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Experimental Investigations on Effect of Compaction, Curing, Water to Cement Ratio, Cement Type and Temperature Variation on the Rebound Hardness of Concrete

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ABSTRACT

It is a known fact that the concrete strength is not only affected by the ingredients present in it, but also by the other factors like types of cement used, compaction deficiency, curing condition, elevated temperature, and different w/c ratios. The influence on the rebound hammer has been illustrated in this paper concerning the hardness of the concrete specimens. The effect of cement types, compacting deficiency, w/c ratio, curing condition, and elevated temperature on concrete compressive strength and rebound hardness has been considered for the analysis. From an experimental study, it is found that the reduction of the compressive strength of concrete is between 6 to 41 percent due to insufficient compaction alone when tested using a destructive method. However, the rebound hammer results revealed that there is no reduction in the rebound index. The rebound hardness test cannot predict the compressive strength due to inadequate curing. It is also reported that the rebound index is significantly reduced, with the destructive strength of the concrete specimens. The study revealed that in the case of M30 and M40 grades of concrete, the percentage reduction of the average rebound index is almost higher in all the cases than the average compressive strength at a temperature ranging from 200°C to 800°C. The strength (rebound hardness) measured is either under or overestimated if no attention has been given to different influencing factors. Thus, a reliable and accurate evaluation of strength cannot be guarantee.

1. Introduction

Concrete quality directly affects the performance of the structure as a whole. Nevertheless, the low quality of concrete may cause structural failure, which eventually leads to serious loss of life and property (Szilagyi et al., 2011). Breysse (2012) reported that the rebound hammer method has mostly been applied in quality investigation and assessment of engineering properties of concrete structures. International Atomic Energy Agency (IAEA) (2002) stated that with the use of different types and cement content, the variation in the rebound results had exceeded by 50%. Bungey and Grantham (2006) and Neville (2001) reported in their studies that, the strength of concrete is increased with an increasing degree of compaction. When fresh concrete is poured in the formwork, air voids can consume 5 to 20% of the total volume. Continuous vibration removes most of the air voids, but the complete removal of entrapped air cannot be achieved easily. Vibration should be equally applied to the whole concrete otherwise; some portions might be completely compacted, while others could not. In the case of compaction, the aggregate particles are set in the form, and entrapped air is expelled out of the concrete. Furthermore, compaction should be continued until air bubbles on the surface no longer exist. Permeability may be similarly affected since compaction promotes a more even distribution of pores as they became discontinuous. As a result, permeability will be reduced and could result in improved durability (Cement Concrete & Aggregates Australia (CCAA), 2006; Szilagyi et al., 2011). Neville (2001) reported that a comparative analysis of the strength of the specimens cured underwater and only in air conditions has shown its influence on concrete strength and rebound hardness. When water curing is stopped, the rate of strength development slows down, and further gain in strength ceases. CCAA (2006) indicated that the

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curing period is always based on the physical properties, purpose to be used, and environmental conditions (temperature or relative humidity) of the concrete. Curing is designed primarily to keep the concrete saturated, by preventing the loss of water from the specimen surface. Szilagyi et al. (2011) presented that the decrease in compressive strength induced by the degree of compaction could not be detected by the rebound hardness test. The Schmidt hammer, as the difference in the rebound index, cannot detect the influence of insufficient curing also and the compressive strength is enormous. In the case of no water or only air curing technique, the reduction in the rebound index is about the half of compressive strength obtained from the destructive test. Most of the researchers (Park and Yim, 2017; Bodnarova et al., 2013) expressed the influence of exposed heat load on the results of the rebound number. The crucial factors affecting test results are concrete dehydration, the synergic effect, and internal structure micro cracks. When the concrete was exposed to heat load, micro-cracks were found on the surface due to the release of free and capillary water, dehydration of cement matrix, and variation in a thermal gradient. Micro-cracks in the structure did not influence the concrete surface hardness significantly.

