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HEAT STRESS EFFECTS ON CONSTRUCTION LABOUR PRODUCTIVITY IN HOT SEASONS: A CASE STUDY OF REBAR AND MOULDING WORKERS IN CAMBODIA

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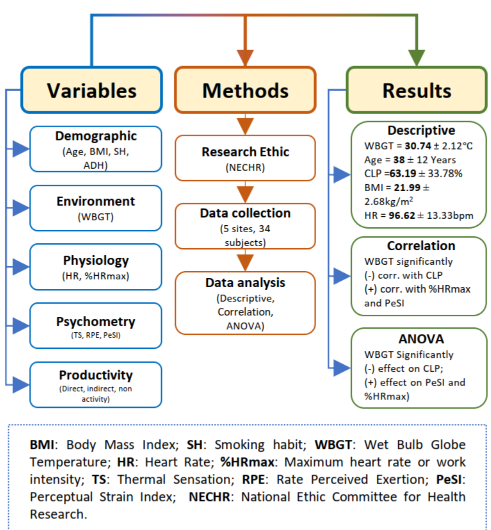
Graphical abstract



Abstract

This study investigates the impact of heat stress on construction labour productivity (CLP), the Perceptual Strain Index (PeSI), and work intensity among rebar and moulding construction workers in Phnom Penh, Cambodia. Thirty-four healthy workers aged 18 to 54 volunteered during the hot months from March to June 2023. Heat stress was measured using the Wet Bulb Globe Temperature (WBGT) collected on-site. Physiological responses, such as heart rate, were monitored. The percentage of maximum heart rate (%HRmax) was computed to determine the work intensity. Perceptual responses were measured using PeSI. CLP was measured by observing the direct work productivity of participants. CLP was then quantified as the percentage of time participants/workers dedicated to direct tasks. ANOVA and correlation were applied for analysing the effect of WBGT on CLP, PeSI, and %HRmax. Results indicate that higher WBGT levels significantly reduce construction labour productivity (Pr = 1.1e-06). The average CLP declines from 74% to 48% as WBGT increases from 26°C to 35°C. Heat stress is significantly positively correlated with PeSI (r = 0.466, Pr = 2e-16)) and %HRmax (r = 0.247, Pr = 4.78e-12), indicating increased heart rates and perceived strain with rising temperatures. Despite stable physical effort, productivity declines due to physiological or psychological factors linked to heat exposure. These findings suggest that workers' perceived exertion intensifies as risk of heat stress increase, negatively impacting well-being and productivity. This study provides valuable insights into the challenges faced by construction workers during Cambodia's hot months and emphasises the need for strategies to mitigate heat-related impacts and enhance productivity in the construction sector.

Keywords: Construction Labour, Heat Stress, Hot Season, Phnom Penh, Productivity, Tropic Region, WBGT.

1.0 INTRODUCTION

The construction industry plays a vital role in the economic development of many countries. In Cambodia, the construction industry is one of the significant contributors to the country's economy, accounting for approximately 10% of the GDP [1]. However, construction workers face significant occupational health risks, particularly from heat stress, which can negatively impact their productivity and well-being [2, 3]. Heat stress is primarily caused by high ambient temperatures, humidity, and physical exertion. Prolonged exposure can result in heat-related illnesses such as heat exhaustion and heat stroke while also impairing cognitive function and increasing the risk of accidents and injuries [4]. The risks posed by heat stress are becoming more pronounced globally. The frequency and intensity of heat waves will increase significantly in the coming decades. Global temperature projections indicate a potential rise of 0.3°C to 1.7°C over the 21st century, with heat waves lasting longer and occurring more frequently [6]. One-third of the world population currently experiences life-threatening heatwaves, a figure projected to increase to nearly 50% by 2100, even with reductions in greenhouse gas emissions [5]. During heatwaves, outdoor workers face greater exposure to direct sunlight and dehydration, exacerbating the risks of heat stress, accidents, and reduced cognitive function [9, 10]. Empirical research has linked heat stress with increased rates of morbidity and mortality [11, 12, 13].

The increase in environmental temperatures has direct and harmful impacts on the occupational sector. Workers in outdoor environments, like construction labourers, are especially vulnerable to the compounded effects of environmental heat and internal heat generated by metabolic activity during physically demanding tasks [7]. Failure to dissipate this heat efficiently leads to elevated core body temperatures and poses serious health risks [8]. For instance, data from Japan show that heat strokes are most prevalent during the summer months [14, 15]. In Phnom Penh, where the monthly average ambient temperature is 28.21°C (1981-2023), seasonal highs reach 35°C during hot months [16]. Global climate change is projected to further intensify the frequency and severity of heat waves, posing an increasingly dire threat to this essential workforce [3, 17].

