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Which environmental indicator is better able to predict the effects of heat stress on construction workers?

Wen Yi[1] * and Albert P.C. Chan[2]

[1] PhD Candidate, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; E-mail address: yiwen96@163.com (corresponding author)

[2] Professor and Acting Dean, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; E-mail address: albert.chan@polyu.edu.hk

Abstract

Extremely hot and humid environments are common in numerous occupational settings. Construction work is tough and physically demanding, and the difficulty is exacerbated by the hot and humid weather of tropical and subtropical regions. Having established heat stress models through different environmental indicators, this study aims to ascertain which environmental indicator would be better able to predict the effects of heat stress on construction workers. Field studies were conducted during summer in Hong Kong from July 2011 to August 2011. Physiological, work-related, environmental, and personal parameters were measured to validate the established heat stress models on the basis of 411 sets of synchronized meteorological and physiological data collected from construction workers in two different construction sites. The mean absolute percentage error (MAPE) and Theil's U inequality coefficient were used to assess these models in terms of predictive accuracy. Wet bulb globe temperature (WBGT) was found to have the highest validity (MAPE = 6.5%, Theil's U inequality coefficient = 0.05) and practicality in predicting the effects of heat stress on construction workers. Specific heat stress guidelines can be formulated based on WBGT, which can protect well the health and safety of site personnel working in hot and humid weather conditions.

Keywords: Hot and humid climate; Construction workers; Environmental indicator; Heat stress model; Heat tolerance time

Introduction

Extremely hot and humid environments are common in numerous occupational settings, such as in fire-fighting, national defense, steel, iron, glass manufacturing, mining, and outdoor operations (Kähkönen et al. 1992; Petersen et al. 2010; Rodríguez-Marroyo et al. 2011). Working under heat stress conditions poses several risks, including impairment of mental function and increased fatigue (Miller and Bates 2002). The evaluation of heat stress is generally based on physiological variables and meteorological parameters (Lu and Zhu 2007). One of the main questions regarding heat stress is the tolerable limit based on the health of a person. This question can be answered from two perspectives: (1) identifying critical physiological conditions that can be considered as tolerable and (2) determining the climatic limits that correspond to such conditions.

Regarding the first perspectives, the predominant view is to assess the conditions of permissible thermal equilibrium (Wenzel et al. 1989). Heat accumulation is reflected by an accelerated heart rate and a continuous increase in body temperature (Wenzel et al. 1989). The physiological values of heat exposure limits should be specified to ensure that heat stress does not result in intolerable strain (Lu and Zhu 2007). The World Health Organization (WHO) has analyzed health factors involved in working under extreme heat conditions and has recommended acceptable increases in physiological responses to heat stress (Gagge 1986; Parsons 1999; Kampmann and Piekarski 2000). However, practitioners often prefer limits in terms of stress instead of strain, that is, limits in climatic conditions, because of two reasons. Data on climatic elements can be obtained easily because the instruments for such measurements and the people trained to use such instruments are typically available whenever evaluations are required, such as in industrial plants. By contrast, collecting physiological data is difficult. Such data can only be obtained

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during or after heat exposure. Predicting the effects of heat stress before a person is exposed to possibly dangerous climatic condition is necessary to adopt a proactive approach. These predictions can be made if climatic thresholds are known.

Some upper tolerance limits have been published in the literature (Brake and Bates 2002a) and adopted by regulatory organizations (National Institute for Occupational Safety and Health 1986; American Conference of Government Industrial Hygienists 2000; International Standards Organization 7243 2003). These limits usually consider the climatic variables that simultaneously contribute to heat stress, such as air temperature, humidity, wind speed, and radiation. Other non-climatic variables, such as metabolic heat production in the body and thermal resistance of clothing, also play essential roles. However, the current occupational health and safety (OHS) requirements on work limits for heat exposure fail to consider personal characteristics, which leads to an under or overestimation of the heat strain of an individual. The heat strain experienced by a worker in a thermal environment can also be influenced by physiological and behavioral factors, such as age, gender, clothing, hydration, physical fitness, use of alcohol or drugs, and a variety of medical conditions (Dishman et al. 1994; Impellizzeri 2004; Spielholz 2006; López-Miñarro and Muyor Rodríguez 2010). All these factors, both environmental and personal, can influence the ability of an individual to dissipate excess heat in the body.

Workers in different industries may have different degrees of susceptibility to heat stress. An industry-specific study can best reflect the real situation. The construction industry is a priority area for research and interventions because of the high number of work-related fatal and non-fatal injuries (Hoonakker et al. 2005). This industry is found to be more susceptible to heat stress than other industries

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(Japan International Center of Occupational Safety and Health 2001). However, the environmental indicator that provides the best prediction of the effects of heat stress on construction workers remains unknown. Earlier studies conducted by Chan et al. (2012&2013ab) assessed the effects of heat stress on construction workers and established heat stress models from different environmental indicators (i.e., HI, WBGT, and TWL). This study aims to evaluate and ascertain which environmental indicator could provide the best prediction of the effects of heat stress on construction workers by validating the accuracy of heat stress models.