Brozovsky and Bodnarova (2016) reported that the rebound index in heat-loaded concrete was often higher than in normal temperature-tested concrete specimens. Yang et al. (2018) reported that both the rebound value and the compressive strength of high-performance concrete had increased with a decrease in the w/c ratio. However, as concrete hydration stopped, concrete hydration products no longer grew, and the rate of concrete compressive strength and rebound index gradually increased. As per the RILEM TC249-ISC committee report Breysse et al. (2019), the conversion model does not specifically consider several other influencing factors that could influence the test results. The aging effect involved potential delamination and cracking (mechanical deterioration) of concrete due to the corrosion of reinforcement. Alwash et al. (2017) reported that, due to the uncertainties inherent with the strength estimates depending upon rebound measurements, the reliability of the hardness values is often a challenging problem. To improve reliability, uncertainties must be minimized by defining and regulating their factors of influence. Toghroli et al. (2018) reported that there are several methods in the ANFIS phase. It evaluates a subsection of the entire set of detailed factors presenting effectiveness. The research focuses on how the key factors used in the design of concrete mixture (age, silica fume, fine aggregate, coarse aggregate, and water) affect the rebound number. Panedpojaman and Tonnayopas (2018) found that high temperatures were detrimental to compressive strength. If concrete has exposed to fire, up to about 420ºC the rebound number does not change in any major way, but compressive strength is lost. This is because calcium carbonate crystals form in the pores, causing hardness to decrease at a much slower rate and thus rendering the rebound hammer test not suitable for determining compressive strength. Kumavat and Chandak (2020) found that, reduction of compressive strength correlates with reduction of strength measured by rebound hammer in temperature range from 600ºC to 800ºC.

Various types of cement were used in construction work according to the content of oxides and locally available raw material for preparing concrete. During the construction stage, there is a possibility that the members of the structure get insufficiently compacted. In addition, some parts of structural members are compacted manually, some remain without compaction. It varies with the types of structures and their location. The same phenomenon is also seen in terms of curing conditions of structure when cured with water or only air. When structural concrete has exposed to heat load, this affects concrete hardness and its microstructural behavior. To prove this, the influence of cement type, compaction methods, curing condition, elevated temperature, and water-cement ratio on the surface hardness needs detailed study. Rebound index and the compressive strength were used as measurement indices to establish the exact relationship. It is essential to inspect the effects of these factors on the performance of the rebound hammer. It will also help to evaluate the actual values along with the error causing by the respective factor.

2. Experimental Program

The destructive and non-destructive test has been performed with five different mixes of concrete prepared at the laboratory. Experimental investigations of 159 cube samples were assessed for their rebound indices and compressive strength. Three different types of cement (CT-I, CT-II, CT-III) are used to prepare these mixes. The oxide content of the different types of cement is listed in Table 1. The fine and coarse aggregate fineness modulus are 2.651 and 2.232, respectively. The composition of mix M_1 to M_5 and testing condition of different mix grades with three types of cement and different water to cement ratios as per (IS 10262:2019, 2019; IS 13311(Part-2)-1992, 1995) for the curing period of 7 to 60 days are given in Table 2. Under the concrete testing unit, a 9 MPa stress is applied to the cube in the direction of casting for taking observations by rebound hammer. Mean results were calculated from twelve hammer impacts that were distributed evenly on two opposite sides of each cube. After that, the same cubes were tested for the destructive compressive strength using the calibrated compression-testing machine.

3. Results and Discussion

3.1 Influence of Cement Type

It is observed from Fig. 1 that, the test performed on CT-I

Table 1. Oxides Content in Cement Used for Study

Oxides (% Content)	CT- I (OPC- 53 Grade)	CT- II (PPC- 43 Grade)	CT- III (PPC-43 Grade)
CaO	63.54	40	37.80
SiO_2	20.56	34.5	35.25
Al_2O_3	5.40	14.5	14.97
Fe_2O_3	3.3	4.5	3.92
SO_3	2.38	3.22	2.98
Mgo	2	1.65	2.1
LOI	1.76	5	13

Table 2. Composition of Mixes with Different Influencing Factors

Mix type	Influencing factors	Grade mix	Composition/water to cement ratio	Testing duration (Days)	Quantity cubes (Nos.)
M_1	Cement type (CT I-PPC 53, CT II -PPC 43)	M15, M20, M25	1:1.9:3.9/0.5 1:1.55:2.98/0.5 1:1:2/0.5	14, 28, 45	54
M_2	Degrees of compaction CT-I (No, Manual, Vibratory)	M20	1:1.5:3/0.5	28, 45, 60	27
M_3	Curing conditions CT-I (Water and air curing)		1:1.5:3/0.5		18
M_4	Elevated temperature (200° to 800°C) CT-I	M20, M30, M40	1:1.49:2.8/0.48 1:0.79:1.48/0.4 1:0.25:0.56/0.36	28	36
M_5	Water to cement ratio (Super-plasticizer Con Plast -500) CT-III	M30	1:1.22:2.45:0.01/0.3, 1:1.58:3.01:0.01/0.36, 1:1.80:3.40:0.01/0.40, 1:2.20:3.90:0.01/0.45	7, 28	24