Several studies have explored the relationship between heat stress and construction labour productivity, offering valuable insights into the extent of its impact across various regions and construction activities. Heat stress has been shown to significantly reduce construction labour productivity, leading to delays and cost overruns [18]. Studies indicate that hot and humid environments, direct sunlight, heavy clothing, and inadequate fluid intake are major contributors to heat stress [19]. Outdoor workers performing moderate to high workloads at temperatures exceeding the 28°C threshold have reported productivity losses ranging from 18% to 35% [18]. Moreover, poor site conditions, including extreme heat, high humidity, inadequate lighting, uneven terrain, and insufficient access to necessary resources or equipment, can significantly impact worker performance and productivity. These unfavourable conditions have been linked to performance losses of up to 50% [20]. For instance, workers engaged in moderate labour lose 50% of their work capacity at temperatures around 33-34°C [21]. The loss in labour productivity due to heat stress in Australia has been reported to reach 38% [22], while a decrease in productivity globally of up to 20% has been observed [23].

In addition, the productivity loss is not directly caused by the increase in temperature; rather, it refers to the environmental conditions as measured by the Wet-Bulb Globe Temperature (WBGT) [3]. Yi & Chan conducted a study in Hong Kong focusing on rebar workers. They measured environmental conditions using the wet-bulb globe temperature (WBGT) index and assessed workers' heart rates and productivity levels. Their findings revealed that for every 1°C increase in WBGT, the percentage of direct work time decreased by 0.33%. This study also highlighted the role of individual characteristics, such as age, work duration, and personal habits, in determining the degree to which heat stress affects productivity [3]. Similarly, Li et al. examined the effects of rising temperatures on construction labour productivity (CLP) in Beijing. They observed a 0.57% reduction in productivity for every 1°C increase in ambient temperature [24]. In another significant study conducted in India, Somanathan et al. found that a 1°C rise in temperature resulted in a 2% decline in productivity, underlining the serious impact of heat stress in tropical climates [25]. Furthermore, Ayessaki and Smallwood reported that poor site conditions in hot climates could lead to a 50% decline in worker performance, a finding that underscores the compounded effects of environmental factors and inadequate site management on productivity [20]. Additional research has emphasised the detrimental impacts of extreme heat on construction workers' health and safety. Studies by Gun, Fatima et al. and Martínez-Solanas et al. demonstrated that heat stress increases the likelihood of accidents due to fatigue, dehydration, and impaired cognitive function. These studies highlight the dual burden of reduced productivity and increased safety risks in construction work environments [9, 10, 26]. These findings are critical for understanding the vulnerability of construction workers in tropical regions, where such temperatures are frequently exceeded during hot seasons.

Despite a comprehensive review of existing research, this study found limited evidence to directly link heat stress to significant productivity losses in the construction sector in Cambodia. This study aims to fill this gap by investigating the productivity of rebar and moulding workers in Phnom Penh during the hottest months of the year, thereby contributing to the global understanding of heat stress in the construction industry.

2.0 METHODOLOGY

This study examines the effects of heat stress on construction labour productivity (CLP), the perceptual strain index (PeSI), and work intensity among rebar and moulding construction workers in Phnom Penh, Cambodia. A systematic approach was developed to guarantee ethical adherence and comprehensive data acquisition. The flowchart in Figure 1 describes the essential processes in the research process, encompassing participant selection, data record and validation and statistical analysis, to guarantee the quality and validity of the obtained data.

2.1 Participants and Site Selection

The study was conducted on 34 rebar and moulding workers from a randomly selected group across five construction sites in Phnom Penh, Cambodia. Participation was voluntary, and from those who expressed interest, a random selection was made. To ensure consistency in demographic analysis, only male workers were included in the study. Participants had to meet specific eligibility criteria, including being at least 18 years old and passing a medical screening to confirm they were in good health. To reduce bias caused by pre-existing health conditions that could impact susceptibility to heat stress, workers with a history of hypertension, diabetes, cardiovascular disease, neurological disorders, high blood pressure, or heart disease were excluded. This approach not only prioritized the safety and well-being of the participants but also aimed to minimize external factors that could influence the study's findings regarding heat stress risks in construction work.

2.2 Ethical Approval and Consent

The study received approval from the National Ethics Committee for Health Research (Ref No: 037 NECHR). To uphold ethical standards, all participants provided informed consent before participating in the study, ensuring voluntary involvement and data confidentiality.

