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# Determination of concrete compressive strength: A novel approach

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**ABSTRACT**

*Compressive strength is an important aspect in the design of concrete structures. Excepting for laboratory casting and testing of concrete samples, no reliable method is available to evaluate the compressive strength of in-situ concrete precisely. The objective of the paper was to develop a different methodology for the determination of concrete compressive strength based on measured acceleration using Artificial Neural Network (ANN). The surface of a cube was struck with an impactor and induced acceleration reading at six different locations on it were recorded. Strength of concrete was determined by testing. Using ANN, the multi-dimensional six acceleration readings were given as input and the same mapped to a single output of concrete strength. The range of acceleration values varied from 0.7 m/s$^2$ to 136.4 m/s$^2$ and compressive strength from 16 to 43.56 MPa. The values pertaining to 54 cubes were used to train the network. The correlation between predicted and measured strength was found to be good.*

**Key words:** Concrete, Impactor, Acceleration, Compressive Strength, ANN mapping, Prediction

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## INTRODUCTION

Concrete is a versatile construction material that can be manufactured using locally available materials like crushed stone, river sand and water. It is very popular when the fact is considered that around the world approximately twice as much concrete is used in construction than the total of all other building materials, such as, steel, plastic, wood, and aluminium. Its compressive strength is an important aspect in deciding its load carrying capacity. Normally, it is determined by casting and testing of concrete specimens in the laboratory. In its service life, many situations may arise wherein measurement and analysis of structural integrity and other properties of concrete structures have to be carried out. Many of the existing methods for the assessment of concrete strength are destructive in nature. The compressive strength of hardened concrete is, generally, determined by destructive testing of control specimens in a Compression Testing Machine (CTM) in the laboratory. However, a direct correlation never existed between the compressive strength of hardened concrete obtained by testing of representative specimens like cubes or cylinders and that available in structures [1]. Unfortunately, test specimens are not an exact representation of *in-situ* concrete, and may be affected by variations in specimen type, size, and curing procedures. The differences in strengths of the same concrete between the laboratory specimen and *in-situ* affect the performance of structures while resisting the applied loads. In fact, a solution is hardly available to determine exactly the strength of concrete that has been placed at site. Moreover, the testing of existing structures is usually related to an assessment of structural integrity or adequacy [2]. However, to a certain extent this problem has been solved by a method called non-destructive testing (NDT) [3]. Non-destructive modalities exist but most of them are inaccurate and prone to uncertainties of the models.

Normally, in the NDT method the condition inside of concrete is ascertained without destroying it. Carino [4] and McCann and Forde [5] have presented a review of a large number of non-destructive testing and evaluation techniques of concrete [6]. Malhotra and Carino [7] have published a Handbook on NDT of concrete to help the civil and structural engineering consultants engaged in quality control of hardened concrete. This is because they need a comprehensive resource that explains the methods of determining strength and other performance characteristics. The focus of the research and development efforts at the NDT-CE division at BAM, Germany has been on methods used to evaluate the geometrical properties of structure such as thickness, location of components as well as detection of the presence of voids, delaminations, and ungrouted tendon ducts, or cracks [8].

The NDT for the evaluation of the actual compressive strength of concrete in existing structures are based on experimental relations between strength and non-destructive parameters. Generally, manufacturers give experimental relationships for their own testing system of devices [9]. Because of that, special techniques have been developed in which attempts were made to measure some concrete properties other than strength, and then relate them to strength, durability, or any other property. Some of these properties are hardness, resistance to penetration of projectiles, rebound number, resonance frequency, and ability to allow ultrasonic pulses to propagate through concrete.

Some NDT methods may be used to identify the location and development of cracks and voids which are not visible at the concrete surface but which may affect the structural or durability performance of concrete. Due to the specialized nature of NDT methods and the specific equipment required for each method, operators must be well trained and familiar with all factors affecting the test conditions and the readings or responses obtained. Also, the results must be properly evaluated and interpreted by experienced personnel who are familiar with the particular NDT technique.

