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Article

Ground Thermal Inertia for Energy Efficient Building Design: A Case Study on Food Industry

Fernando R. Mazarrón [1,*], Jaime Cid-Falceto [2] and Ignacio Cañas [2]

[1] Rural Engineering Department, E.T.S. Agronomics Engineering, Polytechnic University of Madrid, Avda. Complutense s/n. 28040 Madrid, Spain

[2] Construction and Rural Roads Department, E.T.S. Agronomics Engineering, Polytechnic University of Madrid, Avda. Complutense s/n. 28040 Madrid, Spain; E-Mails: jaime.cid@upm.es (J.C.-F.); ignacio.canas@upm.es (I.C.)

* Author to whom correspondence should be addressed; E-Mail: f.ruiz@upm.es; Tel.: +34-913365670; Fax: +34-913363688.

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Abstract: The search for energy efficient construction solutions is still pending in the agro-food industry, in which a large amount of energy is often consumed unnecessarily when storing products. The main objective of this research is to promote high energy efficiency built environments, which aim to reduce energy consumption in this sector. We analyze the suitability of using the thermal inertia of the ground to provide an adequate environment for the storage and conservation of agro-food products. This research compares different construction solutions based on the use of ground thermal properties, analyzing their effectiveness to decrease annual outdoor variations and provide adequate indoor conditions. The analysis undertaken is based on over five million pieces of data, obtained from an uninterrupted four year monitoring process of various constructions with different levels of thermal mass, ranging from high volume constructions to others lacking this resource. It has been proven that constructive solutions based on the use of ground thermal inertia are more effective than other solutions when reducing the effects of outdoor conditions, even when these have air conditioning systems. It is possible to reach optimal conditions to preserve agro-food products such as wine, with a good design and an adequate amount of terrain, without having to use air conditioning systems. The results of this investigation could be of great use to the agro-food industry, becoming a reference when it comes to the design of energy efficient constructions.

Keywords: efficient design; thermal inertia; agro-food construction; indoor conditions

1. Introduction

The goal of energy efficient construction solutions has not yet been accomplished in agro-food constructions, for which technical studies and guidelines are needed to find energy efficient solutions adapted to the environment. The main objective of this investigation is to evaluate the effectiveness of using ground thermal inertia for passive thermal control of indoor conditions in agro-food buildings.

Soil is a good moderator of temperature given its thermal properties. The great heat capacity and high thermal inertia allow a damping of above-ground temperature fluctuations with soil depth at an exponential rate [1]. Because of this, terrain has been used since the beginning of mankind in order to reduce effects of weather fluctuations, especially in areas with great seasonal or daily variations.

There are some research works studying the indoor thermal conditions and the energy efficiency of constructions with high thermal inertia, such as cave dwellings [2], earth-sheltered housing [3,4] and food cellars [5–9]; Studies focused on wall behavior are also available [10].

Amongst the previous applications, its use for agro-food conservation is noteworthy. Underground food storage has been a common practice since pre-neolithic times (9000 to 7000 BC) in the Middle East and since Neolithic times in Europe [11]. This is due to the need for food products to be kept under stable conditions in order to mature and preserve, in some cases, over long periods of time. In addition to reducing the energy consumption, the temperature inside subterranean buildings is very stable, this can be useful in various industrial processes [6]. Many current agro-food businesses have chosen to re-use old underground constructions, or to build new designs with high thermal inertia, taking advantage of its previously described benefits.

The uniqueness of this investigation is in the simultaneous analysis and comparison of different designs based on the use of ground thermal properties, studying its effectiveness to reduce outdoor climate variations and provide adequate indoor conditions for food products. The aim is to reduce the risks taken by companies when they have to decide among designs for new facilities. The approach has been to analyse constructions over a long period of time in order to obtain a realistic perspective of the effectiveness of ground thermal inertia. Constructions situated above surface, with and without air conditioning systems, have also been analysed. These do not use ground thermal inertia (except for the ground surface common to all constructions) and have been compared to constructions which do use terrain.

To delimit the study, constructions used for wine ageing and conservation have been selected. The reasons are:

(a) There are many constructions with different typologies of terrain use, which are used commercially by companies in this industry. It is possible to select representative constructions of different types in a same area.
(b) Traditionally, wine ageing and storage was done in constructions with great thermal inertia to prevent it from being impacted by outdoor climate changes. Nowadays, the constructions for wine production are built on the surface. Subterranean cellars for the ageing of wine are only

being constructed occasionally, being replaced by climate control because of the lower initial cost [12]. This change of construction techniques is the cause of an increase in energy consumption in modern wineries. In these buildings, complex air-conditioning systems are necessary in order to achieve the optimal thermal conditions [13]. The intention is to encourage the industry to go back to using energy efficient constructions.

(c) The winemaking literature stresses the importance of a constant low temperature and high relative humidity inside buildings where wine is stored, in order to produce a high-quality end product and reduce wine losses [12]. In the making of quality wines the conservation and ageing process is the longest stage. In certain countries, such as United States and Australia it is the wine-maker who decides the optimum amount of cask storage time for each wine. In other countries, the time that the wine must spend in cask is regulated by law [14], as is the case in Spain, where the minimum period for red wines ranges between 24 and 60 months. Considering the time required for the aging of wine and the size of the constructions, the use of an air conditioning system implies a considerable increase in energy consumption. Therefore the principal quality of the construction should be that it assures suitable temperature and relative humidity conditions.