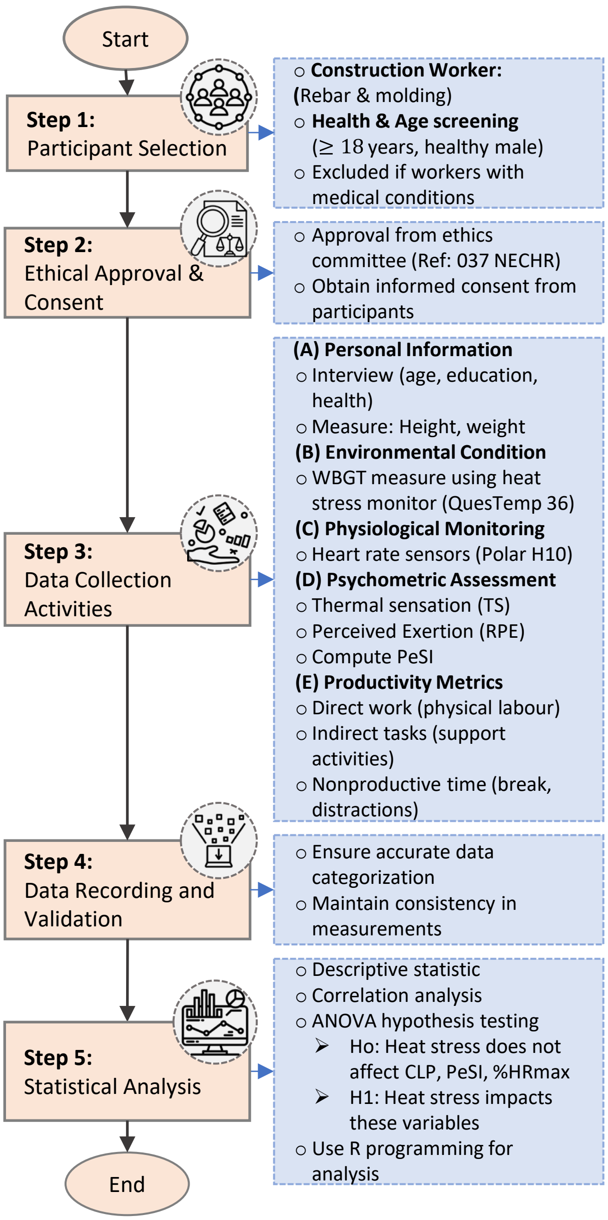


Figure 1 Research methodology flowchart—Illustrating participant selection, ethical approval, data collection, and statistical analysis

2.3 Data Collection

Data collection for this study took place from March to June 2023, during the hot months. Two workers from either the rebar or moulding teams were voluntarily selected each day to participate in the observation.

The data collection process was divided into three distinct parts. First, participants were interviewed to gather personal information and health characteristics, as shown in Figure 2(a). Next, various tools were used to measure physiological and meteorological data, as depicted in Figures 2(b) and 2(c). Finally, the activities of the workers were observed to record their productivity; see Figure 2(d). Four main parameters were collected during the study, including personal information, environmental condition, physiological parameter, and productivity metric.

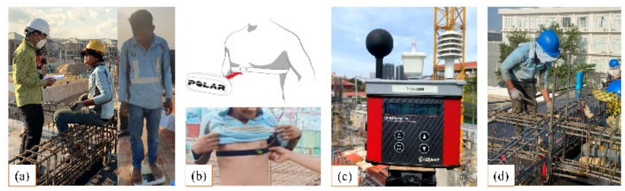


Figure 2 Data collection activities

2.3.1 *Personal Information*

Workers' personal information was collected through oral interviews and practical measurements. Personal data, including name, age, gender, role, level of education, smoking habits, drinking habits, and health-related questions, were gathered via interviews. Additionally, physical measurements such as height and weight were taken before the study commenced. One important measure of weight categories and their possible effects on general health is body mass index (BMI). BMIs are classified by the World Health Organisation (WHO) as follows: WHO guidelines [27] specify underweight (BMI < 18.5), normal weight (BMI 18.5–24.9), overweight (BMI 25.0–29.9), obesity Class I (BMI 30.0–34.9), obesity Class II (BMI 35.0–39.9), and obesity Class III (BMI ≥ 40.0). For BMI computation, Donoghue and Bates [28] offer a precise formula in Equation 1.

$$\text{BMI} = \text{Weight} / \text{Height}^2 \qquad (1)$$

2.3.2 *Environmental Conditions*

The Wet Bulb Globe Temperature (WBGTis widely recognised as the most suitable measure for studying thermal stress on construction sites [3]. The WBGT considers temperature, humidity, wind speed, and solar radiation, providing a comprehensive assessment of the heat stress conditions at the construction sites. The study chose the WBGT as the parameter for assessing heat stress levels. Heat stress monitor model QuesTemp 36 was calibrated and used for measuring outdoor WBGT. The measurement procedure was adopted to standardise protocol for data collection. The data were taken at consistent times and location to reduce variability. The WBGT is calculated using the formula in equation 2 [29, 30].

$$\text{WBGT}_{outdoor} = 0.7T_{nwb} + 0.2T_g + 0.1T_{db} \qquad (2)$$

Where WBGT represents the wet bulb globe temperature (°C), T_{nwb}, T_{db} and T_g are natural wet-bulb temperature, dry-bulb temperature, and globe temperature (°C) respectively.

As stated by the Department of the Army, they have delineated the risk levels of WBGT into three classifications: low risk (WBGT < 29.3°C), moderate risk (29.4°C < WBGT < 32.1°C), and high risk (WBGT > 32.1°C) [31].