## MATERIALS AND METHODS

Among the different NDT methods, two most popular methods are the rebound (Schmidt) hammer technique and the ultrasonic pulse velocity (UPV) technique [10]. The first one is a pure NDT where the strength of the material is determined by correlation to another parameter more easily available and readily apparent. This is typically the hardness of the concrete. Rebound hammer test [11] measures the rebound of a spring-loaded plunger pressed against a concrete surface. A graduated scale in the equipment indicates a number depending on the hardness of the surface. However, this number has nothing to do with the strength of concrete. The harder the surface the greater is the extent of the rebound which is expected to correlate to relatively greater strength. However, it has become popular in the world for NDT of *in-situ* concrete because of its simplicity.

The rebound hammer generally measures the first 20 – 30 mm of the concrete surface and will not detect any deeper defects such as voids or cracks within the body of concrete which reduce the concrete strength. However, as the concrete ages and the surface carbonates, the rebound hammer can become less reliable. Therefore the rebound hammer test is classified as a hardness test and is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which the mass impinges. There is no unique relation between hardness and strength of concrete but experimental relationships can be obtained from a given concrete. However, this relationship depends upon factors affecting the concrete surface such as degree of saturation, carbonation, temperature, surface preparation and location, and type of surface finish. A correlation between rebound number and strength of concrete structure is established by testing different grades of concrete and this can be used for the estimation of strength of concrete structures. This is called calibration chart and is normally supplied by the equipment vendor along with it.

The extent of rebound gives an indication of the strength of the concrete at the surface position tested. The average of about 10 to 20 impacts would give an approximate indication as to the compressive strength of concrete at that location. If the surface is quite hard it records a higher number and if it is soft, it registers a lower number indicating the condition of the concrete in the cover region. However, no relationship exists between the number indicated and the strength of the concrete because the number indicated does not in any way depends on any of the properties of concrete. Moreover, this method of testing essentially indicates the quality of concrete on the surface and not at its interior. After extensive experimentation and collection of field data, the equipment is calibrated and a relation is established between the number and the quality of concrete, i.e., whether any crack or void is present in the concrete, by comparison. The quality of concrete thus determined is considered as representing its strength.

However, mostly it turns out to be not true. Moreover, there are two main groups of limitations, i.e., problems with the actual principles of testing and practical differences between measurements taken and correlating the concrete of the specimen with that existing *in-situ*. The use of the rebound hammer test for the estimation of strength of *in-situ* concrete alone is not recommended unless specific calibration chart is available for correlation [9].

Many other NDT methods are available for the investigation and evaluation of condition of concrete using different aspects of stress–wave propagation through the material. One of the most commonly used NDT is the Ultrasonic Pulse Velocity (UPV) technique. UPV is a survey method based on *time of flight* and can measure through the concrete member. It involves the use of high frequency sound waves of the order of 20 kHz to 250 kHz with 50 kHz being appropriate for field testing of concrete to detect cracks, imperfections or changes in the properties of a material. Furthermore, UPV can be used to determine the homogeneity of a material, which is of particular importance to determine the quality of concrete.

In the UPV technique, an ultrasonic pulse is transmitted through the concrete at one end by a transmitter (probe) and the same is received at the opposite end by a receiver (probe). The ultrasonic wave propagated along a straight line between the probes through the concrete is sensed by the receiving probe. The time taken by the wave to travel along this line is displayed on the instrument. The distant between the probes divided by the time taken by the wave yields the velocity. Therefore by this method the velocity of the pulse passing through the concrete is measured. According to the velocity, the quality of concrete, in general, had been graded as poor, average, good, and excellent.

Ultrasonics, radar and other wave propagation techniques provide information regarding the internal flaws in a concrete structure. The reliability of this information is dependent on the nature of flaw, like size, depth and orientation, as well as testing method itself [12]. From the value of pulse velocity, it is only surmised whether there is any crack or void inside the concrete. In this method, the transmission of the pulse at the location of the steel reinforcements, cracks and voids in the concrete, and the moisture condition of the concrete pose serious problems. The presence of cracks and voids in the concrete hold considerable influence on the measured pulse velocity too. If the cracks and voids are empty, the pulse will then be distracted around the discontinuities, thereby increasing the travel path and the travel time, thus decreasing the pulse velocity.