(d) World wine production in 2009 stood at 271 millions of hectolitres [15]. The world spends 320 billion Euros on wine a year, according to industry insiders gathered at the Vinexpo trade fair, held at Bordeaux, France in June 2011. The costs of processing grape juice into wine can vary significantly, depending on the style of wine produced, e.g., early bottled wine, long-ageing wine, wine aged in barrels, *etc.* On average, it is estimated that producing 1 L of wine sold in a 75 cL glass bottle costs around 0.5–1.2 Euros/L [16]. Ageing wine in barrels will increase this cost. Given the importance of this sector, it is interesting to encourage it to use constructive solutions which help reduce energy consumption and lower the costs of production.

2. Materials and Methods

The aim is to compare the differences and the possible advantages of some of these solutions in terms of hygrothermal ambient. The study proposes a method based on the analysis of indoor conditions in representative constructions carried out with different solutions, which are currently used to control interior conditions. It is of interest to know the effectiveness of different solutions regarding the reduction of outdoor climate variations as well as the hygrothermal condition results, and how all this relates to the well-being of agro-food products.

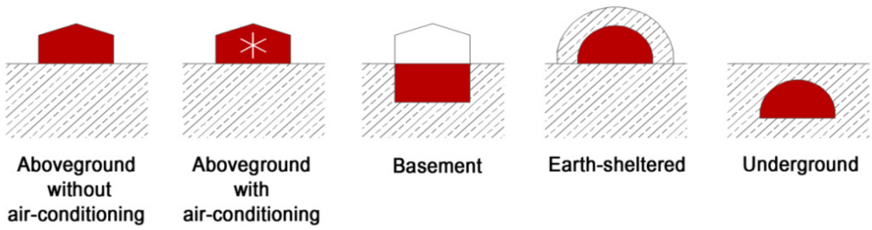
The idea is to monitor existing and functioning buildings with great thermal inertia, comparing their indoor conditions with other buildings without this resource. It is necessary for all buildings to be in the same area, with similar outdoor conditions. The area chosen for this was the *Ribera del Duero* region in Spain, located between Soria, Burgos and Valladolid. It has a long tradition in underground winery constructions and other designs of great thermal inertia because of the area weather conditions, typical of the Mediterranean continental climate. This area is characterized by dry summers and long, cold winters with marked thermal oscillations. The Ribera del Duero is one of the most prestigious and well known Spanish appellations of origin, and some of its wines cost more than 1,000€ per bottle. The region has been associated with wine and vineyards for more than two millennia.

2.1. Representative Constructions

After a thorough analysis in which 189 building were examined, the different constructive solutions found to ensure optimal conditions for wine conservation and ageing were put together in the following groups (Figure 1):

- Aboveground: the construction is on flat ground, similar to other agricultural and industrial facilities. This category of cask cellar includes wine-production facilities equipped with an air-conditioning system in order to control the relative humidity and temperature conditions.
- Basement: the construction is just below ground level, creating a cellar below the other facilities. All four walls are thus in contact with the surrounding earth.
- Earth-sheltered: the construction is on ground level but completely sheltered, as it is under earth to recreate the conditions of an underground cask cellar.
- Underground: the construction has been dug straight out of the soil.

Figure 1. Diagram of building-solution options.



According to the previous groups, a representative construction for each of the main constructive solutions found for the ageing and conservation of wine was selected, after examining dozens of buildings. To maintain confidentiality, the five buildings will be identified by the type of construction: "aboveground without air-conditioning", "aboveground with air-conditioning", "basement", "earth-sheltered" and "underground" (Figure 2). The constructions selected are located in a radius of 50 km. The external conditions are very similar. All are commercial wineries that remained operational for the duration of the monitoring period.

Figure 2. Close-ups of the interior of the selected constructions. From left to right, "aboveground without air-conditioning", "aboveground with air-conditioning", "basement", "earth-sheltered" and "underground".

The main characteristics of each construction are as follows:

(a) "Aboveground without air-conditioning" construction

At this winery the storage and ageing is carried out in a warehouse on flat ground, with dimensions of 60 m by 20 m and an average ceiling height of 8.5 m. This warehouse is separate from other facilities. Its central aisle is oriented north–east, with shadow from a warehouse positioned in parallel, a few metres away, falling on the south-west side. It has metal arches and pillars, and thick prefabricated-concrete walls (40 cm) with built-in insulation. The round-stoned roof drains off in various directions.

(b) "Aboveground with air-conditioning" construction

This winery is made up of four separate units, divided by two circulation aisles forming a cross. The wine ages in the north-west unit. Its dimensions are 38 m × 26 m × 8 m, and the longest aisle runs east–west. The warehouse has concrete walls and the roof is supported on concrete beams, holding up curved metal panels. The warehouse's air-conditioning system consists of three fan-coils and several humidifiers located on one side. They are turned on during the warmest months to counteract the high temperatures and some years they also operate during the winter months to raise the temperature. The target temperature for the air-conditioning system is 16 °C, to avoid increasing excess energy expenditure, and the relative humidity 75–80%.

