- Technical Paper -

A STUDY ON PARAMETERS INFLUENCING MAXIMUM WIDTH OF EARLY-AGE THERMAL CRACKS IN RC ABUTMENTS USING NEURAL NETWORKS

Mehboob RASUL*1, Akira HOSODA*2 and Koichi MAEKAWA*3

ABSTRACT

This paper presents a study on the parameters influencing the maximum width of early-age thermal cracks in massive RC abutments using neural networks. The parametric studies are based on a well-trained neural network which was trained using Yamaguchi prefecture dataset. The effect of unit cement content, width, thickness, lift height, reinforcement ratio, lift interval, ambient temperature and initial concrete temperature was studied. The results have shown the potential of neural networks to extract the essences of construction data and proposing recommendations to mitigate harmful thermal cracks.

Keywords: thermal cracking, RC abutments, neural networks, actual construction data

1. INTRODUCTION

Early-age thermal cracks in mass concrete are caused by thermal stress which is generated due to restraint to the volume change derived mainly from hydration heat of cement and autogenous shrinkage. There are many factors which influence the thermal cracking i.e. structure type, geometry, volume, properties of concrete constituents, mix proportion, boundary conditions, ambient-environmental condition, construction method, construction quality, etc. The presence of many influential factors makes the thermal cracks difficult to control and predict. If water tightness is not the target, then cracking may be permitted by controlling the maximum width of cracks for economy.

Architectural institute Japan recommends limiting value of maximum crack width as 0.15 mm and 0.3 mm for water leakage prevention and outdoor structures against deterioration under normal environmental conditions, respectively. JSCE standard specifications for concrete structures 2017 recommends maximum allowable crack width as 0.1 mm to achieve water tightness and 0.3 mm to maintain satisfactory appearance of structures. ACI 224R.01 suggests limiting crack width as 0.3 mm and 0.1 mm for RC structures exposed to soil or moist air and water retaining structures, respectively.

There are some remedial measures to control thermal cracks, for example, low concrete placement temperature, controlling maximum heat generation, using aggregate with less coefficient of thermal expansion, precooling of materials, insulation, internal curing, reducing restraint level, slow rate of construction, low cement content, etc. Aforementioned remedial measures are mostly qualitative but quantitative measures are limited. In terms of reinforcement ratio to control thermal cracking, ACI 224R-01 recommends 0.6% reinforcement to control cracks to acceptable limit. ACI 350-06 suggests 0.6% and 0.5% reinforcement for Grade 40 and grade 60 steel, respectively, if the length between movement joints is 40 ft or more [1]–[4].

Presently, there are few methods available to predict the maximum width of thermal cracking. JCI guidelines for control of cracking of mass concrete [1] has established a system to predict maximum width of thermal cracking for wall type mass concrete structures. Crack width calculation is based on cracking index which is the ratio of splitting tensile strength and tensile stress. This system requires sophisticated thermal and stress analysis for calculating cracking index. There are some parameters involved in the analysis procedure which requires accurate consideration for more appropriate results, but it is not feasible for every structure. Therefore, parameters such as autogenous shrinkage, creep reduction coefficient for MOE, coefficient of thermal expansion (CTE) and so on are assumed based on the recommendation by JCI guideline which may result into discrepancy in the measured and predicted crack width. This method is under continuous improvement. Hosoda et al. [5] reported significant discrepancy in the measured and calculated crack width using JCI crack width equation.

Yamaguchi prefecture in Japan has established a quality attainment system for mass concrete structures which was officially launched in 2007. In this system, construction practice is monitored at every phase using a checklist. And, data of high-quality structures is stored in the database. This system has shown significant contribution in quality attainment. In this system, cracks must be repaired if crack width is ≥ 0.15 mm. It is recommended to use 0.3% minimum reinforcement ratio when there is a risk of harmful cracking [5].