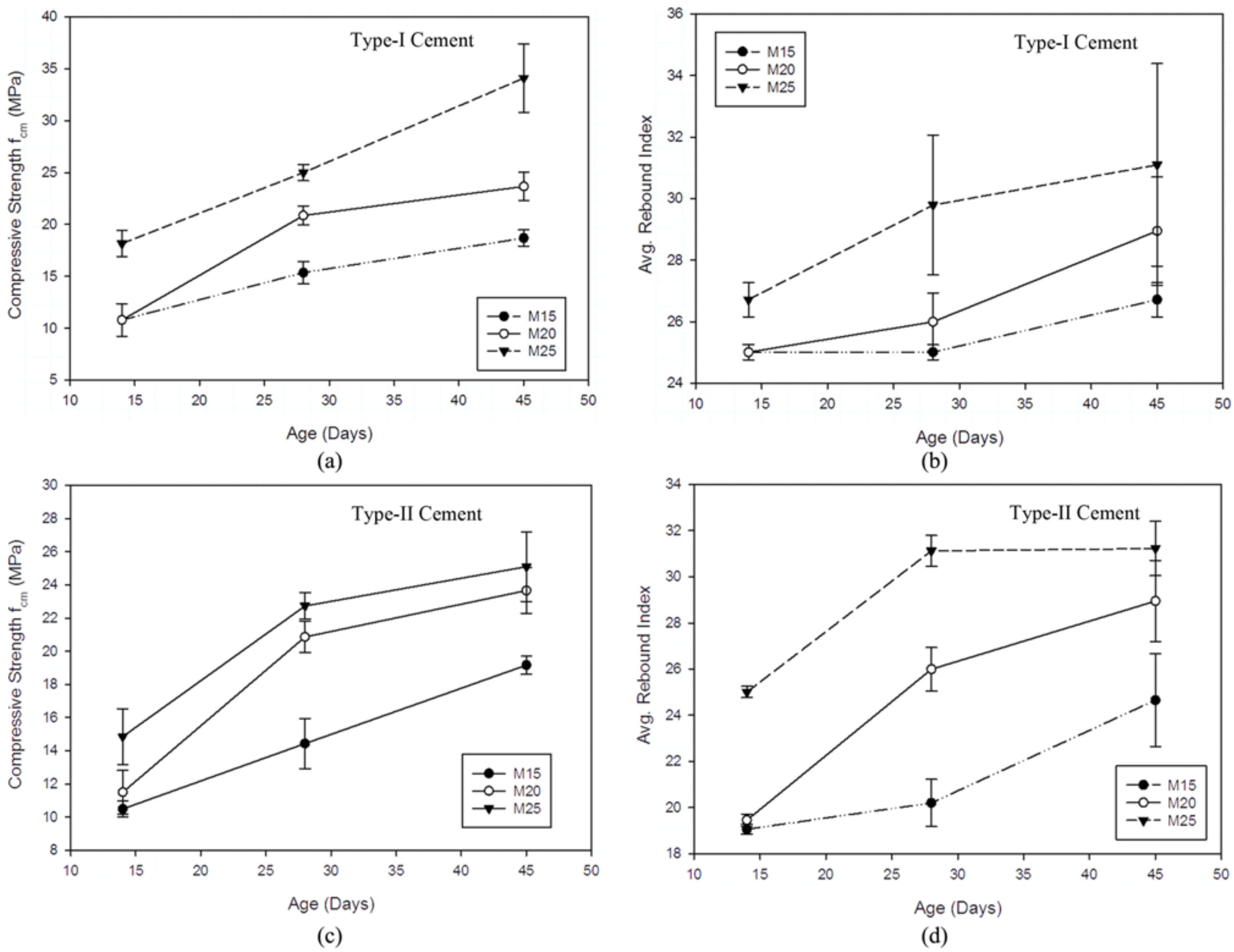

Fig. 1. Effect of Curing Period with Types of Cement: (a) Avg. Compressive Strength, (b) Avg. Rebound Index (CT- I), (c) Avg. Compressive Strength, (d) Avg. Rebound Index (CT- II)

concrete specimen's shows a lesser rebound index than that of CT-II concrete specimens. The average rebound index for the (M_1) mix of specimens is lower in the earlier days. The rebound index ranges from 10 to 25.62 for concrete prepared from CT-I and 10 to 32.03 for concrete prepared from CT-II. The trend lines of the average compressive strength graph, shown in Figs. 1(a) and 1(c) are uniform with the maturity level. However, there is a minor variation in the average rebound index for CT-I cement concrete specimens with different duration of curing as seen from Figs. 1(b) and 1(d). The error bar shown in the graph is resulting from the variability and uncertainties in the measurements and influence of types of cement used. Error bar shows the maximum value for CT-I compared to CT-II at 28 and 45 days. However, a unique error has been observed in the case of the compressive strength of both types of cement.