(c) "Basement" construction

This winery is made up of several units with varying areas and roof heights. The cask warehouse measures 50 m by 17 m and the height is 6 m. The longest aisle runs north-east to south-west. It is in the south corner of the building, below the room used to store the bottle racks. All its walls are in contact with the earth. There are ventilation openings at two heights on the south-east wall.

(d) "Earth-sheltered" construction

This construction has been designed imitating the characteristics of a traditional underground cellar. It is not under a slope, but rather is the result of digging out an adjacent hill and building three concrete tunnels which were then covered with the earth dug from the hill. The vaulted tunnels are 13 m wide at the lowest point, and 10 m high in the centre of the arch. Because of its vaulted section, the amount of terrain that surrounds it varies as we move away from the centre of the section. The upper part is 3 m deep, going down to 13 m in separation zones between naves. The cask warehouse is the central nave of the three. One nave is used as a bottle-storage area and the third nave is for the fermentation tanks. The beginning of the nave leads to the exterior and the end "runs into" the earth. The warehouse is 90 m by 13 m. It has several ventilation chimneys distributed along the length of the nave.

(e) "Underground" construction

Access is through an old wine press. The door faces west. It is set out in ramifications at the beginning and leads into a tunnel that is 100 m long and over 4 m high. Because it is dug in a hill, the average depth varies between 10 and 20 m, depending on the area of the wine cellar. This wine cellar was built relatively recently, by boring into the earth to enlarge the original traditional cave. The walls leave the bare earth visible as it was excavated.

2.2. Monitoring the Constructions

The temperature and relative humidity in the storage facilities for each of the main construction solutions were monitored for four years (2006–2009), gathering over five million pieces of data relative to indoor and outdoor climate. To monitor the internal conditions two Hobo® data logger models were used, with thermistor-type internal sensor for the temperature and a capacity-type sensor for the humidity: the Hobo H8 Pro and the Hobo Pro v2 (an updated version of the former). The precision of these sensors is ±0.2 °C at +21 °C and ±3% relative humidity from 10 to 90% for the Hobo H8 Pro; ±0.18 °C at 25 °C and ±2.5% relative humidity from 10 to 90% for the Hobo Pro v2. The resolution of the Hobo H8 Pro is 0.02 °C and 0.5% relative humidity; 0.02 °C and 0.03% relative humidity for the newer model. The measurement interval was set at 15 minutes for all the loggers.

In all the constructions, loggers were installed near the centre of the storage facilities, at the same height (1.8 m), thus ensuring that meaningful comparisons could be made. In addition, the outside temperature and relative humidity of the study zone was monitored over the period by the same loggers, installed in protective shells designed for outdoor use.

2.3. Quantification of the Construction Effectiveness to Decrease Outdoors Variations

The effectiveness of the construction to decrease annual outdoors variations has been quantified through the annual time lag and decrement factor. The evaluation of time lag and decrement factor provides a measure of the developed indoor thermal comfort conditions and, from an energy point of view, the possibility of reducing the energy load demands [17]. Time lag and decrement factor are very important characteristics to determine the heat storage capabilities of any material [18].

Decrement factor (or decreasing ratio or dimensionless amplitude or temperature attenuation) is defined as the decreasing ratio of its temperature amplitude during the transient process of a wave penetrating through a solid element [17]:

$$f = (T_{i,max} - T_{i,min})/(T_{e,max} - T_{e,min}) \quad (1)$$

where $T_{e,min}$, $T_{i,min}$, $T_{e,max}$, and $T_{i,max}$ are the minimum and maximum developed temperatures on both wall boundaries.

On the other hand, time lag (or phase lag or time shift or time delay) is defined as the time required for a heat wave, with period P, to propagate through a wall from the outer to the inner surface [17]. It can be determined through the maximum of the period:

$$\varphi = t_{Ti,max} - t_{Te,max} \quad (2)$$

where $t_{Te,max}$ and $t_{Ti,max}$ represent the times when exterior and interior surface temperatures are at their maximums.

For the case of high thermal inertia buildings, it is interesting to calculate the annual time lag and decrement factor, unlike in other constructions where the studies focus on the daily time lag and decrement factor. The large thermal inertia of the terrain prevents the daily oscillations from being perceived inside (excluding the ventilation effect). We need to know how the stored heat in the hottest months is released in the coldest months and *vice versa*. For this reason, the time lag and decrement factor are computed considering annual cycles of temperature.

The ventilation effect has been considered, assuming mean values for the entire construction. Thus, $T_{i,max}$ and $T_{i,min}$ are the interior maximum and minimum air temperatures and $T_{e,max}$, and $T_{e,min}$ the exterior maximum and minimum air temperatures registered during a year. $t_{Te,max}$ and $t_{Ti,max}$ represent the date in days when exterior and interior temperatures are at their maximums. The estimated time lag values may experience small variations depending on ventilation conditions.