Artificial neural networks (NNs) are analogous to biological neural networks which are an interconnected assembly of larger number of simple processors called nodes or units. Each connection possesses a weight

*1 Postdoctoral Researcher, Institute of Urban Innovation, Yokohama National University, JCI Member
*2 Professor, Institute of Urban Innovation, Yokohama National University, JCI Member
*3 Professor, Institute of Urban Innovation, Yokohama National University, JCI Member

which is the processing ability of the network. NNs can be used for pattern classification, categorization, function approximation, prediction/forecasting and so on [6]. In civil engineering, neural networks have been used for structural analysis, design automation and optimization, structural health monitoring, material characterization and modeling, etc. [7]. In the area of thermal cracking, Inadsu et al. [8] employed neural networks to predict occurrence of thermal cracks.

Previously, the authors have used the Yamaguchi prefecture database to predict the occurrence of early-age thermal cracks [9] and maximum width of thermal cracks [10] for RC abutments using artificial neural networks. This study is in the continuation of previous research and a comprehensive investigation on the parameters influencing the maximum width of thermal cracks (MCW) is presented. The results obtained from this study are showing the significance of establishing database and the potential of using neural networks to solve practically important complex problems which are difficult to address using conventional methods.

2. METHODOLOGY

In this study, parametric studies were carried out to study the influence of different parameters on maximum width of externally restrained thermal cracking in the vertical wall parts of RC abutments using a well-trained, tested and validated neural network. A typical example of RC abutment with multiple lifts and thermal cracks is shown in Fig. 1. The procedure of training the neural network and study on the influential parameters are explained in this section.

2.1 Preliminary Investigation on CTE

Coefficient of thermal expansion (CTE) is one of the crucial parameters for thermal cracks. An extensive experimental investigation was performed to study the variations in CTE of concrete in Yamaguchi prefecture ready-mixed concrete plants. Concrete specimens from 21 major suppliers of ready-mixed concrete were collected and CTE was measured. The measurement of CTE was conducted after 28 days. The specimens (Φ100mm × height 200mm) were cured in water (20±2°C) after the removal of the mold until the starting of the measurement. A strain gauge was embedded in the center of the specimen.

CTE was measured in water. The temperature of water was increased from 20°C to 60°C, and after that decreased from 60°C to 20°C. The rate of temperature change was about 0.4°C /hr, and it was confirmed that the temperature in the center of the specimen agreed with that of water. It took around 40 hours to reach 60°C. CTE was obtained from the average (increasing and decreasing processes).

The results showed that the minimum value of CTE was 5.76×10^{-6} /°C and maximum as 8.11×10^{-6} /°C. Average CTE was 6.65×10^{-6} /°C and standard deviation was 0.66. The results showed very less variation in CTE in different ready-mixed concrete plants in the prefecture. The results gave confidence in assuming the constant CTE.