Background

A large number of subtropical regions, such as Hong Kong, experience high temperatures (ranging from 29 °C to 34 °C), high humidity (ranging from 75% to 90%), and low wind speed in summer from July to September as a result of global warming and urbanization (Hong Kong Observatory 2011). The incidence of heat stress in the construction industry is alarming and has caused a number of verifiable reported deaths that suggest heat stress to be the probable causal factor (Apple Daily 2010-2011). These incidents have drawn the attention of the government, statutory bodies, and the industry, and have urged them to investigate health and safety problems in relation to working under a hot weather. The same issue has also been a concern of the Construction Industry Council (CIC). The CIC set up a task force on working in a hot weather and promulgated a set of guidelines to prevent heat stress. The task force advocated that further research on thermal stress as measured by established parameters should be conducted to refine the initial guidelines that have been established (CIC 2008).

Workers' heat strain

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The Australian Institute of Occupational Hygienists (AIOH) defines heat strain as the overall physiological and psychological response resulting from heat stress (AIOH 2003). Heat strain can be evaluated by the Rating of Perceived Exertion (RPE) since it was developed to allow a person to subjectively rate their total feelings of physical effort, stress, strain and fatigue to the task. Participants were instructed not to focus or concern themselves with any one factor such as, shortness of breath, musculoskeletal load, leg pain, etc., but to try and concentrate on their total inner feeling of overall exertion (American College of Sports Medicine 2000). RPE provides a useful indication of the capacity to continue a task (Garcin et al. 1998). The scales use both verbal anchors and numbers that have been reported to possess both categorical and interval properties (Borg 1990). Hence, the RPE scale was adopted as a practical and cost-effective approach to estimate the workers' heat strain during exercise such as construction works.

Factors affecting workers' heat strain

Chan et al. (2012&2013ab) developed a number of heat stress models to predict the physiological responses of construction workers when working in a hot and humid environment to address the pressing need of the industry. The RPE scale was used to quantify physiological–psychological responses during work (Chan et al. 2012&2013ab). Related literature showed that RPE is highly correlated with *environmental factors* such as temperature, relative humidity, wind speed, and air quality; *personal factor*s such as age, percentage of body fat, resting heart rate, clothing, and alcohol drinking/smoking habits; *work-related factors* such as duration and type of exercise; and *physiological factors* such as oxygen uptake, heart rate, respiratory rate, ventilation, hydration status, and fatigue in undertaking the work activity (Chan et al. 2012&2013ab). Table 1 summarizes the factors and indicators that affect RPE.

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(Please insert Table 1 here)

Environmental indicators

Heat stress indices that relate environmental conditions to the potential hazards of heat exposure are important to industrial, civilian, and military populations (Santee and Wallace 2005). Different industries use different environmental indicators and different reference data and standards. The heat index (HI) was adopted by the US Department of Labor to protect outdoor workers from heat-related illnesses (US Department of Labor 2010). The wet bulb globe temperature index (WBGT) was used to control serious outbreaks of heat illness in training camps of the United States Army and Marine Corp (Budd 2008). The thermal work limit index (TWL) was implemented in the underground mining industry of Australia and thus resulted in a substantial and sustained fall in the incidence of heat illnesses (Miller and Bates 2002).

Heat Index (HI)

The National Weather Service (NWS) derived HI from a database generated by a complex mathematical model developed by Steadman (Steadman 1979). This complex multi-input model, which can be easily simplified into a single equation with the use of two common meteorological values (temperature and humidity) derived from basic weather input, helps save a considerable amount of computing time. HI, as a rough indicator (a function of temperature and relative humidity), does not fully reflect the heat stress on the human body in terms of environmental parameters and can oversimplify the real environmental condition. When conditions differ significantly from standard conditions, such as a high or low solar load or wind speed, the actual risk may also significantly vary from the level predicted with the use of standard input. Sunlight is the main component of environmental heat load (Brotherhood et al. 1997). Adequate air

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movement is also essential to efficiently evaporate sweat (Brotherhood 2008). Temperature–humidity limits can underestimate or overestimate environmental warmth by ignoring sunlight and wind.

Wet Bulb Globe Temperature (WBGT)

WBGT was invented more than 50 years ago and is now the most widely used index to assess heat stress. The principal sources of guidance in evaluating heat stress are the WHO (Gagge 1986; Parsons 1999; Kampmann and Piekarski 2000), the National Institute for Occupational Safety and Health (1986), the American Conference of Governmental Industrial Hygienists (2000), the International Organization for Standardization (2003), and the American College of Sports Medicine (2007). A common element in the evaluation of heat stress is the use of WBGT. The main strengths of WBGT are its consideration of the effects of the sun and wind, which are the two crucial components of outdoor climate, as well as those of air temperature and humidity (Sports Medicine Australia 2006; American College of Sports Medicine 2007; Budd 2008).

