DEVELOPMENT OF RAPID RUNWAY REPAIR STRATEGIES USING GENE EXPRESSION PROGRAMMING

Final Year Project UG 2017

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This is to certify that the

Final Year Project Titled

"Development of Rapid Runway Repair Strategies using Gene Expression Programming"

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has been accepted towards the requirements

for the undergraduate degree

in

CIVIL ENGINEERING

________________________________.

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ACKNOWLEDGEMENTS

In the name of Allah, the Most Beneficent, the Most Merciful as well as peace and blessings upon Prophet Muhammad, His servant, and final messenger.

We are first and foremost, extremely grateful to Allah Almighty for enabling us to complete our research project, and without Whose willingness we could not have imagined accomplishing such an enormous task.

The efforts and sacrifices that our parents and teachers have made over the course of our lives to reach where we stand today are highly acknowledged. Special mention of our siblings who were a source of constant motivation and stood by our sides during tough times.

We respect and appreciate the efforts put up by our supervisor Dr. Muhammad Usman Hanif, Asst. Prof. Structural Engineering Department and our co-supervisor Dr. Rao Arsalan Khushnood, Head of Structural Engineering Department. Their valuable advice and research commitments were a source of motivation for us. Throughout the research project, their constant support and taking time out of their busy schedule for mentorship kept us proceeding forward. Moreover, their professional grooming of the group in thesis writing and presentation is valuable and something that will help us in our practical life.

Finally, we would extend our appreciation towards our friends and colleagues who kept encouraging us and provided the necessary assistance in the completion of this research project.

Dedication

To

Our Advisor Dr. Muhammad Usman Hanif

& Our Families

ABSTRACT

The Airport infrastructure including approach runways, taxiways, and aprons is the most important and extremely sensitive target to be attacked by the enemy during warfare. Damage to airfield pavements from sophisticated enemy munitions threatens sustained aircraft sorties until the airfield is repaired. Bombing infuses large craters into the airfield infrastructures approaching 20 feet in width. Timely repair to immediately resume the flight operations is the utmost concern of the scenario. Numerous researches in terms of materials, equipment, and techniques are globally practiced in the backfill of craters followed by the placement of crown as prefabricated modular elements or in-situ repair with rapid setting and rapid hardening grout. However, there are multiple associated parameters with local conditions that enforce an optimized solution for a particular site. The project aims to analyze all the available alternatives to extract an optimal solution for the restoration of airfields back on operational status following an enemy attack. In this study, Gene Expression Programming (GEP) was used to derive a predictive model of One-Day Compressive Strength of Rapid Hardening Concrete (RHC) mixes. The first objective of developing a database was achieved by doing an extensive literature review of the internationally published research studies. The database contains 115 different data points of 13 numerical variables. Randomly shuffled, 74% of the data was used for the training of the GEP model while the remaining 26% of data was utilized for the validation of the model. GeneXproTools 5.0 were used in our analysis. GEP Regression Analysis was used with function finding analysis in GeneXPro tools. Various quantitative and qualitative were observed during the analysis i.e., R-Squared Value, Mean Absolute Error (MAE), regression plot, residual plot, variable importance, etc. GEP was observed to be an excellent tool in evaluating and constructing statistical models for the compressive strength of RHC. The derived models can be used in the practical pre-planning phase and pre-design phase in terms of a wide range of cementitious materials, admixtures, and additives.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway And Transportation Officials
ADP	Adenosine Diphosphate
AI	Artificial Intelligence
ASTM	American Standards Of Testing Material
BS	Bachelor Studies
CAA	Civil Aviation Authority
CAC	Calcium Aluminate Cement
CaCL2	Calcium Chloride
CaO	Calcium Oxide
CaSO4	Calcium Sulfate
CBR	California Bearing Ratio
ECT	Evolutionary Computation Techniques
EDS	Energy Dispersive Spectroscopy
FFRP	Folded Fibre Reinforced Polymer
FOD	Foreign Object Damage
FRP	Fibre Reinforced Polymer
GEP	Gene Expression Programming
HAC	High Alumina Cement
HPC	High Performance Concrete
HRWR	High Range Water Reducer
M/P	Ratio Of MgO And ADP
MAE	Mean Absolute Error
MgO	Magnesium Oxide / Burnt Magnesia
MOS	Minimum Operational Strip

MPA	Mega Pascal
MPC	Magnesium Phosphate Cement
MSS	Maximum Segment Size
OD	Oven Dry
OLS	Ordinary Least Squares
OPC	Ordinary Portland Cement
PAF	Pakistan Air Force
PG	Post Graduate
RHC	Rapid Hardening Concrete
RMSE	Root Mean Square Error
RRR	Rapid Runway Repairs
RRRM	Rapid Runway Repairs Method
SEM	Scanning Electron Microscopy
SSD	Saturated Surface Dry
SSE	Sum Of Square Error
SST	Sums Of Squares Total
XRD	Xray Diffraction Analysis