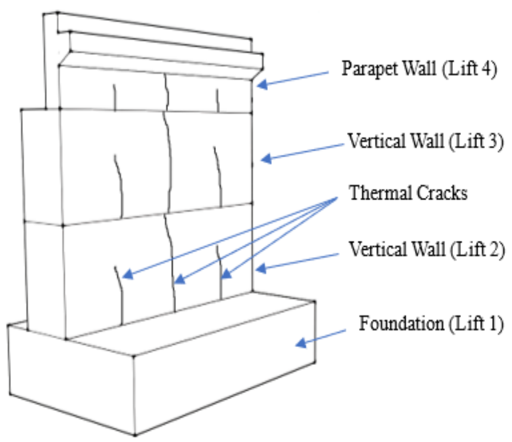

Fig. 1 Typical example of abutment with multiple lifts and thermal cracks

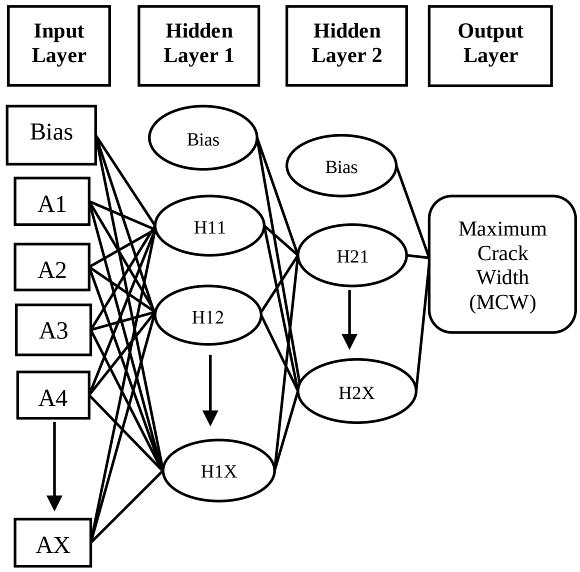

Fig. 2 Architecture of Neural Network

The results gave another perspective, i.e. JCI recommends CTE value for analysis as 12×10^{-6} /°C for concrete with slag cement if real CTE is not known. And, for Yamaguchi prefecture concrete from vast number of ready-mixed concrete plants, average CTE value was 6.65×10^{-6} /°C which was nearly half than the recommended value by JCI which may lead to discrepancy in crack prediction.

2.2 Development of Neural Network

Neural network was developed using Yamaguchi prefecture database. During training, testing and validation phase, 188 lifts of vertical walls were utilized. The input parameters were those which were easy to obtain in the field. The order of input parameters was thickness, width, lift height, reinforcement ratio, unit cement content, expansive additive, initial concrete temperature, ambient temperature, 28-day concrete strength, lift interval, form removal time and curing period.

Initial concrete temperature is defined as the concrete temperature of first batch at the start of concreting work. Ambient temperature is defined as the ambient-environmental temperature at the start of the concreting work. All input parameters were normalized. Database has a wide distribution of all above mentioned parameters.

CTE as an input parameter was ignored due to small variation as discussed in section 2.1. Feedforward multilayer perceptron neural network was employed. NN was well structured, trained and validated by K-fold cross validation to obtain the generalized results. Detailed characteristics of the dataset and procedure to develop NN was explained by Rasul and Hosoda [10]. The architecture of the neural network used in this study is shown in Fig. 2. Number of hidden layers and nodes in each layer were selected by intensive trials. Then, two hidden layers with 6 nodes in the first and 3 nodes in the second hidden layer were obtained. Overall results obtained in terms of relationship between predicted and actual crack width are shown in Fig. 3. Overall accuracy was around 95% with ±0.1mm allowable tolerance.

This well-trained neural network was used to conduct the parametric studies by generating ample cases to study the influential parameters for maximum thermal crack width. It is worth mentioning that present study is not primarily focused on accuracy of the predication but to establish a method and systematic relationship between inputs and output for understanding of influential factors. The accuracy can be improved further by inclusion of more training data.

2.3 Parametric Studies

To study the influence of different parameters on the maximum thermal crack width, parametric studies were performed on two sizes of the wall in terms of width i.e. 10 m and 25 m wide. 10 m and 25 m wide abutments represent relatively shorter and very wide abutments, respectively. All studies were carried out at varying amount of unit cement content, i.e. from 280 kg/m^3 to 330 kg/m^3. 28-day compressive strength was considered as 25 MPa. Form removing time and curing period were kept as 7 days each. Other variable parameters were thickness, lift height, reinforcement ratio, lift interval, and initial concrete temperature.

This study will not only show the influence of different parameters but also give the broader view of crack mitigation by controlling different parameters which are controllable during design and construction stages, such as, lift height, initial concrete temperature,

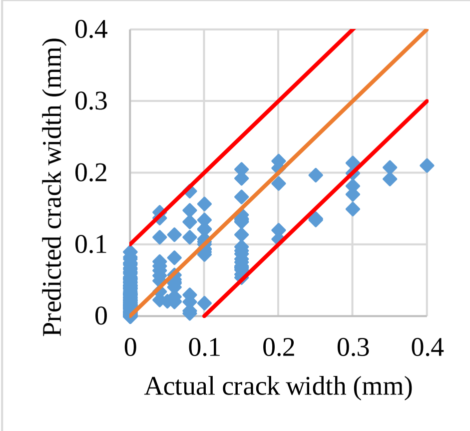

Fig. 3 Relationship between actual and predicted crack width

lift interval, reinforcement ratio, etc.

3. Results and Discussion

In this section, results of parametric studies are categorically explained.