In the case of a mix of M15, M20, and M25 with CT-I concrete, a similar average rebound index is observed. The chemical characteristics of the cement present in the mixture can result in a change in hardness from the interfacial transition zone to the surface of the concrete. Kolek (1970) argued that concrete made from aluminum cement has a compressive strength value 100 percent higher than concrete made from ordinary cement, which consequently contributes to a high rebound index. Besides, the average compressive strength and average rebound index of CT-II concrete are increasing uniformly from 15 days to 45 days.

The shape of trend lines of CT-II is seen the same in both compressive strength and rebound index graph than CT-I. A similar average rebound index has been found for both M15 and M20 grade specimens for all the duration of curing. Specimens with CT-II trend line has matched with trend lines of the average compressive strength graph. It may happen due to the rapid hardening of CT-II concrete at its initial stage. Less percentage of Cao and a high percentage of Sio_2 present in CT-II concrete roughly equivalent to CT-I concrete are also responsible for hardening.

The average rebound index of M15 mix specimens with CT-II concrete is increased by 54.55% at the age of 28 days, 62.57% at 45 days roughly equivalent to the CT-I concrete specimens. The average rebound index of M20 mix specimens with CT-II concrete decreased by 31.67% at the age of 14 days and increased by 19.36% and 36.55% at 28 days and 60 days respectively compared to the CT-I concrete specimens. Similarly, the average rebound index of M25 mix specimens for CT-II concrete specimens decreased by 11.11% at the age of 14 days, 2.69% at 28 days, and increased by 23% at 60 days roughly equivalent to the CT-I concrete specimens. Based on the findings, it inferred that the specimens prepared with CT-II cement have performed better compared to those prepared with CT-I cement. Hence, the use of different types of cement in mix affects the performance of the rebound hammer and does not depict real values.

The rebound hardness is evaluated from the concrete surface area, whereas destructive compressive strength is the resistance of the material of which the cube is made up. However, with age, the surface area of the concrete has hydrated at a much faster rate than the interracial one, so there is always a possibility for the difference between the strength calculated by the rebound hammer and the compressive testing machine.

3.2 Influence of Degree of Compaction

The estimate of concrete compressive strength is related to the attributes of the interface layer between the matrix and the aggregates. It is the weakest element of concrete as a fragmented material form. The increase of 10 liters/m^3 air content in concrete results in a 5% reduction in compressive strength (Neville, 2001). While mixing, the air gets trapped in the fresh concrete, which during the casting and compaction process cannot be removed completely. The air content can be 5 – 20 V percent depending on the actual composition and quality when fresh concrete is poured in the cubes or formwork. Therefore, the design air content is recommended in this range during mix design in the case of ordinary concrete range between 0.5V to 2.5V percent air content. Nepomuceno and Bernardo (2019) reported that the external vibration used to compact normal concrete contributed to increasing the densification near the surface region of concrete. Thus, normally vibrated concrete has higher surface hardness compared to self-compacting for a similar grade of concrete. The concrete mix considered in this case is M_2 is assumed to have an air content of 1.0 V percent. It can be seen easily from Fig. 2, that the cube specimens are compacted by the three different methods resulting in different compaction degrees. The degree of hydration is kept equivalent keeping a similar duration of curing for all three compaction methods.

The trend lines of the rebound index show greater variation at 14 days, after that it shows unique results at 28 and 45 days. The average compressive strength and the average rebound index by N-type hammer are shown in Figs. 3(a) and 3(b) at the age of 28, 45, and 60 days for the specimens compacted using the three different methods. The compressive strength of the specimens