2.3.3 Physiological Monitoring

Workers' heart rates were monitored using wearable sensors (Polar H10). These measurements help assess the physiological impact of heat stress on the workers. Fox and Naughton provide a method, as denoted in equation 3, for determining HRmax [31]. Equation 4 was used to calculate the percentage of maximum heart rate (%HRmax). Each worker wore a heart rate sensor around their chest upon starting their shift and removed it at the end of their work hours.

$$HRmax = 220 - Age \qquad (3)$$

$$\%HRmax = HR / HRmax \qquad (4)$$

In Minard's research, they emphasised that heart rate (HR) acts as a pivotal physiological gauge for measuring work intensity [33]. The classification system, later endorsed by the American College of Sports Medicine (ACSM) in 1998 for application in work environments, divides work intensity into three categories: light (HR < 54% HRmax), moderate (HR < 69% HRmax), and high (HR > 70% HRmax), as specified by Pollock and his colleagues [34]. Furthermore, the ACSM advocated for the adoption of this system to effectively evaluate and characterise the intensity levels in various work-related tasks.

2.3.4 Psychometric Assessment

In the psychometric segment, two parameters—thermal sensation (TS) and rating of perceived exertion (RPE)—are considered. TS was evaluated on a 7-point scale, with 7 indicating "neutral and comfortable" and 13 indicating "intolerably hot" [34]. Participants were directed to assess their Thermal sensation every 15 minutes using a questionnaire. RPE, a subjective measure of perceived effort based on the Borg RPE scale, a 10-point scale ranging from 0 for "resting" to 10 for "maximal exertion" [36], was also assessed at the end of each 15-minute interval using a questionnaire.

The Perceptual Strain Index (PeSI) was used as a measure to evaluate heat strain and assess the health risks related with heat exposure for workers. PeSI is computed using equation 5 [36] and categorised into five ranges. PeSI values falling between 0 to 2 indicate "minimal or no heat strain", 3 to 4 suggest "low heat strain", 5 to 6 represent "moderate heat strain", 7 to 8 reveal "significant heat strain," and 9 to 10 illustrate "very high heat strain".

$$PeSI = 5 \times [(TS - 7)/6] + 5 \times (RPE/10) \qquad (5)$$

Where PeSI is Perceptual Strain index, TS is Thermal Sensation, and RPE is Rate Perceived Exertion.

2.3.5 Productivity Metrics

Work intensity and rest duration are recorded to evaluate how heat stress affects productivity. These metrics are gathered through direct observation. Many studies have proposed that the percentage of time spent on direct work is a valuable metric for evaluating the productivity of construction labour [38].

This study utilised AACE International (Association for the Advancement of Cost Engineering) to gauge labour productivity. Following the methodology proposed by AACE International, work tasks were segmented into three distinct categories. Tasks were classified as either direct, indirect, or nonproductive time. Direct tasks encompassed activities directly supporting product or service output (i.e., make use of wrenches to connect, cut, bend, or modify reinforcing steel bars, place reinforcing steel bars; modify reinforcing steel bars; carry reinforcing steel bars; use meter sticks for measurement). Indirect tasks involved activities crucial for workplace efficiency but not directly tied to production, including (i.e., walking towards equipment, tools, and materials; waiting for materials to be carried; reviewing the list of materials to understand the work; talking with the foreman and co-worker about tasks; taking materials). Nonproductive time was spent on tasks unrelated to product/service output or workplace operation (i.e., work stoppage from any cause due to employees or machines, chatting, smoking, drinking, sitting, using a cell phone, going to the washroom). To gather data on construction labour productivity, each observer meticulously monitored and documented participant activities on a minute-by-minute basis.

2.4 Data Record and Validation

Data was recorded using both paper-based and digital methods. After collection, all information was systematically categorized and consolidated into a single Excel sheet for analysis. To ensure data accuracy, outliers and incomplete datasets were identified and removed during the cleaning process. By applying these validation steps, errors were minimized, and the integrity of the data was preserved for analysis. Before recording began, the timing of measurements was carefully synchronized in advance, ensuring that all manual records and measurement devices started simultaneously. This approach-maintained consistency in data collection and enhanced the reliability of the results.

2.5 Research Hypothesis and Statistical Analysis

This study aims to investigate the impact of heat stress on construction labour productivity (CLP), perceptual strain index (PeSI), and work intensity (%HRmax). We formulated three hypotheses based on the literature review and research objectives: (1) Heat stress significantly reduces construction labour productivity (CLP), as a higher risk level of WBGT is expected to lead to increased fatigue and decreased efficiency among construction workers. (2) Heat stress significantly increases the perceptual strain index (PeSI), grounded in the understanding that workers perceive higher levels of strain when exposed to higher temperatures. (3) Heat stress significantly affects work intensity (%HRmax), based on the premise that workers' heart rates increase with higher temperatures, indicating greater physiological strain. To test these hypotheses, we conducted an experiment involving construction workers exposed to different levels of heat stress. We measured CLP, PeSI, and %HRmax and applied ANOVA to analyse the data, determining whether there are significant differences in these variables under varying levels of heat stress.

For correlation analysis, Pearson's method was employed with listwise deletion to assess relationships among variables, including CLP, WBGT, Perceptual Strain Index (PeSI), %HRmax. This correlation analysis is critical for identifying key relationships among variables, testing hypotheses, understanding the effects of environmental and physiological factors on construction labour productivity and guiding future intervention or analysis.

We used R programming for all statistical computations. Assumption checks included verifying normality and homogeneity of variances to validate the use of ANOVA. Results were presented using column charts and box plots to effectively illustrate the findings. Interpretation guidelines were established to aid in comprehending the statistical results of the research questions, emphasising the significance of heat stress on labour productivity and associated physiological responses.