3.1 Effect of Wall Thickness

To study the influence of thickness of the vertical wall, parametric studies were performed by keeping lift height as 3 m. Reinforcement ratio in transverse direction was considered as 0.3% which is minimum recommended reinforcement ratio in risky lifts to avoid harmful cracking by Yamaguchi prefecture crack control system. Lift interval was kept as 14 days. Initial concrete temperature and ambient temperature were considered as 20^{o}C each. Thickness was varied from 1 to 3 m. The effect of thickness of the vertical wall is shown in Fig. 4 left and right for 10 m wide and 25 m wide walls, respectively.

Fig. 4 shows a tendency that maximum crack width increased with the increase of wall thickness. The effect of unit cement content was quite promising, and the probability of larger crack width was higher for higher unit cement content. It is also evident that the tendency of larger cracks was more in wider walls.

3.2 Effect of Lift Height

To study the influence of lift height of the vertical wall, parametric studies were performed by keeping thickness of the abutment as 2 m. Reinforcement in

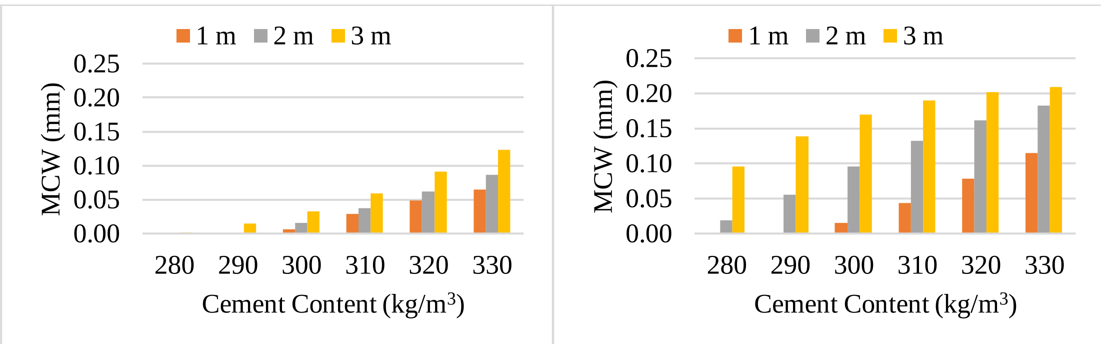

Fig. 4 Effect of wall thickness for 10 m (Left) and 25 m (Right) wide wall

transverse direction was considered as 0.3%. Lift interval was kept as 14 days. Initial concrete temperature and ambient temperature were considered as 20ºC each. Lift height was varied from 1 to 4 m. The effect of lift height of the vertical wall is shown in Fig. 5 left and right for 10 m wide and 25 m wide walls, respectively.

Fig. 5 shows clearly that maximum crack width increased with the increase of lift height. The effect of unit cement content was also confirmed. It can also be observed that the tendency of larger cracks was more in wider walls. These results exhibit the mitigation of thermal cracking by adjusting the lift height in crucial circumstances as lift height can be adjustable on the contrary to other fixed parameters, for example thickness and width. It also showed a possibility of rapid construction by constructing with maximum possible lift height by keeping the maximum crack width within the permissible range. For example, for shorter walls, even at higher cement content, a high lift can be adopted for rapid construction. In the same way, for longer walls with lower cement content, a high lift can be adopted.

3.3 Effect of Lift Interval

Lift interval is the time gap between the construction of two consecutive lifts. To study the influence of lift interval of the abutment, parametric studies were performed by keeping thickness of the wall as 2m and lift height as 3 m. Reinforcement in transverse direction was considered as 0.3%. Initial concrete temperature and ambient temperature were considered as 20ºC each. The effect of lift interval in vertical walls is shown in Fig. 6 left and right for 10 m wide and 25 m wide wall, respectively.

Fig. 6 shows a possibility of mitigation of thermal cracking by adjusting the lift interval in crucial circumstances. Yamaguchi prefecture crack control system recommends maximum lift interval as 14 days, but even a very long lift interval, for example exceeding 100 days was also observed in the database due to some managerial issues, etc. The obtained results as shown in Fig. 6 showed the severity of longer lift interval. The influence was severer in wider walls resulting in harmful cracking. These results can be useful in determining the lift interval by keeping the crack width within permissible range. It can also give a visual understanding of permissible delay which may occur due to several reasons during construction stages.