Thermal Work Limit (TWL)

TWL uses five environmental parameters (dry bulb temperature, wet bulb temperature, globe temperature, wind speed, and atmospheric pressure) and accommodates for clothing factors to arrive at a prediction of a safe maximum continuously sustainable metabolic rate (W/m^2) for the concerned conditions (Miller and Bates 2002). TWL has been introduced to several large industrial operations located well inside the tropical zone, which has resulted in a substantial and sustained fall in the incidence of heat illnesses (Brake and Bates 2002a). TWL is also particularly suitable in situations with significant cooling related to air movement. Therefore, this index may be suitable for application in the construction industry. The TWL

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algorithm accurately predicts the limiting work rates under a given set of environmental conditions. TWL guidelines with recommended interventions were proposed by Brake and Bates (2002b). For example, work status is classified based on the values of TWL. A TWL value < 115 W/m^2 means withdrawal, 115 W/m^2 to 140 W/m^2 means buffer, 141 W/m^2 to 220 W/m^2 means acclimatization, and > 220 W/m^2 means unrestricted (Brake and Bates 2002b).

Heat stress models

Earlier studies advocated that the most reliable method to quantify climatic heat is to plot the observed adverse effects of heat against the thermal environment in which they occur while considering all other relevant factors; this process is often performed with the use of multivariable statistical techniques (Gun and Budd 1995; Budd et al. 1997). Chan et al. (2012&2013ab) used multiple linear regressions to develop a number of heat stress models with different environmental determinants, as shown in Eqs. (1)–(3). Physiological, work-related, environmental, and personal parameters were measured to construct these heat stress models on the basis of 281 sets of synchronized meteorological and physiological data collected from four different construction sites in Hong Kong (July 2010 to September 2010).

Model 1 – HI as the environmental indicator

$$RPE = -7.27 + 0.11HI + 1.26T + 0.08A - 0.05PBF + 2.23ADH + 0.38SH + 0.17EC + 0.17RE + 0.09API \quad \text{Eq.(1)}$$

Model 2 – WBGT as the environmental indicator

RPE = -5.43 + 0.11WBGT + 1.40T + 0.06A - 0.07PBF + 2.28ADH + 0.50SH + 0.14EC + 0.16RE -

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0.01RHR + 0.10API Eq.(2)

Model 3 – TWL as the environmental indicator

RPE = -1.13 - 0.01TWL + 1.30T + 0.07A - 0.06PBF + 2.30ADH + 0.44SH + 0.15EC + 0.16RE - 0.02RHR + 0.10API Eq.(3)

where HI is heat index (°C); WBGT is wet bulb globe temperature (°C); TWL is thermal work limit (W/m^2); T is work duration (hour); API is air pollution index; A is age; PBF is percentage of body fat (%), ADH is alcohol drinking habit ("no consumption"= 0, "no more than 4 drinks on any single day AND 14 drinks per week"= 1, "More than 4 drinks on any single day OR 14 drinks per week"=2, one standard drink contains about 0.6 fluid ounces or 14 grams of pure alcohol); SH is smoking habit ("no consumption"= 0, "1-4 cigarettes per day"= 1, "more than 5 cigarettes per day"= 2); EC is energy consumption; and RE is respiratory exchange.

Research methods

Each model should be validated with virgin data, and the predicted results should be compared with actual data to ascertain which model exhibits the best predictive power. Model validation is the process of demonstrating or obtaining a condition with sufficiently accurate coefficients to provide an acceptable description of the behavior of the subject structure (Ewins 2000). Validation includes checking the prediction performance against reference data from other sources, which are typically obtained from a specially conducted test (Zang et al. 2008). A valid model may not be unique but should be suitable enough to perform the task for which it was created for or should be "fit-for-purpose." (Zang et al. 2008) In the present study, validation is used to determine the degree to a heat stress model accurately represents the construction industry from the perspective of intended use. This study also identifies the environmental indicator that provides the best prediction of the effects of heat stress on construction workers.

Further validating and analyzing cases from the created database are necessary (Landry et al. 1983). The cases that are completely different from the ones used to build the model can provide reliable data to assess the accuracy of the model (Zang et al. 2008). Figure 1 summarizes the methodology employed. The first round of field studies was conducted from July to September 2010 to construct the heat stress models. In order to acquire data for comparison and validation, the second round of field studies that use the same experimental procedures was conducted from July 2011 to August 2011. Nineteen healthy and experienced construction rebar workers were invited to participate in this study. They performed tasks of fixing and bending steel reinforcement bars until voluntary exhaustion. Physiological, work-related, environmental, and personal parameters were monitored and measured to validate the heat stress models. The mean absolute percentage error (MAPE) and Theil's U inequality coefficients were used to identify which environmental indicator is better able to predict the effects of heat stress on construction workers.