CHAPTER 1

INTRODUCTION

1.1 General

The airport infrastructure including approach runways, taxiways, and aprons is the most important and extremely sensitive target to be attacked by the enemy during warfare. There are an estimated 139 airfields in Pakistan operated by Civil Aviation Authority (CAA) and Pakistan Air Force (PAF) to entertain the commercial and military flight operations as shown in Fig 1. The quality of runways and pavements cannot be compromised for the successful operations of aircraft. With the development of substantial airfields, a realization comes that a dedicated workforce, equipment, and materials would be required for instant repair and maintenance of the runways during the war because airfield surfaces would be the major targets of the enemies that could affect the air operations. Therefore, considerations must be given to the coming chemical explosive charges which aim to prohibit the access of aircraft to runways for as long as possible. The expedient Rapid Runway Repairs (RRR) can provide an accessible and functional Minimum Operating Strip (MOS) within the four hours of an attack (Bare Base Conceptual Planning, 2012).

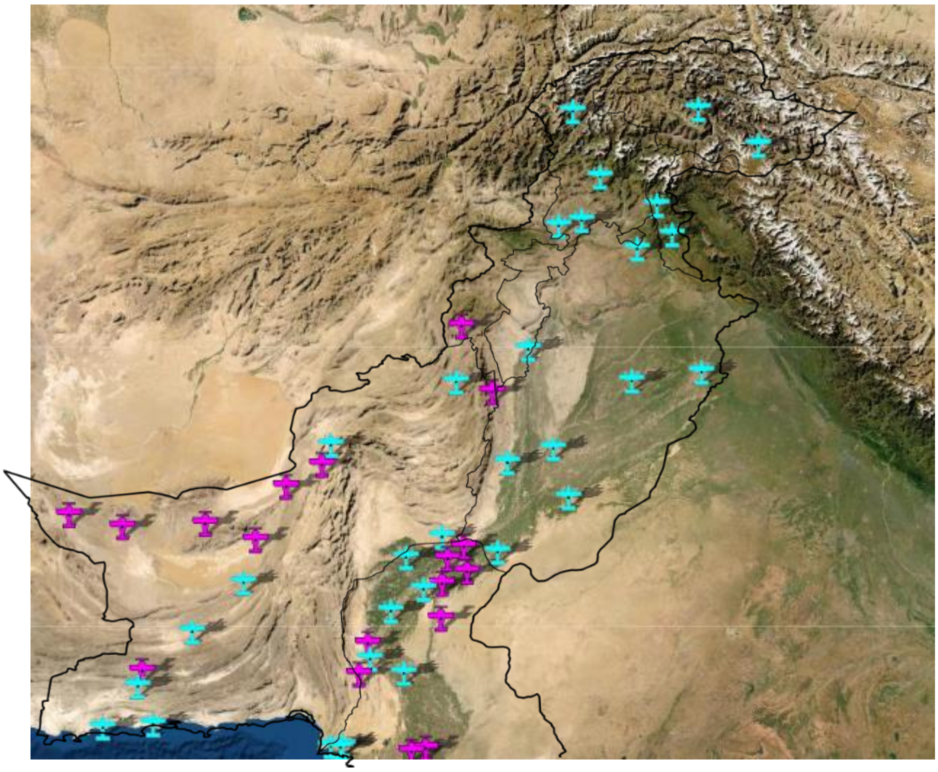


Figure 1.1: Airports and military airbases of Pakistan (Bull and Woodford, 1999)

1.2 Runway Damages

The detonated enemy explosives on runways create deep craters, as shown in (Zone 2 to 4) Figure 1.2. The subgrade is highly compacted at the outer edges of zone 2 because of severe pressure development by an explosion. Zone 3 is the loose debris formed between the compacted subgrade and center of detonation. Most of the debris is distributed along the upper crater boundaries and some of it falls back to the crater resulting in; the thrown-out debris creating a hole in the runway (Zone 4). It is very crucial to timely and efficiently repair the crater by compacting the loos debris (Zone 3), backfilling Zone 4, and/or providing the Foreign Object Damage (FOD) covers (Zone 5). Zones 6 and 7 are the un-cratered runway and sub-base respectively (Bull and Woodford, 1999).