Many times a situation may arise wherein a decision has to be taken to repair/strengthen a concrete building if found to be weak. Under such circumstances NDT is resorted to, to ascertain the condition of concrete. As discussed above, strength of concrete is only presumed based on its quality. Therefore accurate assessment of concrete strength goes awry because the present NDT methods are not reliable and yield only the condition of concretes inside it. However, they are popular because they are traditional methods and no simple and reliable alternative that yields the strength directly are currently available. However, the development of calibration curves to conform to both the rebound hammer and the UPV testing techniques for usual concrete mixes showed that the use of these two methods individually is not appropriate to predict an accurate estimation for concrete strength [9].

The NDT methods such as rebound hammer test and the UPV technique, and some partially destructive tests such as core sampling and depth of carbonation were carried out in a case study of an Intze tank resting on a cylindrical shaft type staging that had been destroyed by age and severely distressed by Bhuj earthquake, to get the complete details of concrete quality and the present strength of concrete [13]. Morchhale et al [14] had used rebound hammer and UPV tests to investigate the extent of damage and the cause of structural deterioration of a 20 year old hospital building and had reported that the assessment based on these tests indicated a poor quality of concrete only.

Saleem et al [15] had carried out non-destructive evaluation of a five storied concrete framed structure. The importance of this investigation was that the construction of the framed structures had been stopped seven years ago. In order to resume the disrupted construction, it was imperative to assess the condition of the existing structure. For this purpose, load tests and core tests were performed on four floors from basement to first floor. It took more than one year to finish the experimental work. Test results showed that the structure had adequate strength for future use although it was unprotected against severe environmental attacks for several years.

The experimental studies using UPV and rebound hammer as NDT were presented by Shariati et al [9] to establish a correlation between the compressive strength of hardened concrete evaluated by compression test and using the NDT parameter. These two tests have been used to determine the concrete quality by applying regression analysis models between compressive strength of *in-situ* concrete on existing building and tests values. The relationship between compression strength of concrete collected from destructive test records and estimated results from NDT's records using regression analysis was compared together to evaluate their prediction for concrete strength. Ozyildirim and Carino [16] have emphasized that *in-situ* strength tests do not provide direct measures of compressive strength, which has to be supplemented by other standard tests. Hence, *in-situ* tests have to be accompanied by laboratory testing to develop a relationship for strength before use in the field.

It is worth noting here that for centuries it had been the practice to ascertain the integrity of a component by striking it with an object and hearing the sound generated. The sound generated by the component was based on the denseness of the material as well as on the propagation of sound wave through the medium. Generally, according to the level of sound generated, the integrity of the component was judged. A strong sound means the integrity of the component is excellent and a hollow sound means the component is weak and it contains a lot of air voids. This is a common method of testing any material/component adopted by people before its selection. It is based on wave propagation technique only.

Quite a different approach was conceptualized and presented in this investigation. In the proposed method, features of both rebound hammer and the UPV technique have been combined. Instead of the rod in the rebound hammer a small hammer was used as an impactor. Instead of the measurement of ultrasonic wave by a probe, the vibration on the surface was sensed by an accelerometer. Instead of time of arrival of the wave, acceleration was measured. This can be justified by the following analogy. It is well known that in earthquake, a rupture in the rock mass releases energy. This point is called focus. This energy is carried through the earth crest in the form of seismic waves and reaches a point on the surface of the earth called epicenter which is felt as vibration. Same analogy is applicable in this technique too. The point where the hammer is struck is the source of energy. The wave is received at another point on the surface in the form of vibration which is measured with a piezoelectric accelerometer in $m/s^2$.

According to ASTM C215 [17], the natural frequency of a simple beam is determined by testing in which it is struck with a small impactor in order to set the beam under vibration and recording it by using an accelerometer. Similar technique was adopted in this investigation in which a concrete surface was struck with a small hammer or an impactor and the vibration induced on the surface was measured in terms of acceleration in $m/s^2$. However, frequency of vibration of concrete is of no consequence here. Rather the propagation of vibration and its amplitude are very important. In UPV method the time of arrival of wave is noted from which velocity is reduced from the distance travelled by the wave. Also, in the UPV method wave of a particular frequency is transmitted through concrete at one end and received at other end. In contrast, in the proposed method waves of many frequencies are randomly generated giving rise to many amplitudes out of which the peak value is measured in terms of acceleration.