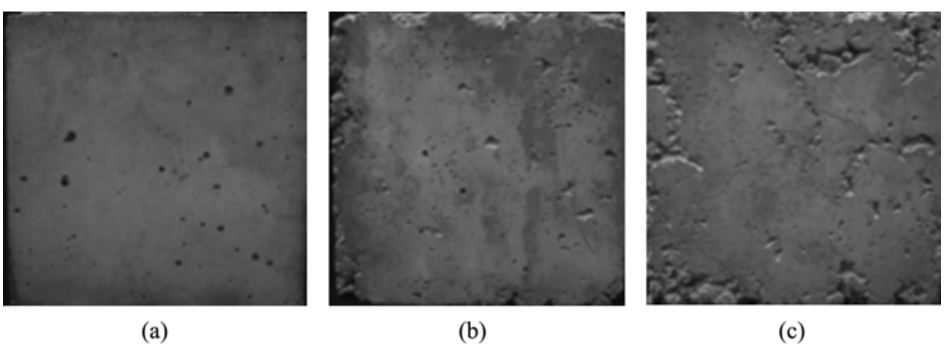

Fig. 2. Cube Compaction: (a) Vibrating, (b) Manual, (c) No Compaction

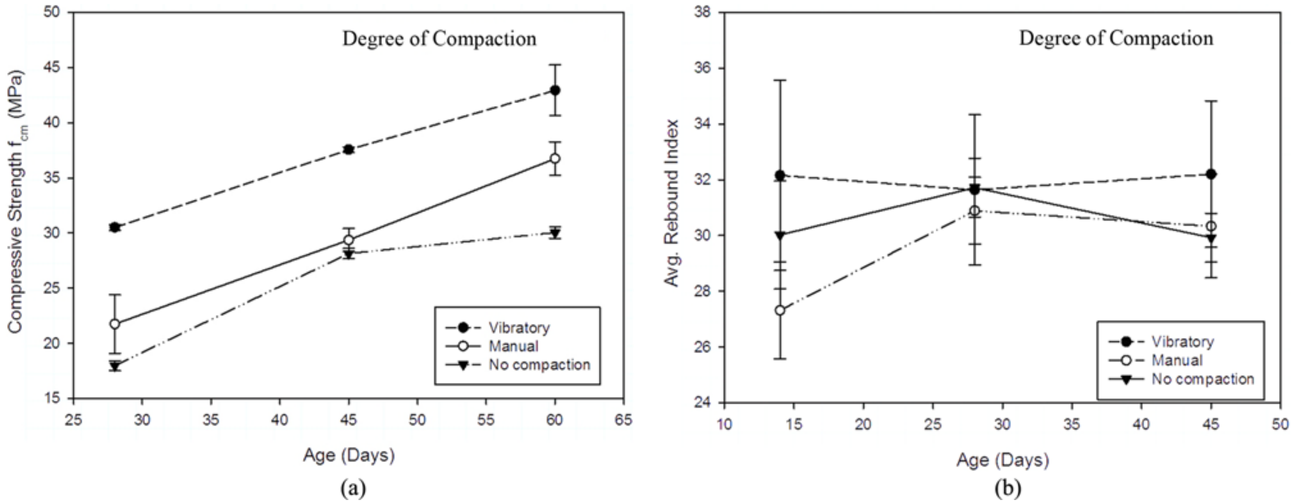

Fig. 3. Effect of Compaction with Curing Age: (a) Avg. Compressive Strength, (b) Avg. Rebound Index

compacted manually is reduced by 25.6% at the age of 28 days and 14.42% at the age of 45 days when compared to the compressive strength of the specimens compacted with a vibrating table for the same duration. The specimen's average compressive strength with no compaction reduced to 41.09% at the age of 28 days and 30% at the age of 45 days when compared to the average compressive strength of the specimens compacted with a vibrating table for the same duration.

The average rebound index recorded by the Schmidt's hammer on the specimens compacted manually for 28 days has decreased by 15.08% and 5.81% at the age of 60 days compared to the average rebound index of the specimens compacted by a vibrating table. The average rebound index recorded by the Schmidt's hammer on the specimens with no compaction reduces by 6.65% at the age of 28 days and 7.11% at the age of 60 days compared to the average rebound index of the specimens compacted with a vibrating table. From the trials done on various specimens, it is found that the reduction in compressive strength is in the range of 6 – 41% only due to the compaction deficiency alone. However, the rebound index for the same specimens is found unaffected. In the case of manual compaction, the reduction in average compressive strength at the age of 28 days is 7.81 MPa, whereas the reduction of the average rebound index reported by Schmidt's rebound hammer is approximately half of it i.e., 4.85 MPa. This indicates that the rebound hammer is ineffective in calculating the strength of concrete compacted by different methods. The error bar indicates the error resulting from the variability and uncertainty of the compaction measurement. In the case of 14 and 45 days, the maximum error is observed as shown in Fig. 3(b).