3.4 Effect of Initial Concrete Temperature

In this study, initial concrete temperature was termed as the temperature of concrete reported as a result of inspection of ready-mixed concrete at the site and included in the construction record database of Yamaguchi prefecture.

To study the influence of initial concrete temperature, parametric studies were performed by keeping thickness of the wall as 2m and the lift height as 3 m, respectively. Reinforcement in transverse direction was considered as 0.3%. Lift interval was kept as 14 days. Ambient temperature was considered as 20ºC and initial concrete temperature was varied by ±10ºC from the initial concrete temperature. The effect of initial concrete temperature is shown in Fig. 7 left and right for 10 m wide and 25 m wide walls, respectively.

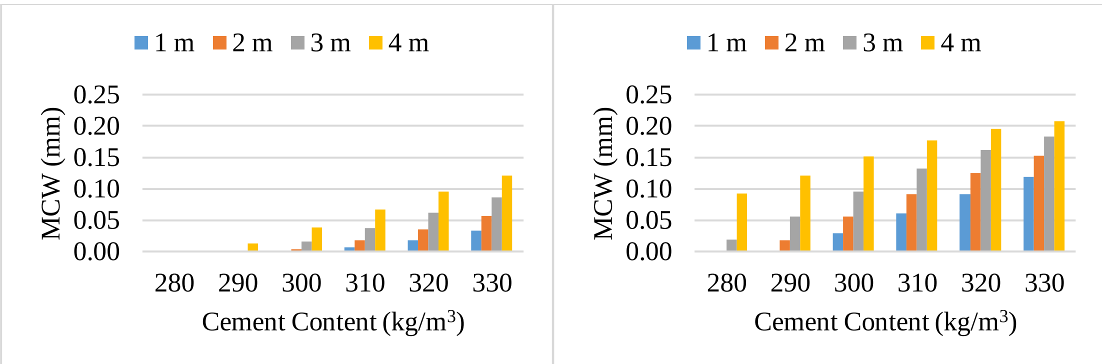

Fig. 5 Effect of lift height of the vertical wall for 10 m (Left) and 25 m (Right) wide wall