3.0 RESULTS AND DISCUSSION

3.1 Results of Descriptive Statistics of Study Variables

According to the descriptive results shown in Table 1, the mean WBGT of 30.74°C indicates that the working conditions were quite hot, with WBGT ranging from 25.9°C to 35.4°C. This high-heat-stress environment is critical for understanding its effects on labour productivity. The average age of the workers was 38 years, with a wide range from 18 to 54 years. This diversity in age helps analyse how different age groups respond to heat stress.

Table 1 Descriptive statistics of key parameters

Parameter	Mean ± SD	Range	Unit
WBGT	30.74 ± 2.12	25.9 - 35.4	℃
Age	38 ± 11	18 - 54	Years
BMI	21.99 ± 2.68	17 - 27.9	kg/m²
HR	96.62 ± 13.33	66 - 152	bpm
%HRmax	53.16 ± 8.09	32.7 - 87.9	%
CLP	63.19 ± 33.78	0 - 100	%

The mean BMI of 21.99 kg/m² falls within the normal range, suggesting that the workers generally had a healthy weight. The range of 17 to 27.9 kg/m² indicates some variability, which could influence individual responses to heat stress. The average heart rate was 96.62 bpm, with a range from 66 to 152 bpm. This variation reflects the physical exertion levels and individual fitness of the workers under heat-stress conditions.

The mean %HRmax of 53.16% shows that, on average, workers were operating at just over half of their maximum heart rate, with some reaching up to 87.9%. This result indicates significant cardiovascular strain potentially caused by heat stress. The mean productivity was 63.19%, with a wide range from 0 to 100%. This variability may be due to the effects of various factors, including heat stress, on productivity, with some workers being severely affected.

3.2 Wet Bulb Globe Temperature (WBGT)

Figure 3 presents the distribution of WBGT at 15-minute intervals from 7:15 AM to 5:00 PM, recorded in Phnom Penh, Cambodia, during the data collection period from March to June 2023. The result showed that from the start of data collection at 7:15 AM, WBGT values fall within the green "low-risk WBGT" zone. The early morning temperature from 7:15 AM to about 8:45 AM consistently stays below 29.3℃, indicating minimal risk of heat stress. Around 9:00 AM to 10:00 AM, the WBGT enters the orange-shaded "moderate risk of WBGT" zone, where there is a potential for heat stress ranging between 29.4℃ and 32.2℃. The WBGT values fluctuate slightly but predominantly rise during this period, with increasing variability as the day progresses. From 10:15 AM until approximately 3:00 PM, the WBGT crosses into the red "high-risk WBGT" zone. This period has the highest heat stress risk, with peak WBGT values nearing 34°C around 1:00 to 2:00 PM. After 3:00 PM, WBGT values begin to drop back into the moderate- and low-risk zones, stabilising below 29.3°C around 4:30 PM and thereafter.

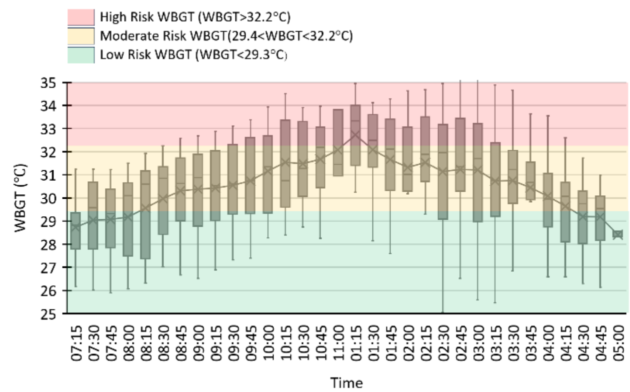


Figure 3 Time series of Wet Bulb Globe Temperature measurements

3.3 Correlation Analysis

The results presented in Table 2 reveal a significant negative correlation between construction labour productivity (CLP) and the WBGT (r = -0.183), meaning that higher WBGT is linked to decreased CLP. Additionally, an examination of age shows that older workers tend to have higher Body Mass Index (BMI) values and higher percentages of maximum heart rate (%HRmax), indicating a greater cardiovascular strain associated with advancing age. Additionally, an examination of age shows that older workers tend to have higher Body Mass Index (BMI) values and higher percentages of maximum heart rate (%HRmax), indicating a greater cardiovascular strain associated with advancing age.

Furthermore, the analysis reveals a significantly positive correlation between WBGT and working shift (r = 0.183), PeSI (r = 0.466) and %HRmax (r = 0.247). These results suggest that during afternoon shifts with higher WBGT levels, workers may experience increased perceptual strain and work intensity. These findings highlight the complex interplay between environmental conditions and worker health, emphasising the importance of managing heat stress in construction settings.

Table 2 Correlation matrix showing the relationships between various variables.