The formation of air voids due to insufficient compaction has a direct impact on the surface hardness of the concrete. The striking energy of the hammer is released when the hammer impacts the face of the specimen; and the presence of voids in concrete in the near-surface region reduces the concrete rebound hardness.

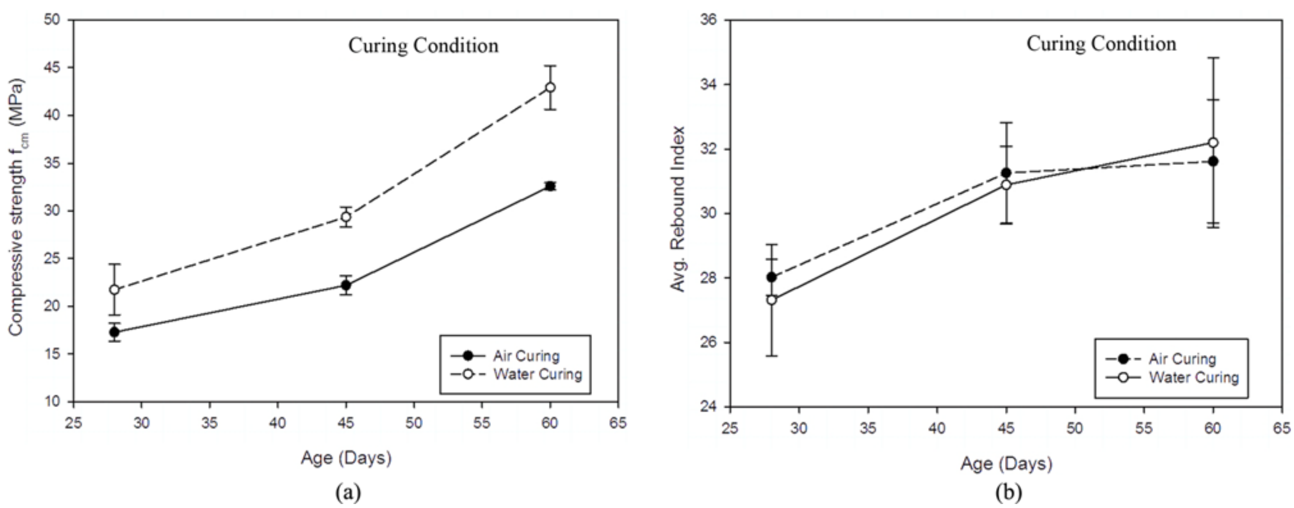

Fig. 4. Effect of Curing Condition with Curing Age, (a) Avg. Compressive Strength, (b) Avg. Rebound Index

3.3 Influence of the Curing Condition

As the duration of curing increases, the rate of hydration of the cement paste also increases. It results in an increase in compressive strength as well as an increase in the rebound index. Szilagyi et al. (2014) presented the effect of an inadequate curing condition on rebound index, but this reduction is lesser than the reduction in the compressive strength. Figs. 4(a) and 4(b) show the average compressive strength and the average rebound index provided by Schmidt's hammer for the specimens of mix M_3 cured in only air and water for three different durations of 28, 45, and 60 days. It is seen from the experiments conducted that the compressive strength of the specimens cured in the air only, is reduced. The reduction in strength is 21.71% at the age of 28 days, 24.89% at the age of 45 days, and 24.10% at the age of 60 days when compared to the average compressive strength of the specimens cured underwater. Similarly, The average rebound index of the specimens cured only in the air is increased by 2.60% at the age of 28 days, 1.20% at the age of 45 days, and decreased by 1.83% at the age of 60 days compared to the average rebound index of the specimens cured underwater. The error bar indicates the error resulting from the variability and uncertainty of the rebound index measurements affected by the different curing methods. In the case of 45 days, the maximum error is observed as shown in Fig. 4(b). The trend lines of compressive strength interpret uniform increase of strength up to 60 days period. In the case of the rebound index, trend lines are parallel up to 45 days, after that reverse index is observed as shown in Fig. 4(b).

Variation in the average compressive strength and the average rebound index is observed when specimens are cured with only air and water method. The rebound indices were raised uniformly as average compressive strength up to 45 days of curing. However, it shows no uniformity at 60 days of curing by both the methods i.e., specimen cured with only air and water method respectively. In addition, there is little variation in the average rebound index of specimens cured by only air and water, regardless of the age of the concrete. The variation of 23.56% is found in the average compressive strength for the same specimens when tested under the compression-testing machine. While the variation of only 1.87% is found in the average rebound index for specimen cured with both the methods. Therefore, it can be inferred that the rebound hardness test cannot predict the compressive strength of concrete members affected by inadequate curing or cured by different methods.