It is well known that the acceleration depended on the elastic modulus of concrete and also that elastic modulus and the strength of concrete are well correlated. Multiple acceleration readings, totaling six, on the surface of a cube at different locations, were measured in the experiment conducted here. Subsequently, the same concrete specimen was experimentally tested in a CTM to determine its compressive strength. Only one strength value was obtained by this test. Mapping was done between the measured multi-dimensional input of impact accelerations and the measured single output of strength of the concrete using ANN. The purpose of this exercise was to develop a more reliable scientific method of assessment of true strength of a concrete directly and non-destructively in any condition existing anywhere, i.e., in the laboratory control specimens or *in-situ* and at any time.

### 1.1 Features of ANN

As discussed above, the compressive strength of concrete is its principal and the most important mechanical property which is generally obtained by destructive testing of the concrete specimen in the laboratory only after a standard curing of 28 days and used for design purposes. However, obtaining the strength of *in-situ* concrete by both the standard destructive test or by the NDT as described above is hardly possible. It requires mathematical modelling of various properties of concrete which are normally obtainable from experimentation. For modelling, the traditional methods currently available are the well known deterministic or regression models. In a regression analysis a single experimental parameter is validated with that predicted. These models cannot adequately deal with complex and multi-dimensional dynamic engineering systems, i.e., it cannot deal with several inputs at a time and correlate with a single output. In recent decades, ANN known as intelligent method, has been used for modelling the behaviour of physical phenomena. Moreover, it is the most commonly used method by a majority of researchers in spite of the fact that many other prediction tools are available. The strength model based on the ANN is more accurate than the model based on regression analysis. The ANN model is based on multiple input and single output whereas regression analysis involves single input and single output and determines the scatter of measured input from the output. The ANN is a solution for multi-dimensional problem. The compressive strength could be predicted in a reliable manner using the ANN model developed herein.

Alilou and Teshnehlab [18] have developed an ANN for the prediction of compressive strength of hardened concrete at third day. The investigation of Noorzaei et al [19] focused on the development and application of ANN for the prediction of targeted compressive strength of concrete after 28 days taking into account six input parameters of basic ingredients of concrete. The results of this investigation indicated that ANN had strong potential as a feasible tool for predicting the compressive strength of concrete.

An ANN is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. ANN, like people, learns by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is true of ANN as well.

The ANN theory was developed based on the behaviour of human brain in handling efficiently a lot of dispersed and distributed data in parallel as well as learning ability. This technique had been applied to various fields of science successfully. It had, of late, become a powerful tool for engineering applications. ANN operated as powerful tools to capture and learn significant structures in data. They are particularly suitable for problems that are too complex to be modelled and solved by classical mathematics and traditional procedures. In ANN technique, back propagation algorithm is very popular and also simple to apply. The great majority of civil engineering applications of ANN are based on this algorithm only. Training of an ANN with a supervised learning algorithm primarily means finding the weights of the links connecting the nodes using a set of training examples.

A back propagation network was trained by Malasri et al [20] based on eight basic ingredients of concrete mix to predict the desired strength achievable for high strength concrete (HSC) using ANN. According to Hakim et al [21], the ANN models gave high prediction accuracy, and the research results demonstrated that using ANN to predict concrete strength was practical and beneficial. According to Chine et al [22], ANN was a powerful method for obtaining a more accurate prediction through learning procedures which outperformed the traditional multiple linear regression analysis, with lower estimating errors for predicting the High Performance Concrete slump.

The objective of the present investigation is to develop for the first time a totally different non-destructive technique based on the measurement of acceleration induced by an impact given to concrete and combine it with ANN for predicting the concrete strength. The measured acceleration values were used in establishing a correlation with measured strength by training a data set to get an ANN model. With the help of this trained ANN model, the strength of the unknown and altogether different concrete samples considered representing the *in-situ* concrete was predicted.