(Please insert Figure 1 here)

Measurements

The environmental parameters of construction sites and the physiological conditions of the participants were measured and monitored. A heat stress monitor (QUESTemp° 36, Australia) was used to measure prevailing environmental data (e.g., dry bulb temperature, wet bulb temperature, globe temperature,

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relative humidity, and wind speed). Entering related environmental parameters into the calculation formulas of HI (Steadman 1979), WBGT (Budd 2008), and TWL (Department of Employment, Economic Development and Innovation 2009) can determine the values of these parameters. The API measured and broadcasted hourly by the Environmental Protection Department (Environmental Protection Department 2013) was adopted in this study.

The demographic data of the participants, such as age, percentage of body fat (InBody 230, Biospace Co., Ltd., USA), resting heart rate (heart rate monitor, Polar, Finland), and drinking/smoking habits, were obtained prior to the study. Other physiological parameters, such as oxygen consumption, minute ventilation, respiratory exchange ratio, metabolic equivalent, energy expenditure, heart rate, and a train of physiological parameters, were captured through a telemetry system ($K4b^2$, COSMED, Rome, Italy) during the study. Energy consumption and respiratory exchange were computed with Eqs. (4) and (5) (Chan et al. 2012&2013ab). The measuring instruments and parameters were shown in Table 2.

$$\text{Energy consumption} = 0.98EE + 0.97MET + 0.97VO_2 + 0.35MV + 0.28HR - 0.26RER \quad (4)$$

$$\text{Respiratory exchange} = -0.10MET - 0.10\,VO_2 + 0.80MV + 0.56HR + 0.93RER \quad (5)$$

where EE is energy expenditure (Kcal/min); MET is Metabolic equivalent; VO_2 is oxygen consumption (ml/min/Kg); MV is minute ventilation (l/min); HR is heart rate (bpm); RER is respiratory exchange rate.

(Please insert Table 2 here)

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Validation methods

The best forecast yields an error with minimum or zero variance (Wong et al. 2005). Different statistical methods can be used to measure quantitatively how closely the forecasted variable tracks actual data (Wong et al. 2005). The evaluation was conducted through two measures of accuracy, namely, the mean absolute percentage error (MAPE) and Theil's U inequality coefficient. MAPE, a widely used metric to evaluate forecast accuracy, is commonly used in quantitative forecasting methods (Goodwin and Lawton 1999; Chen 2007) wherein the absolute values of all percentage errors are summed up and the average is computed (McKenzie 2011). Theil's U statistic is a relative accuracy measure that compares forecast results with those that have minimal historical data (Theil 1978). The advantage of U is the use of a denominator as a scaling factor to consider the size of the variables to be predicted (Theil 1978). Scaling this measure produces an appropriate method to standardize differences between time intervals (Fitzgerald and Akintoye 1995). The MAPE and Theil's U statistics for the variable $\mathrm{RPE_t}$ is defined as Eqs.(6) and (7) respectively:

$$\mathrm{MAPE_j} = \frac{1}{\mathrm{T_j}} \sum_{t=1}^{\mathrm{T_j}} \frac{|\mathrm{e_{tj}}|}{\mathrm{RPE_{tj}^a}} * 100 \tag{6}$$

$$\mathrm{U_j} = \sqrt{\frac{\frac{1}{\mathrm{T_j}} \sum_{t=1}^{\mathrm{T_j}} (\mathrm{e_{tj}})^2}{\frac{1}{\mathrm{T_j}} \sum_{t=1}^{\mathrm{T_j}} (\mathrm{RPE_{tj}^a})^2}} \tag{7}$$

where e_{tj} is the forecast error at time t (actual value – forecasted value) of participant j; RPE_{tj}^{a} is the actual value of RPE_{tj} of participant j; and T_j is the number of periods of participant j.

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The magnitude of the prediction MAPE can be assessed by a general acceptable limit of 10% (Goh 2000). The scaling of Theil's U coefficient falls between zero and unity (Theil 1978). If U = 0, the forecast error (e_{tj}) is zero for all *t,* which achieves a perfect fit. If U = 1, the predictive performance of the model completely fails.

Discussion

Validity

A total of 411 sets of meteorological and physiological data collected over 14 working days were collated. The statistical results (Mean ± Standard Deviation) of the meteorological and physiological data are shown in Table 3. The computed values based on the out-of-sample forecasts of the model are presented in Table 4. The results show that the WBGT-heat stress model achieves the highest accuracy (MAPE = 6.5%), followed by the TWL-heat stress model (MAPE = 7.1%) and the HI-heat stress model (MAPE = 10.8%). The MAPEs of the WBGT- and the TWL-heat stress models are consistently within the acceptable level of 10%. The Theil's U statistics for the WBGT-heat stress model (U = 0.054) and the TWL-heat stress model (U = 0.055) indicate that these two models have better predictive ability than the HI-heat stress model (U = 0.102). Thus, the WBGT-heat stress model achieves the highest accuracy and reliability based on the evaluation of MAPE and Theil's U statistics.