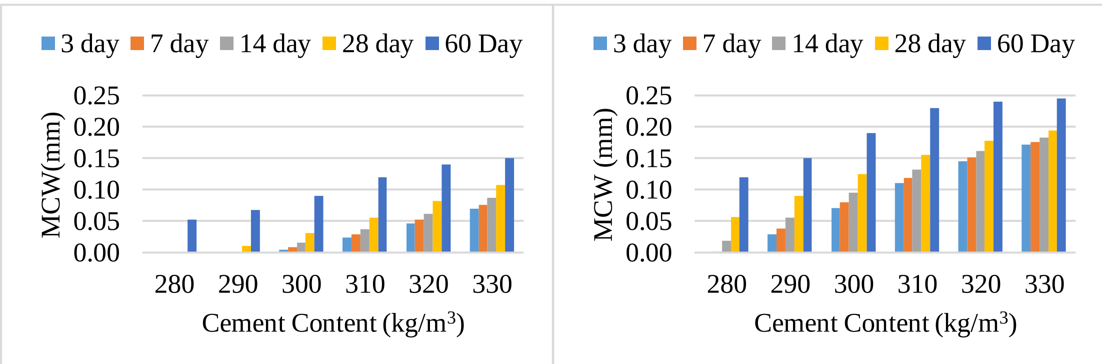

Fig. 6 Effect of lift interval for 10 m (Left) and 25 m (Right) wide wall

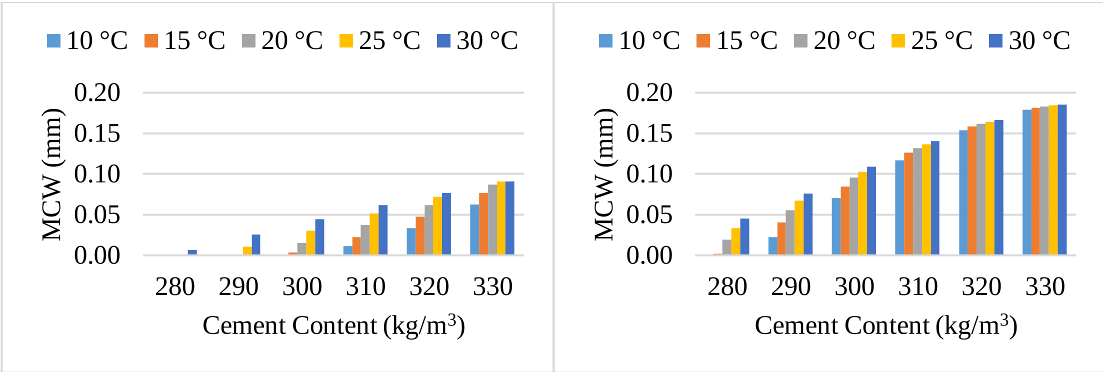

Fig. 7 Effect of initial concrete temperature for 10 m (Left) and 25 m (Right) wide wall

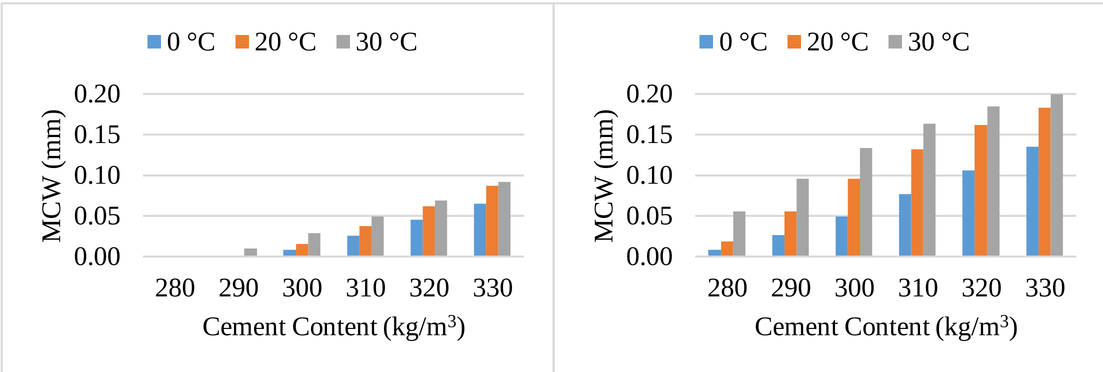

Fig. 8 Effect of ambient temperature for 10 m (Left) and 25 m (Right) wide wall

Fig. 7 left and right shows that the tendency of larger crack widths increased with the increase of initial concrete temperature. It is also evident that the tendency of larger cracks is more in wider walls. These results exhibit the mitigation of thermal cracking by adjusting the initial concrete temperature in crucial circumstances. Although initial concrete temperature is mostly governed by the ambient-environmental conditions but still a feasible reduction in initial concrete temperature can reduce the tendency of larger cracks.

For shorter walls in terms of width, even at high cement content and high initial concrete temperature, the tendency of larger cracks was low. It can also be observed that at lower unit cement content, the tendency of larger cracks was lower even if the initial concrete temperature was quite high so it can be implied that unit cement content played a vital role in determining the maximum width of cracks.

3.5 Effect of Ambient Temperature

In this investigation, ambient temperature was considered as the ambient environmental temperature measured at the start of placing of concrete and reported in the database of Yamaguchi prefecture.

To study the influence of ambient temperature at the time of casting, parametric studies were performed by keeping thickness of the abutment as 2 m and lift height as 3 m. Reinforcement in transverse direction was considered as 0.3%. Lift interval was kept as 14 days. Initial concrete temperature was considered which was compatible with the ambient temperature. For example, at 0ºC ambient temperature, initial concrete temperature was considered as 10ºC. For 20ºC and 30ºC ambient temperature, initial concrete temperature was considered as 20ºC and 30ºC, respectively. The effect of ambient temperature is shown in Fig. 8 left and right for 10 m wide and 25 m wide abutments, respectively.