### 1.2 Experimental Programme

In this experimental investigation M20 grade concrete designated as the characteristic strength by IS: 456 [23] equivalent to BS: 8110 [24] with a nominal mix proportion of 1:1.5:3 was used to cast concrete cubes of size 150 mm × 150 mm × 150 mm as shown in Fig. 1. The materials were weigh-batched and a water cement ratio of 0.45 was adopted. The ingredients were mixed thoroughly using a drum mixture. The cubes were cast using wooden moulds in a field at a contractor's place and not in the laboratory using steel mould. The degree of supervision and the compaction procedures were varied to achieve variation in strength. A total 54 cubes were cast and they were cured for 28 days by immersing them in water. After 28 days, they were removed from water and wiped clean and dry. The weight of the cube was recorded. An impact was given to one of the faces of the cube resting on floor with a hammer as shown in Fig. 2. A piezoelectric accelerometer, installed on the cube, was used to measure the peak acceleration in $m/s^2$ induced by the impact. The readings displayed on a portable digital meter (Fig. 3) were recorded. Similarly, two more impacts were given on the same face and for each impact the peak acceleration reading was recorded. The same procedure was repeated on the opposite face of the cube. So, a total of six peak acceleration readings, three for each face, were collected for every cube. After this, the same cube was tested in CTM till it was destroyed and its strength was determined. Thus, altogether 54 cubes were tested individually and the peak acceleration readings and the strength values were collected. The range of acceleration values for all 54 cubes varied from 0.7 m/s$^2$ to 136.4 m/s$^2$ and the compressive strength from 16 to 43.56 MPa.

**Fig. 1 Preparation of cubes**

**Fig. 2 Impact testing**

### 1.3 ANN Mapping

In this investigation six acceleration readings measured by experimentation were treated as input variables to train the ANN model and map them to the single measured output value of the strength of the concrete. The ANN model was a two layer feed-forward Neural Network (NN) with twenty hyperbolic sigmoidal functions in the hidden layer and a linear function in the output layer (Fig. 4). The input to the network was six measured accelerations in m/s$^2$ which were recorded using appropriate instrumentation (Fig. 3) whereas the output of the network was a single concrete strength. A total of 54 cubes were tested experimentally and the results were used for training the NN model.

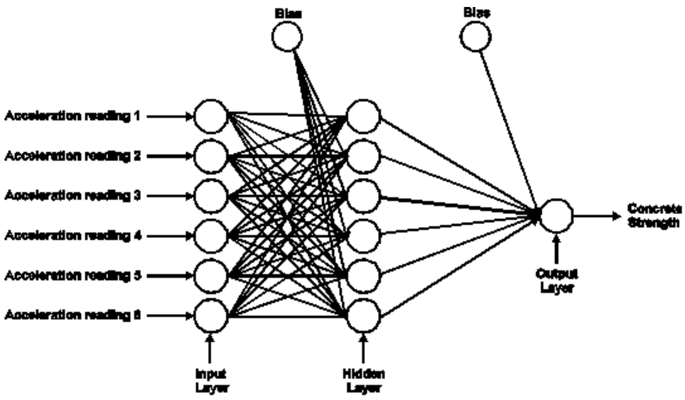


**Fig. 3 Impactor and vibration meter Fig. 4 Proposed ANN strength prediction model**

The NN model was trained using a variant of the back propagation method called Levenberg Marquadat algorithm [25, 26]. The test results of 54 cubes were used as the training data. The six impact accelerations were considered as input variables and plotted as data points on the abscissa. Each data point consisted of 6 acceleration values. The ordinate consisted of values of actual strength of tested cubes that varied from 16 MPa to a maximum value of 43.56 MPa. Each value of the ordinate consisted of only one value of strength. Also, the input and output experimental data were normalized by using their highest impact acceleration value of 136.4 m/s$^2$ and the actual strength of 43.56 MPa, respectively. The reason for normalizing the data was due to the fact that the input had very large variations, i.e., from 0.7 m/s$^2$ to 136.4 m/s$^2$, which unfortunately the network cannot handle. Technically speaking, the network will not be able to map the actual values of input and output as such, hence normalization was used.

For training the network, 54 data points were used and the network was trained for five hundred epochs with a target mean square error less than the order of $1\times10^{-3}$. The outcome of this exercise was plotted in Fig. 5 against the actual strength of the concrete obtained by testing. Figure 5 shows the result of the ANN output obtained from the training data set and is compared with the corresponding actual concrete strength. It should be remembered here that since the variables with the same values of impact acceleration and strength obtained from the experiments were used as that employed for training the ANN, accurate results could be obtained. It is quite evident from Fig. 5 that there is close agreement between the ANN trained concrete strength and the actual strength. With this training, the ANN model is ready for prediction of strength of altogether different concrete which may either belong to control specimens or *in-situ*.