Variable	*CLP*	*WBGT*	*PeSI*	*%HRmax*
CLP		-0.183***	0.074*	0.079*
WBGT	-0.183***		0.466***	0.247***
PeSI	0.074*	0.466***		0.147***
%HRmax	0.079*	0.247***	0.147***	

Computed correlation used pearson-method with listwise-deletion
*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

3.4 Relationship between CLP and WBGT

Figure 4 illustrates the relationship between Wet Bulb Globe Temperature (WBGT) and construction labour productivity (CLP). The result showed that as WBGT increases from 27°C to 35°C, there is a noticeable decline in CLP. For example, at 27°C, CLP is relatively high (average CLP = 75%), but it decreases significantly as the WBGT rises to 35°C (average CLP = 48%). The graph highlights the importance of managing heat stress in construction environments. As temperatures rise, productivity decreases, which can impact project timelines and worker health. To mitigate the effects of high WBGT, it may be necessary to implement measures such as providing cooling areas, scheduling work during cooler parts of the day, and ensuring adequate hydration and rest breaks for workers.

The negative correlation between WBGT and construction labour productivity (CLP) supports previous findings that indicate a significant productivity drop within temperature ranges above 28℃ [20]. As the WBGT rose, CLP decreased from approximately 75% at low-risk levels to about 48% at high-risk levels. This trend reflects the physiological strain on workers, as evidenced by increasing heart rate and Perceptual Strain Index (PeSI) alongside rising temperatures. Such findings are consistent with [3, 18, 21] who documented similar declines in productivity among construction workers under heat stress conditions.

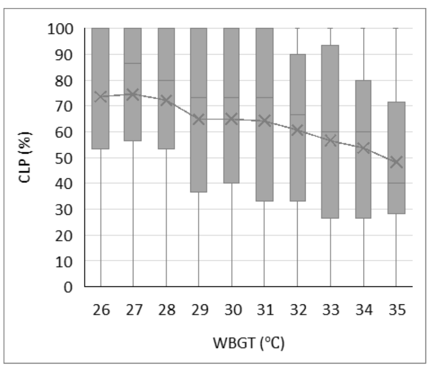


Figure 4 Relationship between WBGT and CLP

3.5 Relationship between Heart Rate and WBGT

Figure 5 illustrates the relationship between heart rate (bpm) and WBGT among the workers observed in the study. The result showed a slight upward trend in heart rate as WBGT increases. This evidence suggests that as heat stress level (WBGT) rises, the worker's heart rates tend to increase, which is consistent with physiological responses to heat. In the lower WBGT range (26℃ to 29.3℃), the median heart rate fluctuates slightly between approximately 90 and 95 bpm. The interquartile range (IQR) remains relatively stable, and the variability (whiskers) is moderate. This finding indicates that at these lower WBGT levels, heart rates are more consistent, and fewer extreme heart rate values (outliers) are observed. For heart rate at moderate WBGT (29.4℃ - 32.1℃), there is a noticeable upward shift in mean heart rate, which reaches approximately 90 to 98 bpm. For heart rate at high WBGT (above 32.2℃), the mean heart rate rises to around 100 bpm, with even higher variability in heart rates. The whiskers show wider ranges of heart rates up to 140 bpm, indicating that in extreme heat stress conditions, some workers experience significantly elevated heart rates.

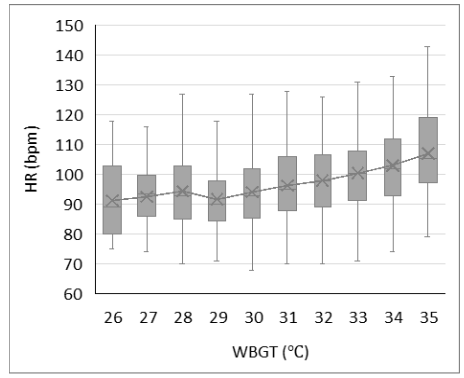


Figure 5 Relationship between WBGT and heart rate

As WBGT increases, the heart rate of workers also increases. An increase in heart rate under heat stress (WBGT > 29℃) is expected as the body works harder to maintain core body temperature by increasing circulation to the skin and through sweating. The rise in heart rate at a higher WBGT level could indicate a higher risk of heat-related illness, such as heat exhaustion or heat stroke, especially for workers whose heart rate reaches 120 bpm or higher.

The physiological responses observed, including elevated heart rates and increases in %HRmax, highlight the cardiovascular strain that workers endure in high-heat stress environments. As noted by NIOSH [19], factors such as direct sunlight, humidity, and inadequate hydration exacerbate the effects of heat stress, which can lead to serious health risks including heat exhaustion and heat stroke. Additionally, prolonged exposure to hot and humid environments has been shown to impair cognitive and perceptual-motor performance, leading to decreases in productivity and increased risk of accidents [39, 40].

3.6 Relationship between Work Intensity and WBGT

The graph in Figure 6 shows the relationship between the percentage of maximum heart rate (%HRmax) or work intensity and wet bulb globe temperature (WBGT).

