate what the thermal benefits are for adding scrap-tire pieces into building envelope materials. A room whose exterior walls are fully made with scrap-tire added concrete is constructed here for obtaining better thermal protection. Two types of scrap-tire processing approaches are applied to reuse whole part of a scrap-tire, without leaving any piece into the environment. Planar front side piece with steel-belt of a scrap-tire is utilized in non-loaded bottom and top walls of the room. Annular side pieces with no metal inclusion are grinded and used as aggregates in load-bearing side walls of the room. It provided reasonable compressive strength satisfying the requirement of related Turkish Standard (TS 705) for load bearing masonry. In terms of construction technique, such an application is observed to be usable and practical, especially for individual houses. Thermal behavior of this room with rubberized walls (RR) is compared with a standard room with conventional concrete walls (SR). Experiments under exact outdoor environmental conditions are conducted during a year-long and measured parameters are statistically analyzed.

The range value of indoor temperature and its fluctuations around the mean (CV value) are determined to be always smaller for the RR, verifying that it has a more uniform and more stable temperature variation. It is also an indication of that the RR is less affected by the outside environmental conditions. These favorable effects become more clear when drastic changes in outside temperature range exist. The time lag (φ) values for the RR are found to be higher for all seasons, which is a direct signal of having better thermal protection. It thus reduces the energy need for heating and cooling.

It is verified in this study that the introduction of the scrap-tire pieces into building walls reduces the heat transfer through them by increasing their thermal resistances. Such an application will currently be extremely cost-effective solution for people with low-income and/or individuals living in rural areas.

Acknowledgements

The authors wish to acknowledge the financial support of The Scientific and Technological Research Council of Turkey, TÜBİTAK (Under Project Number of TUBITAK-MAG-105M021). Contribution provided by Yusuf Isiker, Harran University ME Dept., during experimental phase of this work is also highly appreciated. Many thanks to the anonymous reviewers for that their detailed comments in both the technical and the grammatical issues were extraordinarily constructive and critical.

References

[1] A.M. Papadopoulous, E. Giama, Environmental performance evaluation of thermal insulation materials and its impact on the building, Building and Environment 42 (2007) 2178–2187.
[2] The European Parliament and the Council of the European Union, Council Directive of 2002/91/EC: the Energy Performance of Buildings, issued on 16 December 2002.
[3] H. Haydock, J.-A. Arbon, Study on energy performance of building, Report No: SIP/A/ITRE/ST/2008-10, manuscript completed in February 2009, 107 pp.
[4] B. Yesilata, P. Turgut, A simple dynamic measurement technique for comparing thermal insulation performances of anisotropic building materials, Energy and Buildings 39 (2007) 1027–1034.
[5] R. Siddique, T.R. Naik, Properties of concrete containing scrap-tire rubber—an overview, Waste Management 24 (2004) 563–569.
[6] The European Parliament and the Council of the European Union, Council Directive of 2006/12/EC: Waste, issued on 5 April 2006.
[7] B. Yeşilata, Y. Işıker, P. Turgut, Thermal insulation enhancement in concretes by adding waste PET and rubber pieces, Construction and Building Materials 23 (2009) 1878–1882.
[8] P. Turgut, B. Yeşilata, Investigation of thermo-mechanical behaviors of scrap rubber added mortar plate and bricks, Journal of the Faculty of Engıneerıng and Archıtecture of Gazi University 24 (2009) 651–658.
[9] M.M. Reda-Taha, A.S. El-Dieb, M.A. Abd. El-Wahab, M.E. Abdel-Hameed, Mechanical, fracture, and microstructural investigations of rubber concrete, Journal of Materials in Civil Engineering 20 (2008) 640–649.
[10] P. Turgut, B. Yesilata, Physico-mechanical and thermal performances of newly developed rubber-added bricks, Energy and Buildings 40 (2008) 679–688.
[11] L.H. Chou, C.K. Lu, J.R. Chang, M.T. Lee, Use of waste rubber as concrete additive, Waste Management & Research 25 (1) (2007) 68–76.
[12] E. Ganjian, M. Khorami, A.A. Maghsoudi, Scrap-tyre-rubber replacement for aggregate and filler in concrete, Construction and Building Materials 23 (2009) 1828–1836.
[13] A. Yilmaz, N. Degirmenci, Possibility of using waste tire rubber and fly ash with Portland cement as construction materials, Waste Management 29 (2009) 1541–1546.
[14] B.S. Mohammed, Structural behavior and m–k value of composite slab utilizing concrete containing crumb rubber, Construction and Building Materials 24 (2010) 1214-1221 doi:10.1016/j.conbuildmat.2009.12.018.
[15] A. Benazzouk, O. Douzane, K. Mezreb, B. Laidoudi, M. Quéneudec, Thermal conductivity of cement composites containing rubber waste particles: experimental study and modelling, Construction and Building Materials 22 (2008) 573–579.
[16] H. Zhu, N. Thong-On, X. Zhang, Adding crumb rubber into exterior wall materials, Waste Management & Research 20 (2002) 407–413.
[17] H. Bulut, B. Yesilata, P. Turgut, Y. Işiker, Investigation of indoor thermal behaviors for scrap tire added structures, Engineer and Machinery 49 (578) (2008) 19–27 (in Turkish).
[18] K.J. Kontoleon, E.A. Eumorfopoulou, The influence of wall orientation and exterior surface solar absorptivity on time lag and decrement factor in the Greek region, Renewable Energy 33 (2008) 1652–1664.
[19] K. Ulgen, Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor, Energy and Building 34 (2002) 273–278.
[20] H. Asan, Y.S. Sancaktar, Effects of wall's thermophysical properties on time lag and decrement factor, Energy and Building 28 (1998) 159–166.
[21] H. Asan, Effects of wall's insulation thickness and position on time lag and decrement factor, Energy and Buildings 28 (1998) 299–305.
[22] M. Ozel, K. Pihtili, Optimum location and distribution of insulation layers on building walls with various orientations, Building and Environment 42 (2007) 3051–3059.
[23] R. Yumrutas, O. Kaska, E. Yıldırım, Estimation of total equivalent temperature difference values for multilayer walls and flat roofs by using periodic solution, Building and Environment 42 (2007) 1878–1885.