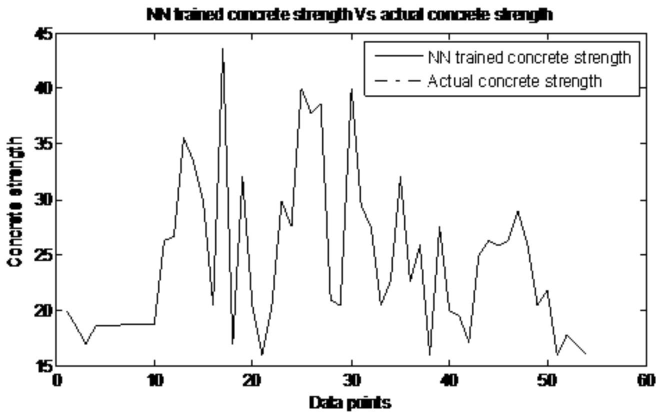


**Fig. 5 ANN trained output and actual concrete strength for the training data**

## RESULTS AND DISCUSSION

The compressive strength of concrete is the backbone of a concrete and is normally determined by casting control specimens, curing by immersing them under water preferably for 28 days and at the end of it tested in a CTM and destroyed till failure. From this failure load the compressive strength is computed. This is quite acceptable as far as standard specimens are concerned and tested under laboratory conditions. However, in construction, concrete is prepared at site perhaps with control on its rheological properties and placed in formworks. After curing for 28 days during hardening the formworks are removed and the structure is loaded directly. There is no way the strength of this concrete can be ascertained. With unknown strength of the concrete, the performance of the structure is left to chances. To circumvent this difficulty the NDT methods were developed. These were earlier applied to test the soundness of mechanical components and subsequently extended to test concrete. The most popular NDT methods applied to testing of concrete are the rebound hammer test and the UPV technique. However, these NDT methods could ascertain only the quality of concrete, i.e., presence of voids, cracks, etc., and did not yield its strength directly. Over the years the vendors developed calibration charts for their own equipments which can be used to determine the strength of concrete. In this process the NDT parameters like hardness, velocity, etc., collected from the field is correlated with the strength given by calibration chart supplied by the equipment supplier. Most of the times the strength obtained by this method is at variance with that obtained from testing of control specimens. Therefore it has been proposed to develop an innovative technique to ascertain the strength. According to this method, an impact is given to the concrete. This process induces vibration in concrete. The amplitude of vibration in terms of acceleration is measured. The strength of the concrete is evaluated by testing control specimens in a conventional manner. The acceleration value and the strength of concrete are mapped together using ANN. First a set of values are used here to train the network. This trained model is later used to predict the strength of concrete.

Experimental investigation was carried out here in which 54 cubes were cast using M20 grade concrete and cured for 28 days. These cubes were cast in a field condition using wooden mould in contrast to the laboratory practice of using steel moulds. Site practice as well as the degree of compaction was varied in mixing and casting the specimens to achieve a variation in strengths. Subsequently, after the concrete has hardened, test was conducted on these cubes by giving impacts on opposite faces of the cube and collecting the impact acceleration for each impact using an accelerometer and digital meter. A total of six acceleration readings, three on each face, were collected. Afterwards, the same cube was tested individually under CTM and the strength was determined by destroying the concrete. The measured impact acceleration ranged from 0.7 $m/s^2$ to 136.4 $m/s^2$. The tested strength of concrete varied from 16.00 MPa to 43.56 MPa. A mapping was done between the multi-dimensional six measured impact acceleration and a single strength of concrete using ANN in MATLAB. A close agreement was observed between the actual concrete strength and the NN predicted strength after training.

## CONCLUSION

A methodology to correlate the concrete compressive strength from measured multi-dimensional impact acceleration has been developed, perhaps for the first time, based on the modern ANN technique. This methodology has been based primarily on experimental results coupled with analytical modelling. The concrete compressive strength covered in this investigation was in the practical and realistic range of strength of normal concrete used in construction, i.e., 16.00 MPa – 43.56 MPa. Similarly, the peak acceleration covered has a very wide range of 0.7 $m/s^2$ and 136.0 $m/s^2$. The impact given is purely arbitrary and no specific technique has been adopted in giving the impact. The concrete of any condition and anywhere can be tested by this method and its strength *in-situ* can be predicted within reasonable accuracy. This methodology can be a great boon to concrete technologies for decision purposes in case there is suspicion about the concrete not having the required strength. It is a portable method and can be used in the field with relative use.