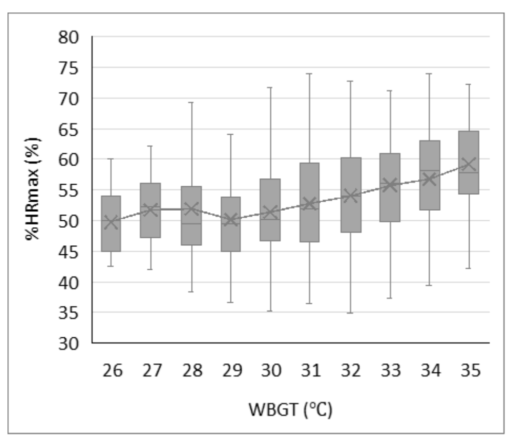


Figure 6 Relationship between WBGT and work intensity

As WBGT increases from 29°C to 35°C, there is a noticeable trend of higher %HRmax values changing from 50% to 60%, indicating that workers' heart rates approach a higher percentage of their maximum as the WBGT rises. These results show the direct correlation between heat stress and physiological response, emphasising the need for effective heat management strategies in hot working environments.

3.7 Relationship between PeSI and WBGT

The results depicted in Figure 7 show a clear relationship between Wet Bulb Globe Temperature and Perceptual Strain Index. The result provides additional insights into the variability of the Perceptual Strain Index. The scatter plot with a trend line shows a positive correlation between WBGT and the Perceptual Strain Index. As WBGT increases from 26°C to 35°C, the Perceptual Strain Index also rises from 1 to 4. This data indicates that higher WBGT is associated with greater perceived strain among the subjects.

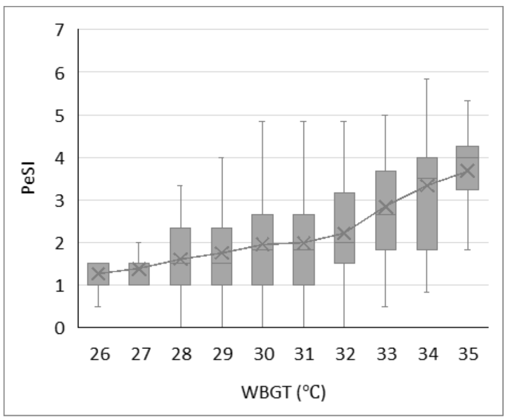


Figure 7 Relationship between WBGT and perceptual strain index

The trend line suggests a consistent increase in the Perceptual Strain Index as WBGT rises. This trend highlights the direct impact of increasing heat stress on perceptual strain. The differences in the Perceptual Strain Index become larger at higher WBGT levels, shown by the bigger IQRs and more outliers. This evidence suggests that individual perceptions of strain vary more significantly in hotter conditions.

3.8 Analysis of the effect of WBGT risk levels on CLP, PeSI, and Work Intensity

The analysis of the impact of heat stress, as measured by the Wet Bulb Globe Temperature (WBGT), on construction labour productivity (CLP), perceptual strain, and work intensity reveals clear trends to different WBGT risk levels (low risk, moderate risk, and high risk). To statistically validate these trends, an Analysis of Variance (ANOVA) test was employed. This method helped compare the average value across the different WBGT risk levels, determining whether the observed differences in CLP, perceptual strain, and work intensity were statistically significant. The ANOVA table presented in Table 3 demonstrates the statistically significant effect of WBGT on various parameters, including construction labour productivity, perceptual strain index, and work intensity.

Table 3 ANOVA on the effect of WBGT risk levels on CLP, PeSI and work intensity

Response	df	Sum Sq	Mean Sq	F-Value	Pr(>F)
CLP	2	30822	15411	13.93	1.1e-06***
PeSI	2	258.2	129.09	114.8	<2e-16***
%HRmax	2	3319	1659.6	26.83	4.78e-12***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.8.1 Effect of WBGT Risk Levels on Construction Labor Productivity (CLP)

Figure 8 illustrates a negative correlation between WBGT risk levels and CLP. At low-risk levels of WBGT, median productivity is relatively high, around 80%. However, productivity shows a notable decline as the WBGT risk increases. In moderate-risk conditions, median productivity drops to around 70%, while high-risk conditions show a more significant decrease, with median productivity falling to approximately 60%. This result highlights the sensitivity of construction labour productivity to the increase of heat stress, with productivity decreasing as the level of heat stress rises. Despite some variability across the data, the overall trend indicates that high WBGT levels lead to substantial reductions in CLP. Additionally, the ANOVA test results in Table 3 shows that heat stress (WBGT) significantly affects construction labour productivity (Pr < 0.05).