2.4. Hygrometric Conditions and Interior Comfort

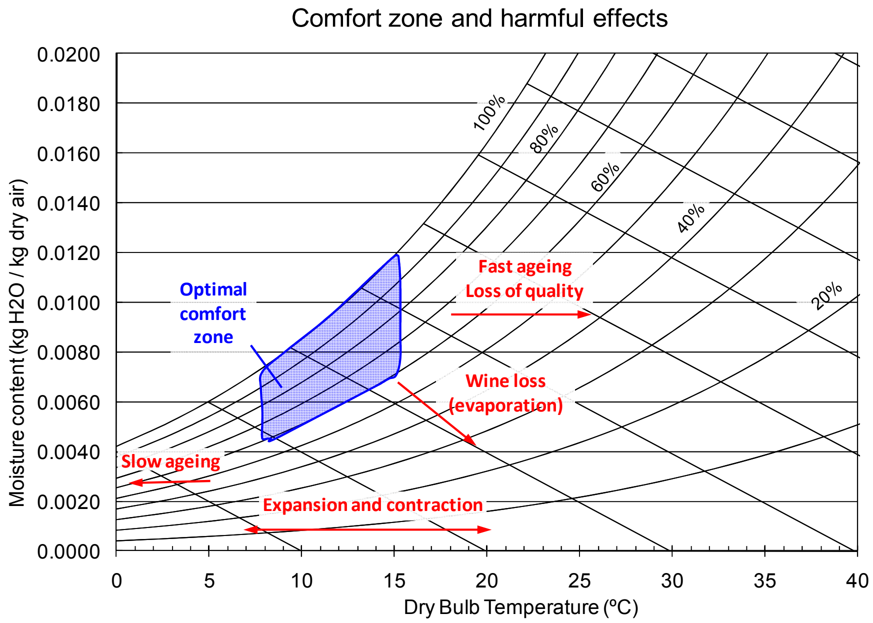
In addition to the effectiveness of the construction to reduce outdoor weather conditions and to produce a time lag between outdoor and indoor temperatures, it is important to take into account the evolution of hygrometric conditions throughout the year, and how it relates to required comfort conditions. For that purpose, a psychometric chart for atmospheric pressure of 90.99 kPa (900 m) has been used.

In the particular case of wine, there are numerous studies on the optimal conditions for the conservation and ageing [19–22]. Despite the varied recommendations on optimal conditions for wine-ageing, there is some degree of unanimity when it comes to the following aspects:

- High temperatures above 18–20 °C make the wine age more rapidly, with the consequent loss of quality.
- Very low temperatures, below 4–5 °C, sustained over long periods mean that the wine will age slowly.
- The relative humidity must be high so as to reduce losses due to evaporation, provided that the appearance of harmful mould can be ruled out. Therefore we can recommend high relative humidity to reduce the evaporation losses, provided that the ventilation is adequate.
- The annual interval and temperature variations should not be high as contraction and expansion phenomena affect the handling and quality of the wine.

Working from the previous recommendations, an optimal comfort zone between 8 °C and 15 °C and relative humidity above 60% can be assumed; this would mean compliance with the optimal conditions recommend by most authors. According to most of the wine ageing and preservation bibliography, not being in the optimal comfort zone does not necessarily imply inadequate conditions for wine, but it does imply a stronger impact of negative effects such as evaporation, rapid colour evolution, *etc*., especially when conditions are stable over time. Temperature and relative humidity values can be outside the optimal comfort zone as long as they do not surpass critical values. Beyond these there would be problems of wine quality, handling or significant losses from evaporation. Figure 3 shows the diagram used as the basis for the analysis, showing the optimal comfort zone and the harmful effects on the wine when the values move away from this zone during the aging process.

Figure 3. Recommended optimal comfort zone for wine aging and possible harmful effects outside this zone.



3. Results and Discussion

3.1. Quantification of the Construction Effectiveness

Because of the great thermal mass these buildings have, outdoor climate variations throughout the day barely affect the interior stability. For that reason, the study analyses variations throughout the year, using daily mean values, and eliminating random fluctuations occurred each day (Table 1).

Outdoor condition differences between opposite locations in the studied area are not significant, as shown by a mean daily standard deviation of 0.6 °C. For that reason, conditions have been simplified: all outdoor conditions are considered the same.

Table 1. Representative temperature values inside and outside the constructions. Average year over the 2006–2009 period, calculated from daily mean values.

	Mean Daily Temperature (°C)					
		Inside				
	Outside	**Aboveground without air-conditioning**	**Aboveground with air-conditioning**	**Basement**	**Earth-sheltered**	**Underground**
Annual mean	11.2	14.4	13.6	13.2	12.5	9.9
Annual max.	24.4	21.8	16.9	17.3	14.9	11.1
Annual min.	−1.1	7.8	9.6	8.9	10.3	8.6
Annual interval	25.5	14.0	7.3	8.4	4.6	2.5

The studied area has a Mediterranean-continentalized climate. This area is characterized by vast seasonal differences. Considering average daily values, the average annual temperature over the period of time in which the study was completed was 11.2 °C, with a maximum temperature value of 24.4 °C and a minimum value of −1.1 °C. Taking values by the hour, the maximum temperature was 35.7 °C and the minimum −18.9 °C. Under these unfavourable conditions, the aboveground construction without air-conditioning system has the highest mean temperature (14.4 °C) and annual interval (14 °C). In the aboveground construction with air-conditioning the average annual temperature is close to 14 °C. The air-conditioning system keeps the annual interval around 7 °C. The basement construction has acceptable interval and average temperature, around 8 °C and 13 °C respectively. The earth-sheltered and underground constructions, thanks to the earth's thermal inertia around them, have both the lowest intervals (4.6 °C and 2.5 °C respectively) and lowest average temperatures (12.5 °C and 9.9 °C respectively).