(Please insert Table 3&4 here)

When used appropriately, properly validated models can result in major benefits in various application fields (Yang et al. 2011). Inaccurate models or those applied beyond their validity range, are insignificant

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and can lead to major problems in interpretation (Kirk Nordstrom 2012). Therefore, testing simulations and obtaining objective measures of performance are necessary. Testing simulations has two aspects: internal verification and external validation (Murray-Smith 1995). The former is the process of proving that a computer simulation is consistent with the underlying model to a specified degree of accuracy. The latter is the process of demonstrating that the mathematical or conceptual model has an acceptable accuracy over a range of conditions relevant to an application (Murray-Smith 1995). Earlier research has verified the HI-, WBGT-, and TWL-heat stress models against virgin data (collected from July to September 2010) to provide proof of the internal consistency and accuracy of each mathematical model (Chan et al. 2012&2013ab). Internal verification showed that these heat stress models were statistically acceptable. The present study used external data (collected from July to August 2011 in the following year) to ensure that mathematical equations are appropriate within the context of the intended application. External validation indicates that the WBGT-heat stress model is better able to predict the effects of heat stress on construction workers than the other models.

Practicability

Although TWL uses five environmental parameters (dry bulb temperature, wet bulb temperature, globe temperature, wind speed, and atmospheric pressure) and accommodates clothing factors, WBGT remains more practical than TWL because the model can be easily measured (Brake and Bates 2002a). WBGT can be easily computed from the readings of three thermometers on wet bulb temperature (WBT), globe temperature (GT), and dry bulb temperature (DBT). Budd (2008) explained the basic idea in WBGT. GT responds to environmental heat load, while WBT responds to the difficulty of evaporation. Radiant heat warms GT to some level above DBT, whereas wind cools GT toward DBT. GT consequently measures the

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combined effects of radiant heat, air temperature, and wind speed (Budd 2008). Evaporation similarly cools WBT, where the amount of cooling increases with low humidity and wind, whereas radiant heat warms WBT (Budd 2008). Therefore, WBGT responds to all four elements of the thermal environment. In practice, the weighting coefficients are 0.7 WBT + 0.3 GT + 0.1DBT responds when instruments are placed under the sun and 0.7 WBT + 0.3 GT during other times. The three thermometers are simple to use and inexpensive (Parsons 2006). From the perspectives of internal verification, external validation and the application to the construction industry, WBGT is therefore regarded as better able to predict the effects of heat stress on construction workers.

Heat tolerance time (HTT)

The protection of workers in hot environments requires a mechanism that identifies the conditions in which excessive thermal stress places the health of workers at risk. Numerous agencies have recommended a threshold limit value in providing useful advice to individuals exposed to heat stress (ISO 7243 2003; American Conference of Government Industrial Hygienists 2000). However, the current OHS requirements on work limits on heat exposure fail to consider personal characteristics, which could under or overestimate the personal heat tolerance time (HTT). Heat stress models can be developed to determine the HTT of construction workers in practice. HTT was defined as the duration during which a construction worker can continuously work until voluntary exhaustion. Voluntary exhaustion is reached when participants report an RPE of 7 (very hard) or request to stop working, whichever comes first. Such a report implies that workers are physically exhausted and can no longer work. The HTT mathematical models [Eqs.(8)-(10)] can be developed when RPE is set to 7 based on heat stress models. Entering environmental, physiological, personal and work-related parameters into the HTT mathematical models,

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the HTT that a construction worker would work continuously without jeopardizing his health can be computed. Table 5 illustrates the HTT at different levels of heat exposure by age groups. For example, the HTT for a 45 year-old rebar worker with a percentage of body fat of 12.3%, who smokes cigarettes and consumes alcohol occasionally and works continuously at a WBGT of 30°C (HI of 39°C, TWL of 165 W/m^2) and API of 30 with moderate workload, was 72 min [Eqs.(8)-(10); Table 5].

$$HTT = [7\ (RPE) + 7.27 - 0.11 * 39\ (HI) - 0.09*40\ (API) - 0.08*45\ (A) + 0.05*12.3\ (PBF) - 2.23*1\ (ADH) - 0.38*1\ (SH) - 0.17*2\ (EC) - 0.17*2\ (RE)]/1.26*60 \quad \text{Eq. (8)}$$

$$HTT = [7\ (RPE) + 5.43 - 0.11 * 30\ (WBGT) - 0.10*40\ (API) - 0.06*45\ (A) + 0.07*12.3\ (PBF) - 2.28*1\ (ADH) - 0.50*1\ (SH) - 0.14*2\ (EC) - 0.16*2\ (RE) + 0.01*78\ (RHR)]/1.4*60 \quad \text{Eq. (9)}$$

$$HTT = [7\ (RPE) + 1.13 - 0.01 * 165\ (TWL) - 0.10*40\ (API) - 0.07*45\ (A) + 0.06*12.3\ (PBF) - 2.3*1\ (ADH) - 0.44*1\ (SH) - 0.15*2\ (EC) - 0.16*2\ (RE) + 0.02*78\ (RHR)]/1.3*60 \quad \text{Eq. (10)}$$

where HI is heat index (°C); WBGT is wet bulb globe temperature (°C); TWL is thermal work limit (W/m^2); T is work duration (hour); API is air pollution index; A is age; PBF is percentage of body fat (%), ADH is alcohol drinking habit ("no consumption"= 0, "no more than 4 drinks on any single day AND 14 drinks per week"= 1, "More than 4 drinks on any single day OR 14 drinks per week"=2, one standard drink contains about 0.6 fluid ounces or 14 grams of pure alcohol), SH is smoking habit ("no consumption"= 0, "1-4 cigarettes per day"= 1, "more than 5 cigarettes per day"= 2); EC is energy consumption; and RE is respiratory exchange.