## REFERENCES

[1] Verma SK, Bahadauria SS, Akhtar S, *J Constn Engg*, **2013**, ID 834572, 11.
[2] IAEA, *Guidebook on Non-destructive Testing of Concrete Structures*, International Atomic Energy Agency, Vienna, Austria, **2002,** pp 242.
[3] Raikar CR, *The Indian Conc J* **2005**, 79, 35.
[4] Carino NJ, *Concrete Technology – Past, Present, and Future*, ACI SP-144, American Concrete Institute, Detroit, **1994**, pp. 623.
[5] McCann DM, Forde M.C, *NDT & E International*, **2001**, 34, 71.
[6] Carino NJ, *Concrete Construction Engineering Handbook*, CRC Press, Boca Raton, **1997**, pp 1.
[7] Malhotra VM, Carino NJ, *Handbook on Nondestructive Testing of Concrete*, CRC Press, Malabar, Boca Ratan, **2004**, pp. 392.
[8] Wiggenhauser H, *Concrete Repair, Rehabilitation and Retrofitting II*, Taylor & Francis Group, London, **2009**, pp. 210.
[9] Shariati M, Ramli-Sulong NH, Arabnejad KHMM, Shafigh P, Sinaei H, *Scientific Res and Essays*, **2011**, 6, 213.
[10] Feldman RF, *Canadian Building Digest*, NRC Institute for Research in Construction, NRC - IRC Publications, National Research Council of Canada, Ontario, **2005**, Archived CBD-187.
[11] ASTM C805, *Rebound hammer determination of compressive strength of hardened concrete*, WSDOT Materials Manual M 46-01.15, **2013**, pp. 1-6.
[12] Unruh III RC, *The use of non destructive testing methods for the condition assessment of concrete bridge girders*, Master's Thesis, Massachusetts Institute of Technology, Cambridge, USA, **2004**.
[13] Pandya SG, *The Indian Conc J*, **2007**, 81, 32.
[14] Morchhale RK, Waghmare SS, Murali S, Chaurasiya AK, Goel MD, *The Indian Conc J*, **2010**, 84 50.
[15] Saleem MA, Siddiqi ZA, Javed MA, Aziz M, *Pak J Engg and Appl Sci*, **2012**, 11, 66.
[16] Ozyildirim C, Carino NJ, *Significance of Tests and Properties of Concrete & Concrete-Making Materials*, ASTM International Standards Worldwide, **2006**, 169, 4, 125.
[17] ASTM C215-08, *Standard test method for fundamental transverse, longitudinal, and torsional frequencies of concrete specimens*, ASTM International, West Conshohocken, PA, USA, **2014.**
[18] Alilou VK, Teshnehlab M, *Inter J Engg*, **2009**, 3 565.
[19] Noorzaei, J, Hakim SJS, Jaafar MS, Abang Ali AA, Thanon WAM, *The Indian Conc J*, **2007**, 81, 17.
[20] Malasri S, Thorsteinsdottir E, Malasri J, *Proc. MAESC 2006 Conference*, Memphis, Tennessee, **2006**.
[21] Hakim SJS, Noorzaei J, Jaafar MS, Jameel M, Mohammadhassani M, *Inter J Phy Sci*, **2011**, 6, 975.
[22] Chine HWL, Chen L, Hsu HH, Wang TS, Chiu CH, Modeling slump of concrete using the artificial neural networks, *Proc. Int. Conference on Artificial Intelligence and Computer Intelligence (AICI)*, Sanya, **2010**, 3, 236.
[23] IS: 456, *Indian standard plain and reinforced concrete code of practice*, Bureau of Indian Standards, New Delhi, India, Fourth Revision, **2000**.
[24] BS: 8110 – Part 1, *Structural use of concrete: code of practice for design and construction*, British Standards Institution, London, **1985**.

[25] Howard BD Beale MK, *Neural network toolbox for use with MATLAB*, The Mathworks Inc., Gatwick, **2004**.
[26] Haykin, S., *Neural networks: a comprehensive foundation*, Prentice Hall, Upper Saddle River, **1998**.