The effectiveness of the construction in reducing outdoor climate variations and producing a time lag is quantified through the "decrement factor" and "time lag" of the year mean for the studied period (Table 2).

Table 2. Parameters that quantify the effectiveness of the construction to decrease annual outdoors variations.

	Construction Effectiveness				
	Aboveground without air-conditioning	**Aboveground with air-conditioning**	**Basement**	**Earth-sheltered**	**Underground**
Decrement factor	0.55	0.29	0.33	0.18	0.10
Time lag (days)	1	−30	38	58	51

The underground construction presents the lowest decrement factor (0.10), which means that the indoor annual temperature interval is 10% of the interval registered outdoors (Table 2). Also, the thermal inertia of the terrain in which it is dug, allows the accumulation of heat from the hottest months of the year, to later provide heat during colder periods. However, the estimated time lag is not only influenced by the ground thermal inertia, but it is also influenced by a natural ventilation increase. Considering temperatures throughout August and September constant (10.9 ± 0.1 °C), the penetration of cold air, as described in Mazarrón and Cañas [8], produces an indoor temperature drop of a few decimals. This is enough to change the tendency of the charts curve and to establish the annual maximum temperature towards the end of September. Thus, the maximum indoor temperature is registered 51 days after the maximum outdoor temperature.

In comparison with the underground construction, the earth-sheltered one has similar effectiveness. The annual indoor interval is only 18% of the outdoor interval, registering the maximum indoor temperature two months later than the outdoor temperature one. The earth-sheltered construction shows a broader temperature interval than the underground one. This implies a higher ascent rate of the temperature curve towards the beginning of September. Therefore, winter ventilation effects take a few more days before changing the temperature curve tendency and determining the annual maximum temperature.

In the case of the basement construction, both the effectiveness to reduce outdoor oscillations and to produce a time lag become weaker. This is due to a smaller amount of adjacent terrain. However, values are still good: a 0.33 decrement factor, which is close to the value of an air-conditioned construction, and a 38 day time lag.

In spite of having isolation and thick concrete walls, the aboveground construction without air conditioning shows the worse effectiveness of all analyzed constructions. It has an annual outdoor interval lower than 50%, and the maximum annual temperature time lag is hardly noticeable.

The aboveground construction with air conditioning would need an increased energy expenditure in order to reduce the outdoor interval and come close to the values of constructions with more adjacent terrain. When the indoor temperature surpasses the established limit (16 °C in the studied construction), the air conditioning system maintains temperatures close to the set-point value during numerous months. Therefore, the time lag parameter is not representative.

To conclude, in order to characterise the behaviour of each type of construction in greater depth, the variations that occur over the course of a single day have been analysed. The variations have been calculated as the difference between the maximum and minimum of the 96 values that are recorded each day (Table 3). All the constructions have great indoor stability. The greatest variations are recorded for the aboveground with air-conditioning construction, with a mean daily variation of 1 °C, evidencing a greater instability of these systems. In the aboveground without air-conditioning constructions the variations are somewhat lower, 0.7 °C. The constructions with higher thermal inertia have low temperature variations, between 0.1 °C and 0.2 °C. This is less than 2% of the outdoor variation.

Table 3. Mean of the daily temperature intervals recorded over the 2006–2009 period.

Mean of Daily Temperature Interval (°C)					
Outside	**Aboveground without air-conditioning**	**Aboveground with air-conditioning**	**Basement**	**Earth-sheltered**	**Underground**
12.1	0.7	1.0	0.1	0.2	0.1

3.2. Hygrothermal Conditions and Interior Comfort: Particular Case of Wine

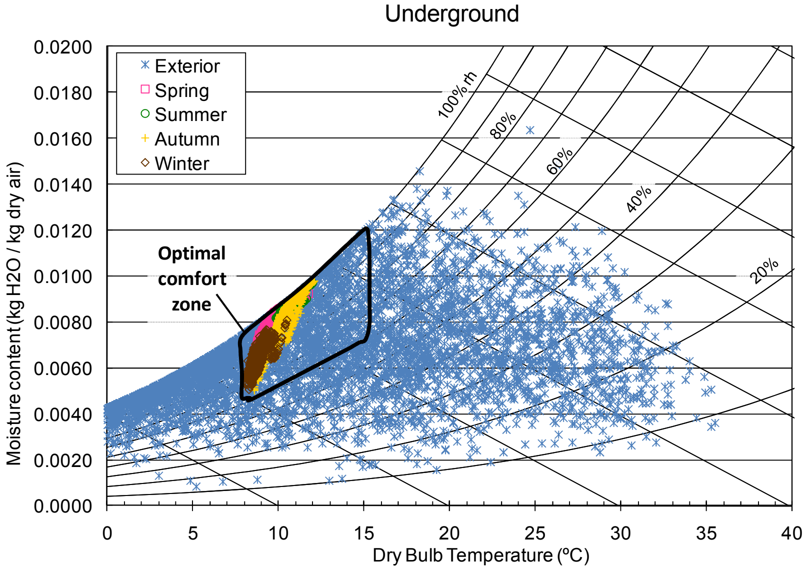
The outdoor conditions in the area of the study are inadequate for wine conservation. Summers are hot and dry, and winters are cold and damp. Throughout the four years of the investigation, the outdoor hygrothermal conditions were only within the optimal comfort zone during 23% of the time (Table 4).