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(Please insert Table 5 here)

Many government agencies have issued heat warnings to provide advance warning of an extremely hot weather and thus allow a timely response. An "early warning system" for the construction industry can be established and linked with the local weather forecast based on the HTT at different degrees of heat exposure. However, different countries use different heat stress indices. For example, most cities in the United States use NWS excessive heat alerts based on HI. The Australian Bureau of Meteorology observes thermal comfort through WBGT. HTTs at different levels of heat exposure with different heat stress parameters (i.e., HI, WBGT, and TWL) are summarized in Table 5 as a reference for the construction workers in different countries/regions. The "early warning system" can be implemented through an alert to construction workers to take necessary precautions at different levels of heat exposure.

Strengths and limitations

This study pioneers the application of experimental approach to identify the best environmental indicator in predicting the effects of heat stress on construction workers. Experimentation is a rigorous, structured, and reliable research approach that is viable for conducting Construction Management (CM) research, which enables the academia to influence and improve work practice in the construction industry (Yi and Chan 2013). Our findings may benefit the industry to produce solid guidelines for working in hot weather. Validation studies are important because the performance of prediction models tends to be poorer when applied to new individuals than in the sample from which it was developed. Truly external validation with independent data is conducted to evaluate the various newly developed heat stress models. Previous studies

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shows the sample sizes of validation sets differ a lot (Altman and Royston 2000; Timsit et al. 2002). If the model is developed in a training set and subsequently validated in a test set, the sample size is often relatively small (Vergouwe et al. 2005). Although the current study is limited in sample size, further research work with enlarged sample size should be launched to verify the current findings.

Conclusion

Heat stress is a recognized hazard among construction workers. Assessing the effects of heat stress and developing practical solutions to avoid its adverse health effects and incidence are necessary to ensure the health and safety of construction workers. Different heat stress models have been developed to predict the effects of heat stress on construction workers (Chan et al. 2012&2013ab). However, the model that provides the best predictive power remains unknown. This study ascertains that WBGT is the best model to predict the effects of heat stress on construction workers by validating the accuracy of various heat stress models. WBGT remains a comprehensive and convenient index to assess heat stress even after 50 years of use. WBGT is a reliable and practical indicator to predict the effects of heat stress on construction workers. Additional specific heat stress guidelines can be formulated based on WBGT to safeguard the health and safety of workers under hot and humid conditions.

Workers in different industries may have different degrees of susceptibility to heat stress. An industry by industry specific study would better reflect the real situation. Although this study applies specifically to the construction industry, more work is needed to further investigate other industries and to other climates to provide a holistic view in future. This would be of tremendous value in better improving labor productivity and safeguarding workers' occupational health and safety.

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Notation

The following symbols are used in this paper:

A   Age (years)

ADH   Alcohol drinking habit ("no consumption"= 0, "no more than 4 drinks on any single day AND 14 drinks per week"= 1, "More than 4 drinks on any single day OR 14 drinks per week"=2, one standard drink contains about 0.6 fluid ounces or 14 grams of pure alcohol)

API   Air pollution index

CM   Construction Management

Clo   Clothing insulation factor

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DBT Dry bulb temperature (°C)EC Energy consumption

EE Energy expenditure (Kcal/min)

GT Globe temperature (°C)

HI Hear index (°C)

HTT Heat tolerance time (min)

HR Heart rate (bpm)

MAPE Mean absolute percentage error

MET Metabolic equivalent

MV Minute ventilation (l/min)

NWS National Weather Service

OC Oxygen consumption (ml/min/Kg)

OHS Occupational health and safety

PBF Percentage of body fat (%)

RE Respiratory exchange

RER Respiratory exchange rate

RHR Resting heart rate (bpm)

RPE Rating of perceived exertion

SH Smoking habit ("no consumption"= 0, "1-4 cigarettes per day"= 1, "more than 5 cigarettes per day"= 2)

T Work duration (hour)

TWL Thermal work limit (W/m^2)

WBT Wet bulb temperature (°C)

WBGT Wet bulb globe temperature (°C)

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Figure Caption List

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Figure 1 Flowchart of research methodology

Figure 1

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Figure 1 Flowchart of research methodology