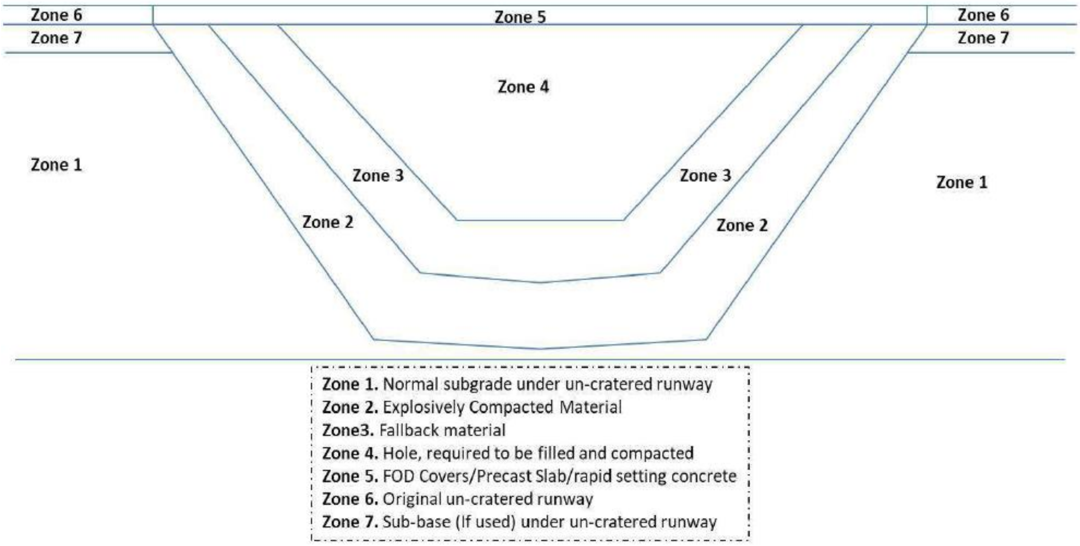


Figure 1.2: Schematic Section through the Crater Repair showing the Subgrade and Repair Zones (Bull And Woodford, 1999)

1.3 Rapid Runway Repairs

Research shows that sometimes the aircraft can compromise with the quality of repair during the taxiing to takeoff position. At less speed, the aerodynamic lift is small and the rough crater repairs induce high dynamic loads within the craft. But with the increase of speed, the aerodynamic lift also increases while reducing the runway-induced load, which does not damage the low-quality repairs (Bull And Woodford, 1999; Anthony, 1982). This type of variation in the acceptance of runway quality allows the repair team to introduce suitable and rapid repairing methods. Multiple advanced techniques have been analyzed for the repair of these bomb-infused craters. These techniques can be divided into three major categories: polymer-modified cement-based materials, resin or polymer materials, and cement-based materials (Guo, Xie, and Weng, 2018). However, an in-depth investigation is needed to optimize the most suitable RRR recipe workable in local conditions qualifying the evaluation benchmarks of repair time, cost, and complexity.

1.4 Problem Statement

Damage to airfield pavements from sophisticated enemy weapons threatens sustained aircraft attacks until the airfield is repaired. Bombing infuses large craters into the airfield infrastructures approaching 20 feet in width. Timely repair to immediately resume the flight operations is the utmost concern of the scenario. Numerous researches in terms of materials, equipment, and techniques are globally practiced in the backfill of craters followed by the placement of crown as prefabricated modular elements or in-situ repair with rapid setting and rapid hardening grout. However, there are multiple associated parameters with local conditions that enforce an optimized solution for a particular site. The project aims to analyze all the available alternatives to extract an optimal solution for the restoration of airfields back on operational status following an enemy attack.

1.5 Objectives

To address the abovementioned research needs, the fundamental theme of this research is to explore the Rapid Runway Repair Methods (RRRM) for full-depth rehabilitation in the airfield having durable, long-lasting, and high early strength. The specific objectives of the research are as follows:

- To select the most appropriate RRR strategies among the global practices considering the evaluation parameters of repair time, cost, and complexity based on extensive literature review.
- Experimentally investigate the selected techniques in laboratory conditions for an optimized RRR recipe in local conditions
- To develop a novel GEP based predictive model for selected techniques.

1.6 Project Methodology

The Project methodology is divided into the following five phases, depending upon the linkage between different activities, shown in Figure1.3.