Table 4. Percentage of hourly mean values, broken down into seasons, in which the outdoor and indoor hygrothermal conditions complied with the optimal comfort intervals.

Hourly Mean Values within Optimal Comfort Interval (8–15 °C; >60%RH) as Percentage of the Period (%)						
Period	**Outside**	**Aboveground without air-conditioning**	**Aboveground with air-conditioning**	**Basement**	**Earth-sheltered**	**Underground**
Spring	33%	52%	61%	96%	97%	100%
Summer	18%	0%	20%	7%	96%	100%
Autumn	30%	18%	84%	49%	61%	100%
Winter	11%	56%	66%	87%	67%	100%
06–09	23%	31%	58%	58%	80%	100%

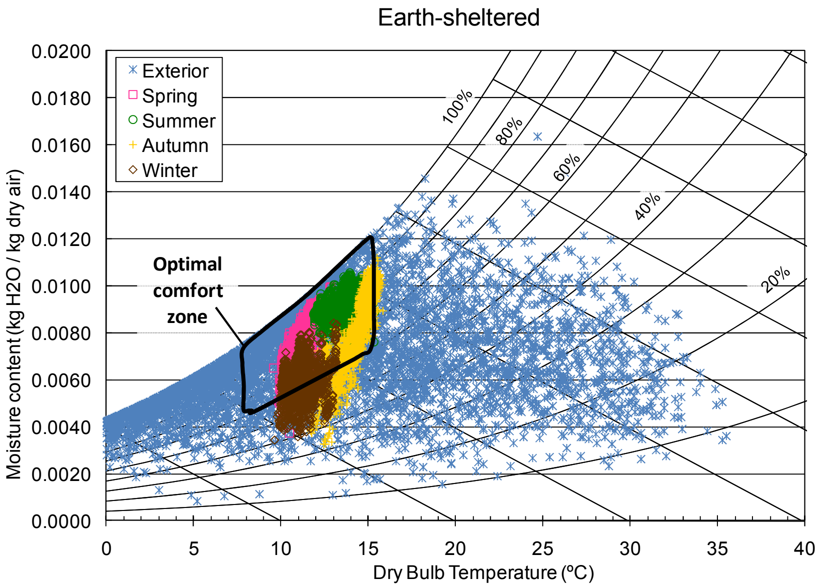
Of all the buildings studied, the underground construction is the one which assured most days (100%) in optimal comfort conditions for wine conservation (Figure 4), without the energy consumption of air-conditioning equipment. The difference in temperature between summer and winter is normally less than 4 °C, ranging from 12 °C to 8 °C. The humidity is high all year round: the values are close to 98% in summer, fall to 70% in autumn, and then gradually rise again in winter and spring.

Figure 4. Indoor and outdoor hygrothermal conditions of the underground construction. Four daily values represented (00:00, 6:00, 12:00 and 18:00) over the 2006–2009 period.



The earth-sheltered construction seems to be the best alternative to the underground buildings when it comes to controlling the indoor temperature and relative humidity (80% values within optimal comfort interval). After the underground construction, it is the one that assures the best comfort conditions in summer, the most critical period for the wine's comfort.

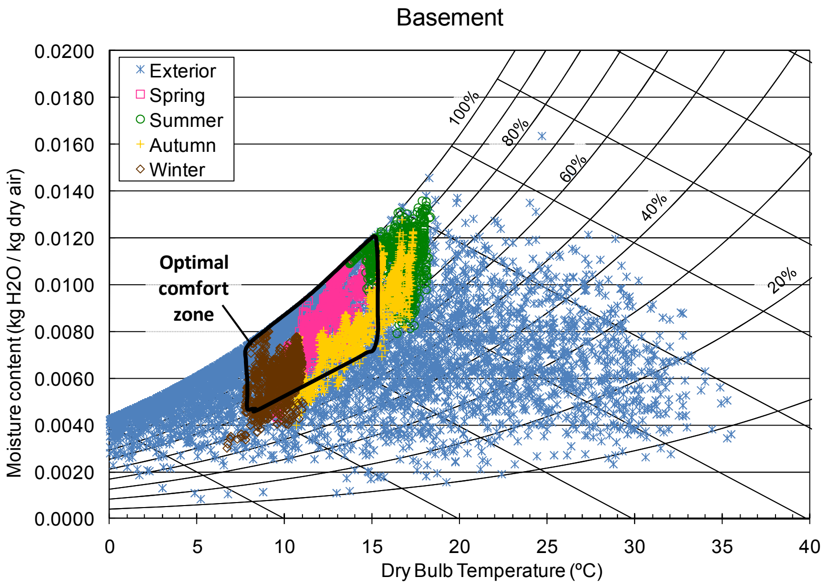
Figure 5. Indoor and outdoor hygrothermal conditions of the earth-sheltered construction. Four daily values represented (00:00, 6:00, 12:00 and 18:00) over the 2006–2009 period.