3.4 Influence of the W/C Ratio

The influence of water-cement ratios used in mix M_5 on the average strength and the average rebound index is shown in Figs. 5(a) and 5(b). The average rebound index and the concrete compressive strength has enhanced with the reduction of the water to cement ratio. Yang et al. (2018) concluded that, due to the change in the water-cement ratio at the same age, the change in the rebound index significantly increased and thus the concrete compressive strength. This implies that with the rise in cement content, more cement paste hydration products are filled in the pores. This results in increased concrete density contributing to higher surface hardness and compressive strength of concrete as well. Figs. 5(a) and 5(b) illustrates that, at the initial stage i.e., at 7 days, there is a slight variation in average rebound index to that of 28 days. The variation in the curve is also uniform as the average compressive strength for the different w/c ratio of 0.3 to 0.45. The average rebound index and compressive strength error bar show unique values. The trend lines of the average compressive strength graph show unique variation at 7 days and 28 days respectively. In the case of average rebound index, trend lines are varying largely at 28 days than that of at 7 days.

The concrete strength for w/c ratio of 0.36, 0.40, and 0.45 reduced by 8.11%, 12.78%, and 17.56% respectively, at an average age when compared to the concrete strength for w/c ratio of 0.3. The average rebound index of the specimens for w/c ratio of 0.36, 0.40, and 0.45 reduced by 4.91%, 8.78%, and 9.88% respectively, at an average age when compared to the average rebound index of the specimens for w/c ratio of 0.3. The strength

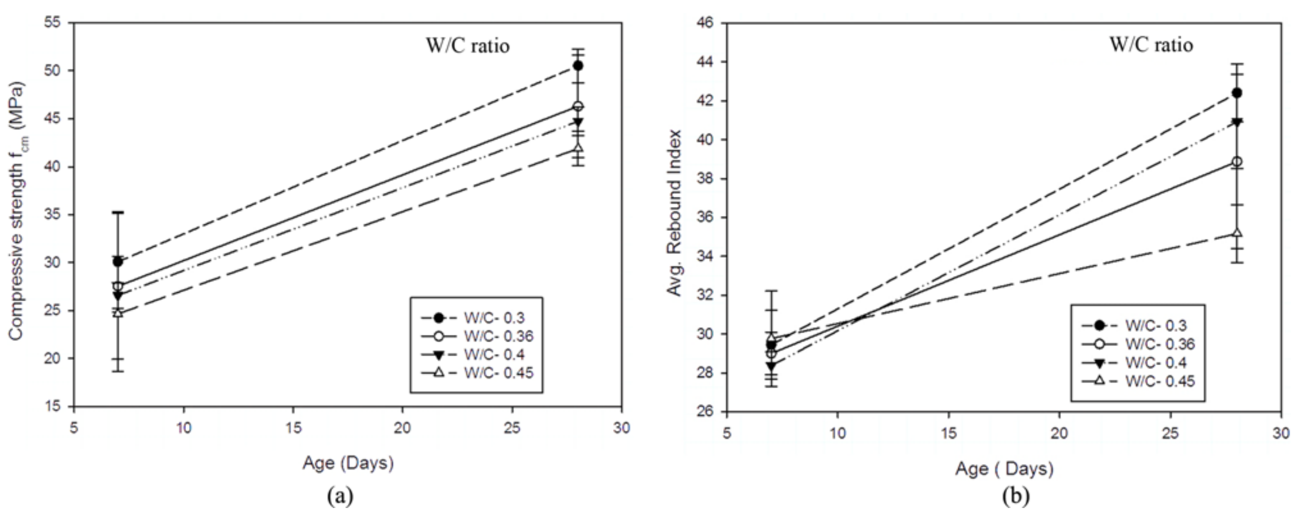

Fig. 5. Effect of w/c Ratio with Age: (a) Average Compressive Strength, (b) Average Rebound Index