- Phase A- Technical review for selection of suitable RRR techniques
- Phase B- Analysis of selected RRR strategies
- Phase C- Lab Testing and Field trials of laboratory optimized RRR techniques
- Phase D- Cost-benefit analysis of optimized RRR techniques
- Phase E- Implementation plan & documentation

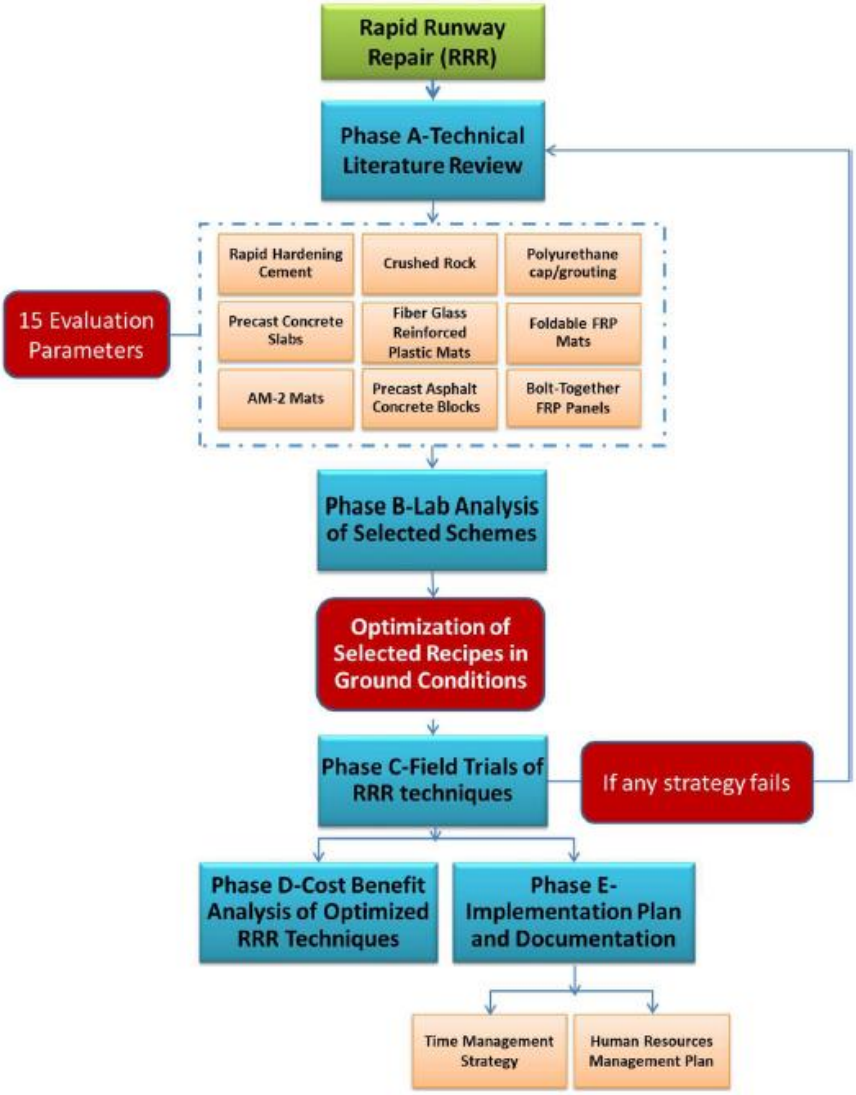


Figure 1.3: Flowchart of activities

1.7 Thesis structure

Followed by an introduction, a detailed literature review has been provided in chapter 2 about Rapid Runway Repair Techniques and Gene Expression Programming.

Chapter 3 explains the materials used, material testing utilized in the project, in-depth experimental methodology, and field testing for this research study.

The results of the analysis and their critical explanations have been presented in Chapter 4 for Rapid Hardening Concrete.

The conclusions drawn from this research work and recommendations for future study are summarized in chapter 5 of this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Rapid Runway Repairs

In this phase, various modem and rapid crater backfilling techniques will be studied in detail. Moreover, this phase will be defining the required and available mechanical compaction alternatives and respective machinery to meet the acceptable bearing capacity of the backfilled materials. Few RRR methods, the most used, reliable, and widely acceptable are illustrated here.

2.1.1 Rapid Hardening Cements

There are various cements that can harden quickly. The most common are High Alumina Cements (HAC), Magnesium Phosphate Cement (MPC), and Type 3 cements. They may set quickly in a short time to achieve the strength as compared to conventional Portland cement concrete, ranging from about a few minutes to a couple of hours.