The least favourable conditions do not occur in summer as the earth's thermal inertia causes the maximum temperatures to occur at the beginning of October. The temperatures vary by approximately 3 °C in each season (Figure 5). Most of the values outside the comfort zone are due to a low relative humidity. Thanks to moderate temperatures, these values will not cause significant losses through evaporation.

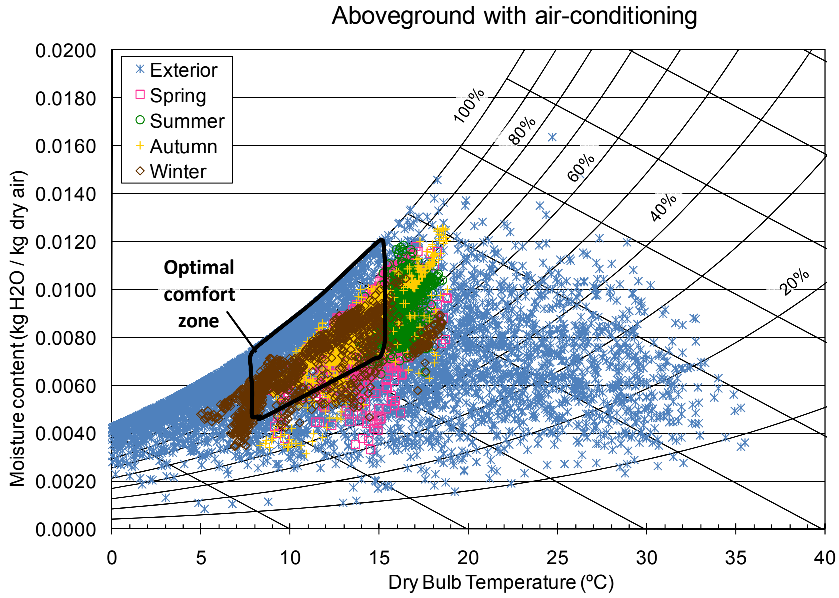
For most of the year, the basement construction studied provides acceptable conditions for wine-conservation (58% values within optimal comfort interval), similar to the values obtained in the aboveground constructions with air-conditioning. The thermal inertia of the surrounding earth limits the external temperature changes with no need for air-conditioning systems. As the possible weak points of these types of construction we could highlight the temperature, which approaches critical values at the end of the summer (Figure 6). In comparison with earth-sheltered and underground constructions, the percentage of points inside the optimal comfort zone throughout the summer is a lot lower. This is due to a smaller amount of adjacent terrain. Temperature usually surpasses 15 °C during most of the summer, however, risky temperatures (>18 °C) are hardly ever exceeded and relative humidity is high. Conditions can be considered acceptable.

Figure 6. Indoor and outdoor hygrothermal conditions of the basement construction. Four daily values represented (00:00, 6:00, 12:00 and 18:00) over the 2006–2009 period.



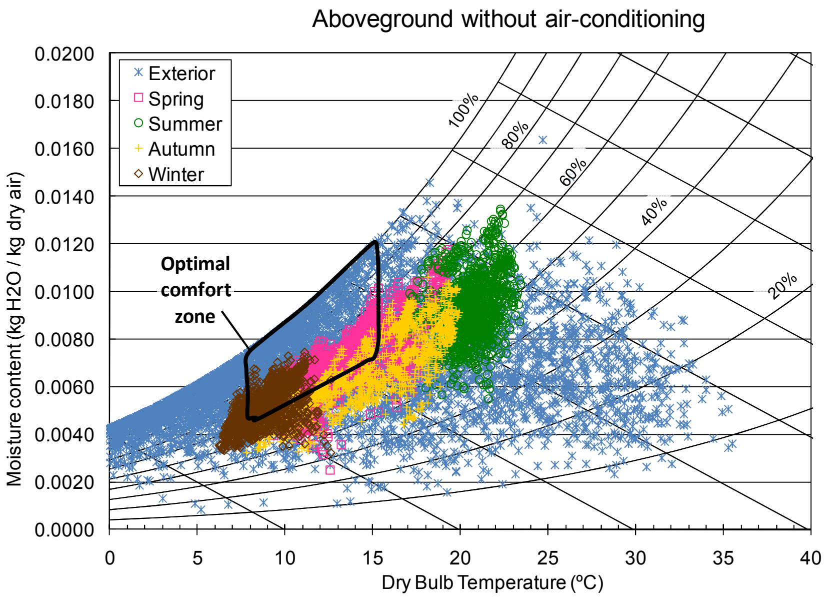
The aboveground construction with air-conditioning has temperature and relative-humidity intervals that are suitable for wine conservation and can be modified in accordance with the oenologist's requirements. The main disadvantages of this type of constructions are the cost of the air-conditioning equipment and the energy expenditure of its use. To reduce this, the values during the summer are concentrated between 15 and 17 °C, as 16 °C is the temperature at which the system is set. Throughout the rest of the year it is possible to distinguish periods when the temperature control system was not on, with great variation in the values, and periods during which the system was on, when the temperature and relative humidity values were more concentrated (Figure 7). This construction achieves 58% in the optimal comfort zone. Changing the operating parameters of the equipment would modify the optimal comfort conditions, though this would lead to higher energy consumption.