Fig. 8 left and right shows a clear tendency that crack width increased with the increase of ambient temperature. It can be observed that the tendency of larger cracks was more in wider walls. For shorter walls in terms of width, even at high cement content and high ambient temperature, the tendency of larger cracks was low. It can also be observed that at lower unit cement content, the tendency of larger cracks was lower even if the ambient temperature was quite high. These results can be helpful in building the confidence in mitigating harmful cracking even in hot weather by considering other parameters as well.

3.6 Effect of Reinforcement Ratio

To study the influence of reinforcement ratio in transverse direction, parametric studies were performed by keeping thickness of the abutment as 2 m and lift height as 3 m. Initial concrete temperature and ambient temperature were considered as 20ºC. Lift interval was kept as 14 days. Reinforcement ratio was varied from 0.05% to 0.5%. The effect of reinforcement ratio is shown in Fig. 9 left and right for 10 m wide and 25 m wide abutments, respectively. Fig. 9 shows clearly that crack width is decreased with the increase of reinforcement ratio. It is also evident that harmful cracking can be mitigated in wider walls by increasing reinforcement ratio.

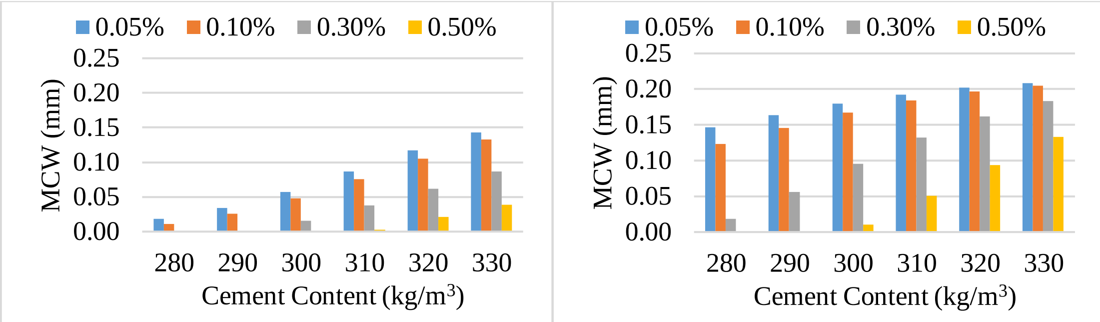

Fig. 9 Effect of reinforcement ratio for 10 m (Left) and 25 m (Right) wide wall

As explained in the introduction of this paper, different standards define different requirements of minimum reinforcement ratio, i.e. 0.6% by ACI 350-06, 0.3% by Yamaguchi prefecture crack control system. But those standards may be overestimating in many cases, for example in case of shorter walls or even wider walls with lower unit cement content. And, the standards may be underestimating in many cases, for example, in case of wider walls with even moderate cement content. The obtained results showed a broader view for alternative ways to propose recommended minimum reinforcement for different cases rather than a general value.

4. CONCLUSIONS

Based on the outcomes of this research related to study on the parameters influencing the maximum thermal crack width (MCW) in vertical wall part of RC abutments by neural networks, following conclusion are drawn;

1) Neural networks have shown their capability in extracting the essence from the field data related to cracking, predicting MCW of actual structures, and presenting it in an understandable way.
2) In vertical walls of RC abutments, unit cement content was quite influential in all cases. For larger amount of unit cement content, the tendency of larger cracks increased. And, this effect was more prominent in very wide 25m walls.
3) The tendency of larger cracks increased with the increase of thickness of the wall, lift height, lift interval, initial concrete temperature and ambient temperature at the time of casting.
4) MCW was apparently decreased with the increase of reinforcement ratio. For shorter walls, even low reinforcement ratio than the recommended one was sufficient leading to economical design. On the other hand, for very wide walls when higher unit cement content was used, the recommended reinforcement ratio i.e. 0.3% was insufficient.
5) This study has shown the possibility of using remedial measures against harmful thermal cracking by not only in terms of reinforcement ratio but also by adjusting the maximum lift height, lift interval and/or initial concrete temperature.
6) This study has shown that it is useful to establish a databases of engineering structures for solving complex problems by utilizing machine learning.

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