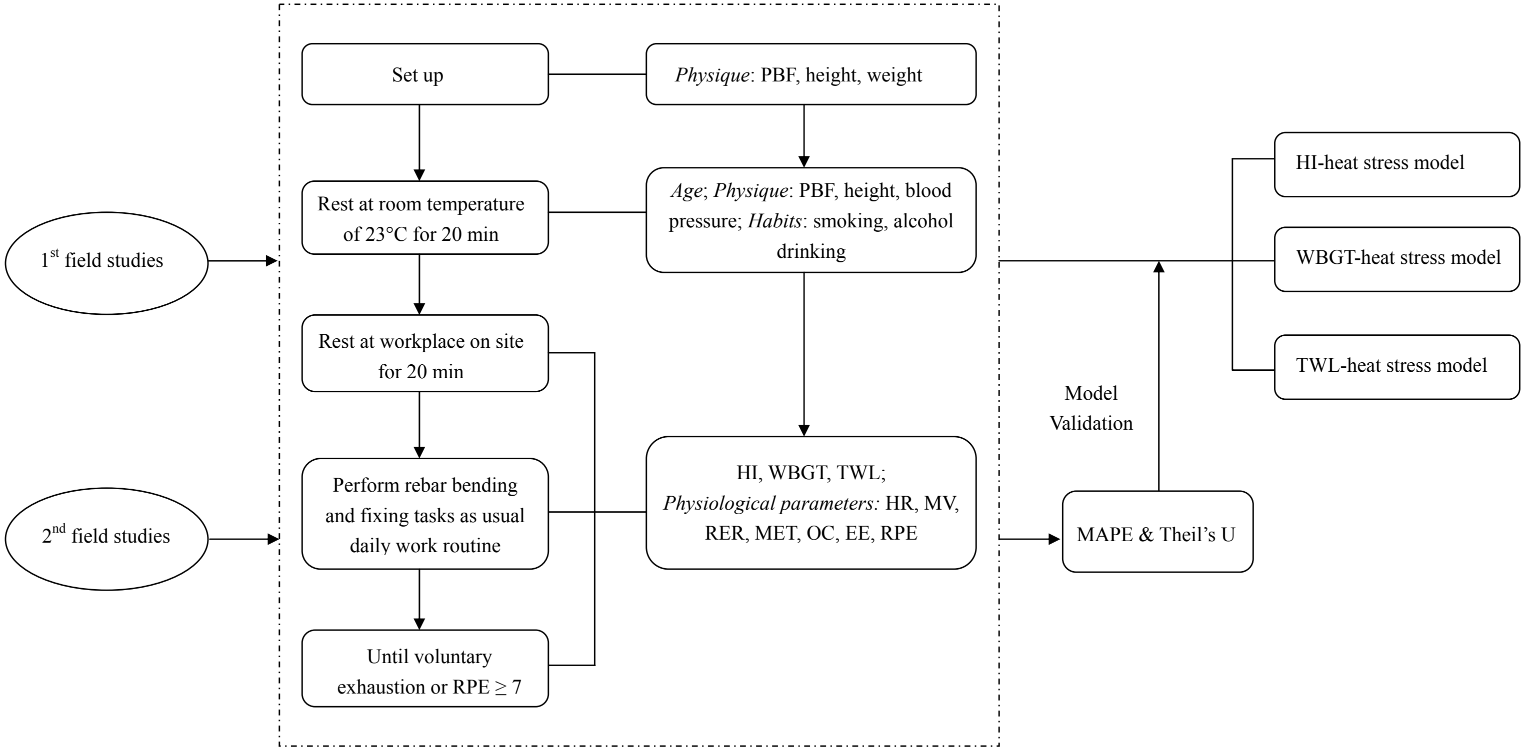

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Table 1 Factors and indicators influencing the Rating of Perceived Exertion (RPE)

	Factor	Indicator to measure the identified factors
Physiological factors	Energy expenditure Metabolic equivalents Oxygen consumption	Energy consumption (EC)
	Minute ventilation Heart rate Respiratory exchange ratio	Respiratory exchange (RE)
	Hydration	Total body water (TBW)
Work-related factors	Work type	Job nature (JN)
	Time	Work duration (T)
Environmental factors	Temperature Relative humidity Wind speed Radiation	Environmental indicator
	Air pollution	Air pollution index (API)
Personal factors	Age	Age (A)
	Physique	Percentage of body fat (PBF) Resting heart rate (RHR)
	Alcohol/tobacco intake	Smoking habit (SH) Alcohol drinking habit (ADH)
	Clothing	Clothing insulation factor (Clo)

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Table 2 The measuring instruments and parameters

Type	Parameter	Measuring instrument	Model
Environmental parameter	Dry bulb temperature (°C)	Heat stress monitor	QUESTemp° 36
	Wet bulb temperature (°C)		
	Globe temperature (°C)		
	Relative humidity (%)		
	Wind speed (m/s)		
Physiological parameter	Body weight (Kg)	Body composition analyzer	InBody 230
	Percentage of body fat (%)		
	Heart rate (bpm)	Heart rate monitor	Polar
	Minute ventilation (l/min)	Metabolic cart	COSMED K4b^2
	Oxygen uptake (ml/min/Kg)		
	Energy expenditure (Kcal/min)		
	Metabolic equivalent		
	Respiratory exchange ratio		
	Ratings of perceived exertion	Ratings of perceived exertion scale	Borg CR 10