Figure 7. Indoor and outdoor hygrothermal conditions of the aboveground with air-conditioning construction. Four daily values represented (00:00, 6:00, 12:00 and 18:00) over the 2006–2009 period.



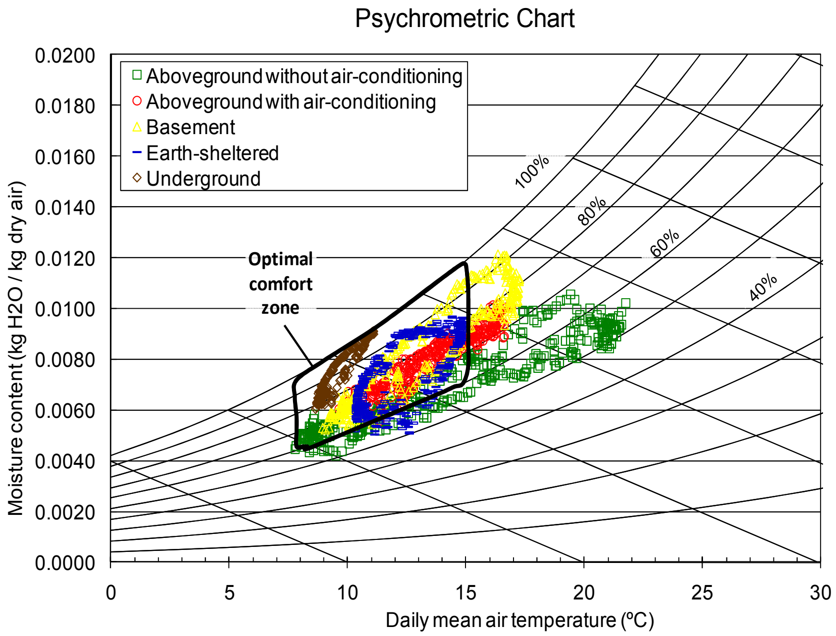
The aboveground construction without air-conditioning presents the least favourable conditions for wine-conservation. On only 31% of the total days are the conditions within the optimal comfort interval, principally in spring and winter (Figure 8). The least favourable values occurred in summer, with very high temperatures, combined with very low relative humidity. The annual interval is as high as 14 °C, with variations of 10 °C in autumn and spring.

Figure 8. Indoor and outdoor hygrothermal conditions of the aboveground without air-conditioning construction. Four daily values represented (00:00, 6:00, 12:00 and 18:00) over the 2006–2009 period.



The effectiveness of using ground thermal inertia for passive control in indoor conditions becomes clear when comparing indoor hygrothermal conditions of the different studied constructions, representing in a single psychometric chart the average year for the 2006–2009 period (Figure 9).

Figure 9. Indoor hygrothermal conditions for the different constructive solutions. Representation of daily average values for the average year.



4. Conclusions

The design of energy efficient constructions has yet to grow in the agro-industrial sector. This study is an important step along the way. For the first time, different construction solutions which use terrain to control indoor conditions are evaluated simultaneously. These types of constructions are also compared with other construction solutions without passive control systems. In addition, it provides the industry with reliable and objective data which can be used as references when designing energy efficient agro-industrial constructions.

It has been proven that solutions based on the use of ground thermal inertia are more effective when reducing variations from outdoor conditions than other constructions without this use, even when they have air-conditioning systems. With a good design and an adequate amount of terrain it is possible to reach optimal conditions for agro-food conservation without air-conditioning systems.

In areas with large temperature variations, deep underground constructions (>10 m) present the highest capacity to reduce outdoor climate variations and maintain thermal stability all year round. Relative humidity is usually high for most part of the year, which should be taken into account for possible applications. Earth-sheltered constructions are the best alternative to underground constructions in order to maintain a stable interior temperature close to the outdoor temperature in the surrounding area. These have the advantage of being close to the surface, which makes it easier to design wider spaces. Basement constructions have an acceptable capacity to reduce outdoor variations, and can be an inexpensive solution for indoor climate control. Results are similar to the values obtained by the aboveground constructions with air-conditioning systems functioning for various months. On the contrary, aboveground constructions without air-conditioning systems or ground thermal mass present lower capacities to reduce outdoor variations, having less control over climate conditions.

For the particular case of wine conservation and ageing, the underground construction is the one which assured most days in optimal comfort conditions, without the energy consumption of air-conditioning equipment. The earth-sheltered construction seems to be the best alternative to the underground construction, with over 80% of the time within the optimal comfort zone. For most of the year basement cellar provides acceptable conditions for wine-conservation. The aboveground construction without air conditioning presents the least favourable conditions for conservation and ageing, as the indoor temperature is too high during the summer months, and the relative humidity is too low. The aboveground construction with air-conditioning temperature and relative-humidity intervals can be modified in accordance with the requirements, at the expense of energy consumption and the cost of the equipment.

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