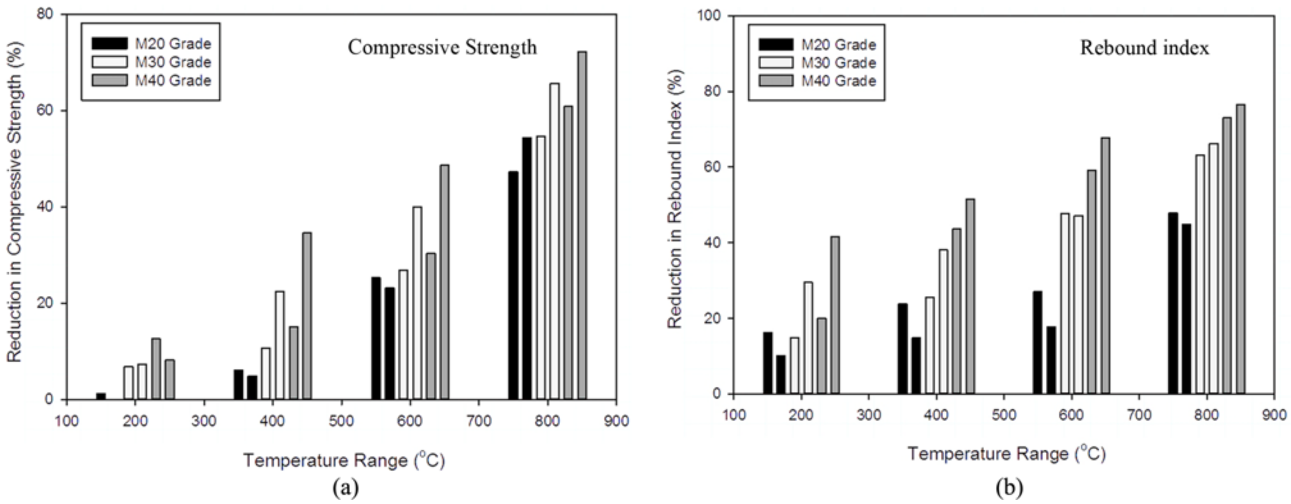

Fig. 6. Percentage Reductions with Grade of Mix: (a) Avg. Compressive Strength, (b) Avg. Rebound Index

estimated by the rebound hammer is almost half of the values found by destructive test. It implies that the rebound hammer is not giving realistic values of the compressive strength for specimens prepared with different w/c ratio.

3.5 Influence of Temperature Variation

The percentage reduction of the average compressive strength and the rebound index depending on the temperature variation at room temperature for the M_4 grade mixture is shown in Figs. 6(a) and 6(b). The variations in compressive strength will occur due to the presence of micro-cracks on the concrete surface. In addition, the lower grade of concrete shows ductile behavior than the higher grades when subjected to the heat load. The average compressive strength above the temperature of 600°C is reduced significantly. It is also observed that the average rebound index is significantly reduced, with the destructive strength of the concrete specimens. Brozovsky and Bodnarova (2016) concluded that the increase in the rebound index (9%) of concrete subjected to elevated temperatures (200°C to 400°C) was higher than the concrete specimens tested under normal temperature (27°C).

The percentage reduction in the average rebound index of the M30 and M40 grade mixtures is almost higher in all cases than the average compressive strength at a temperature range of 200°C to 800°C. The average rebound index concerning to higher grades is also reduced. This indicates that the average compressive strength is higher by some units than the average rebound index. Similarly, the results indicate that, in the case of M30 and M40 grades, the percentage reduction of the average rebound index is higher than the average compressive strength at the temperature range from 200°C to 800°C.

4. Conclusions

From the experimental work conducted considering various factors, the following conclusions can be drawn:

1. The effect of the types of cement used for the preparation of concrete mix can be observed prominently. CT-I shows poor performance particularly in the lower grades of concrete when compared to that of CT-II.
2. The compressive strength is reduced by 6 – 41% due to compaction deficiency alone. The reduction of the rebound index reported by Schmidt's rebound hammer is almost half of the compressive strength in the case of the specimens compacted manually.
3. The variation in the average compressive strength of samples cured under only air and water are noticeable. However, the average rebound indices reported by Schmidt’s hammer are almost the same, regardless of the age of concrete. Hence, it is concluded that the rebound hardness test cannot predict compressive strength affected by inadequate curing.
4. The rebound hammer is not giving true values for cube specimens prepared with different w/c ratio. Nevertheless, decrease in w/c ratio has enhanced both the average rebound index and the average concrete compressive strength, when tested at the same age.
5. The percentage reduction of the average rebound index of the M30 and M40 grade mixtures is almost higher in all the cases than the average compressive strength at temperatures ranging from 200°C to 800°C. The percentage variation in loss of compressive strength for both of M30 mix and M40 mix grade at temperatures i.e., 400°C to 800°C is higher than that of M20 mix concrete specimens.

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