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Table 3 Statistics (Mean ± Standard Deviation) on meteorological and physiological data

Parameters	Mean ± Standard Deviation	Range
HI (°C)	34.9 ± 5.3	27.1-45.8
WBGT (°C)	31.4 ± 3.1	26.3 -36.9
TWL (W/m^2)	153 ± 42.9	61 - 283
Air pollution index	35.1 ± 15.2	10-90
Age (year)	45.8 ± 6.8	18-65
Percentage of body fat (%)	14.3 ± 3.7	5-32
Resting heart rate (bpm)	77.8 ± 8.4	57-99
Alcohol drinking habit	1.0 ± 0.7	0-2
Smoking habit	0.8 ± 0.7	0-2
Energy consumption	2.5 ± 0.5	0-4
Respiratory exchange	1.9 ± 0.4	0-4

Note: Alcohol drinking habit ("no consumption"= 0, "no more than 4 drinks on any single day AND 14 drinks per week"= 1, "More than 4 drinks on any single day OR 14 drinks per week"=2, one standard drink contains about 0.6 fluid ounces or 14 grams of pure alcohol), smoking habit ("no consumption"= 0, "1-4 cigarettes per day"= 1, "more than 5 cigarettes per day"= 2)

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Table 4 Measure of accuracy for out-of-sample

Participant	HI-heat stress model		WBGT-heat stress model		TWL-heat stress model	
	Adj.R^2 = 0.778		Adj.R^2 = 0.785		Adj.R^2 = 0.787	
	MAPE (%)	Theil U	MAPE (%)	Theil U	MAPE (%)	Theil U
1	12.9	0.1409	9.4	0.0983	9.7	0.0874
2	12.7	0.0801	7.3	0.0732	7.3	0.0761
3	8.5	0.0768	6.5	0.0862	6.9	0.0663
4	11.6	0.1011	8.3	0.0571	9.2	0.0572
5	13.3	0.1679	8.3	0.0846	10.2	0.0626
6	10.5	0.0773	8.1	0.0622	7.4	0.0481
7	9.6	0.1068	6.4	0.0426	6.1	0.0482
8	13.4	0.0892	5.4	0.0354	7.2	0.0482
9	17.5	0.1023	10.8	0.0793	11.3	0.0734
10	8.9	0.0329	4.8	0.0239	5.1	0.0383
11	9.5	0.473	5.3	0.0462	5.9	0.0398
12	8.2	0.0782	3.2	0.0121	4.8	0.0212
13	12.6	0.1029	7.8	0.0879	8.2	0.0783
14	6.9	0.0263	2.8	0.0168	3.2	0.0187
15	8.9	0.0485	5.6	0.0392	5.1	0.0382
16	12.8	0.0627	7.3	0.0461	8.0	0.0623
17	9.7	0.0428	8.2	0.0768	8.2	0.0687
18	7.5	0.0529	5.3	0.0431	6.0	0.0528
19	10.7	0.0822	3.4	0.0221	4.2	0.0582
Average	**10.8**	**0.102**	**6.5**	**0.054**	**7.1**	**0.055**

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Table 5 Heat tolerance times at different levels of heat exposure, different age groups, and by different environmental indicators

T (°C)	RH (%)	HI (°C)	WBGT (°C)	TWL(W/m^2)	Age				Interventions
					25	35	45	55	
25	90	27	24	⩾220	152	126	101	75	Unrestricted
26	90	29	25		147	122	96	70	
27	90	30	26		143	117	91	66	
28	75	31	27		138	112	87	61	
29	75	33	28	140-220	133	108	82	56	Acclimatization
30	75	36	29		129	103	77	51	
31	75	39	30		124	98	72	47	
31	90	42	31		119	93	68	42	
32	90	45	32	115-140	114	89	63	37	Buffer
33	75	47	33		110	84	58	33	
34	75	50	34		105	79	54	28	
35	75	53	35	⩽115	100	75	49	23	Withdrawal
35	90	57	36		96	70	44	18	
36	90	59	37		91	65	39	14	

Note: Air pollution index is 30; percentage of body fat is 12.3 (%); resting heart rate is 78; alcohol drinking habit is 1 (no more than 4 drinks on any single day AND 14 drinks per week, one standard drink contains about 0.6 fluid ounces or 14 grams of pure alcohol); smoking habit is 1 (1-4 cigarettes per day); workload is moderate (EC = 2; RE = 2); T is temperature (°C); RH is relative humidity (%); HI is heat index (°C); WBGT= -12.065+1.193T+0.0688RH (Leung et al. 2009), is wet bulb globe temperature (°C); TWL is thermal work limit (W/m^2); wind speed = 0.5 m/s; guidelines for TWL are proposed along with recommended interventions by Brake and Bates (2002b).