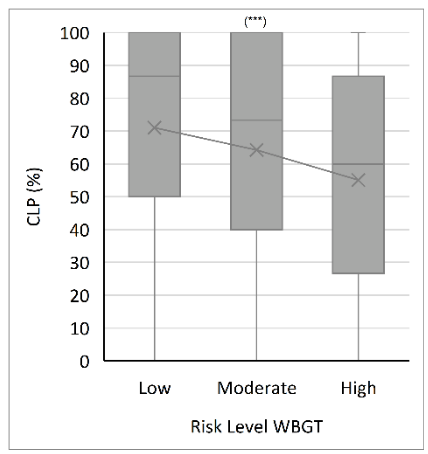


Figure 8 Effect of WBGT risk levels on CLP

3.8.2 Effect of WBGT Risk Levels on Perceptual Strain Index (PeSI)

Figure 9 examines the effect of WBGT risk on the Perceptual Strain Index (PeSI). Workers' perceptual strain increases markedly with higher WBGT risk levels. Under low-risk conditions, the median PeSI is close to 1, indicating relatively low strain. As WBGT reaches moderate risk levels, the median PeSI rises to around 2, while high-risk conditions result in a sharp increase, with the median PeSI reaching 3. The variability of PeSI values is also greatest at high WBGT risk levels, suggesting that workers experience a wider range of strain responses under extreme heat conditions. These results indicate that workers' perceived exertion intensifies as the risk level of heat stress increases, which could negatively affect both well-being and productivity. ANOVA test results shown in Table 3 illustrate the effect of the risk levels for heat stress on the Perceptual Strain Index, indicating that WBGT risk levels significantly affect workers' perceptual strain (Pr < 0.05).

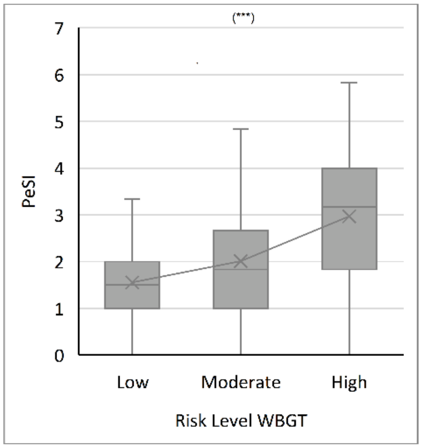


Figure 9 Effect of WBGT risk levels on PeSI

3.8.3 Effect of WBGT Risk Levels on Work Intensity (%HRmax)

Figure 10 shows the relationship between WBGT risk levels and work intensity, measured as a percentage of maximum heart rate (%HRmax).

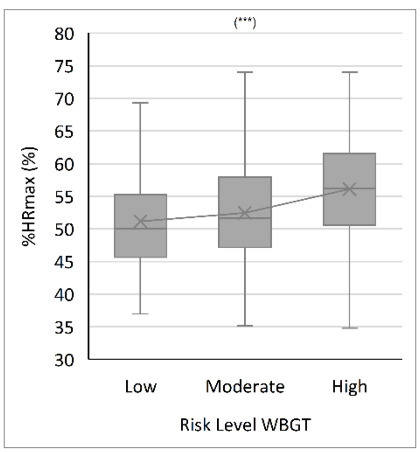


Figure 10 Effect of WBGT risk levels on work intensity

These results suggest that as WBGT risk levels increase, workers experience higher cardiovascular strain, as indicated by the rising %HRmax. The greater variability at high-risk levels also implies that individual responses to heat stress can vary widely. In contrast to the other two variables, work intensity remains relatively consistent across different WBGT risk levels. Median work intensity at Low Risk is approximately 50% HRmax, increasing slightly under moderate risk and reaching around 60% HRmax at high-risk levels. The increase in work intensity with higher WBGT is small but noticeable. This finding suggests that while workers maintain a relatively stable physical effort regardless of heat stress, the perceptual strain and decline in productivity occur due to other physiological or psychological factors associated with heat exposure.

The study highlights the negative impact of heat stress on construction labor productivity (CLP) while increasing perceptual strain index (PeSI) and work intensity (%HRmax). For construction companies, adjusting work schedules, implementing cooling stations, and providing suitable protective equipment can help mitigate risks. Policymakers should enforce regulations on maximum working temperatures, mandatory rest periods, and funding for further research and cooling infrastructure. Workers can protect themselves by staying hydrated, wearing breathable clothing, using wearable health monitors, and reporting heat stress concerns. Linking these findings to international studies enhances their global relevance and application.

4.0 CONCLUSION

This study investigates the effects of heat stress on construction workers in Phnom Penh, Cambodia. Result showing that construction labour productivity declines from 75% to 48% as WBGT rises from 27°C to 35°C. Furthermore, WBGT risk levels have a notable positive impact on perceptual strain (Pr<2e-16), therefore hotter conditions cause more stress on employees, so increasing their fatigue and the risk of heat-related diseases.

These results demonstrate the need of effectiveness heat stress control techniques for the construction sector. Construction industry should change their work schedules, enhance safety precautions, and apply monitoring and training programs to protect employees from the negative consequences of severe heat. To mitigate strain employees can also be proactive in keeping hydrated, schedule break and using shade rest area.

Beyond industry-level responses, policy maker has to create and enforce regulations protecting workers' health and productivity in high heat stress environment. Additionally, further research should focus on evaluating and mitigate heat stress risk in construction environments.

Overcoming these obstacles will help the building sector raise general worker well-being, efficiency, and safety. This study expands knowledge of heat stress worldwide, especially in tropical environments. Future research should concentrate on long-term solutions and evaluate the success of various interventions to guarantee sustainable developments in workers' health and productivity. Stakeholders in the face of climate change have to help construction workers to guarantee worker well-being and economic stability in Cambodia and the neighbouring regions.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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