The ammonium phosphate is used to manufacture MPC. Ammonia gas is nonetheless produced during hydration and generates a severe smell. Many researchers strive to identify alternate phosphates because of its disadvantage. Therefore, a substitute was identified as potassium di-hydrogen phosphate. The experiments with MPC utilizing potassium dihydrogen phosphate have shown that it has low drying shrinkage and high bond strength. The Ratio of MgO and ADP or M/P ratio had a major effect on the hydration rate; the lower M/P ratio leads to increased heat of hydration and hence more chemical reactivity. The fixed time would therefore be probably related to magnesia's purity. The 88.5% pure magnesia in cement results in 15-22 minutes setting time and purer can reduce further setting time. The presence of Borax in cement also plays a significant role to shorten the set duration, at 0.1 of borax to magnesia ratio give the lowest setting time. The fly ash and aluminum cement mixture of MPC mortar create extraordinarily low shrinkage and good bonding strength in the old concrete pavement, which might reduce the possibility of repair material spalling. The MPC mortar has a far higher abrasion resistance than is normally needed for road construction, ensuring a more secure and durable repair(Roh et al., 2015; Li, Zhang, and Cao, 2014).

This method uses a non-shrunken grout to fill the void spaces between the backfill aggregates in the crater. The general procedure for this repairing technique is given here.

i. Fill the crater with the blast
ii. Place a crushed and graded stone layer of aggregates.
iii. Place a grout geotextile overlain.
iv. After setting area will be ready to use for aircrafts

2.1.2 Rapid Hardening Grout and Concrete

This type of repair is considered a sustainment airfield repair (Jung, Roh, and Chang, 2015). Polyurethane grout is prepared to penetrate the voids of the base aggregates. It is blended with the setting time accelerators to get the rapid setting and high strength polymer-based mixes. The commonly adopted procedure of RRR by polyurethane grout is sketched in Fig 8 and summarized as follows.

i. Backfilling and compaction of existing debris
ii. Filling the crater with uniform size gravel
iii. Apply polymer concrete and allow it to percolate into the gravel voids.
iv. Continue filling until level with the existing pavement.
v. Use for aircraft just after five minutes of setting.

Sometimes rapid setting concrete is also laid over the crushed stone layer. Uniform compaction of backfill material is critical. The first five steps will be the same as for the crushed stone backfilling method.

i. The material extending from the original pavement should be cut off and removed.
ii. The crater is to be backfilled with the debris and is to be leveled up to 2.3 ft. beneath the already existing pavement surface.
iii. The backfill material is to be solidified to a min CBR value of 4.
iv. A geo-membrane fabric is to be used between the different backfill and the next material to be placed if we think settling problems might happen.
v. A layer of crushed stone is to be placed over the material that is backfilled. Then the crushed stone is to be compacted using four passes of a vibratory roller. If a 10-ton vibratory roller is used then 2 passes are enough.
vi. The remaining 12 inches are to be filled with concrete and then leveled.

Figure 2.1: RRR by grouting or placing concrete.

2.1.3 Pre-Cast Concrete Slabs

This method was firstly developed by the US Air Force, where pre-cast slabs, of size 2x2 m2 and l 50mm thick with reinforcing strips along the top edges, were used. The most adopted procedure of this method is elaborated below.

i. Removal of existing debris from the crater
ii. Make a rectangular or square shape of a crater by cutting the edges.
iii. Filling of the crater with blast rock about 10 inches below the existing pavement surface
iv. Overlay 3/8-inch gravel about 5 inches thick.
v. Leveling of gravel with screed beam
vi. Placement of precast slab and compaction with a roller.

Figure 2.2: RRR by Concrete Slab

2.1.4 Fiberglass Reinforced Plastic (FRP) Mats

These mats are composed of two to three plies of fiberglass saturated with polyester resin. They are usually 60ft by 60ft in size but can also be used in other dimensions depending upon the crater size. The alternation in the sizes of mats can also be made on-site depending upon the appropriateness of the mat with the crater. They can be glued together and cut by the circular saw to achieve the required size as given in Fig 2.3.

i. The execution procedure of RRR by FRP mats is given below.
ii. Backfilling the crater with debris
iii. Pour crushed stones.
iv. Compact with a vibratory roller.
v. Place FRP mats over pavement surface and anchor bolt with the ground
vi. For the tail, hook operations construct a ramp with rapid hardening cement

Figure 2.3: RRR by FRP mat

2.1.5 Folded Fiberglass Reinforced Plastic (FFRP) Mats

The folded FRP mats are constructed of rigid fiberglass mats and joining panels that are used to join two mats together. The mats are connected by flexible polyurethane elastomer hinges and the joints are flexible, which allows the mats to be folded and transported to the desired field. They can also be cut or patched together if necessary (Tuan and Dass, 2014; Joseph, 1983). The crater filling, compaction of different repaired layers, and fixing of mats with the ground are the same as in the case of FRP mats. In some cases, the sand grids can also be used with geo-membranes in place of the crushed stones then they are compacted to the desired compaction values as shown in Figure 2.4.

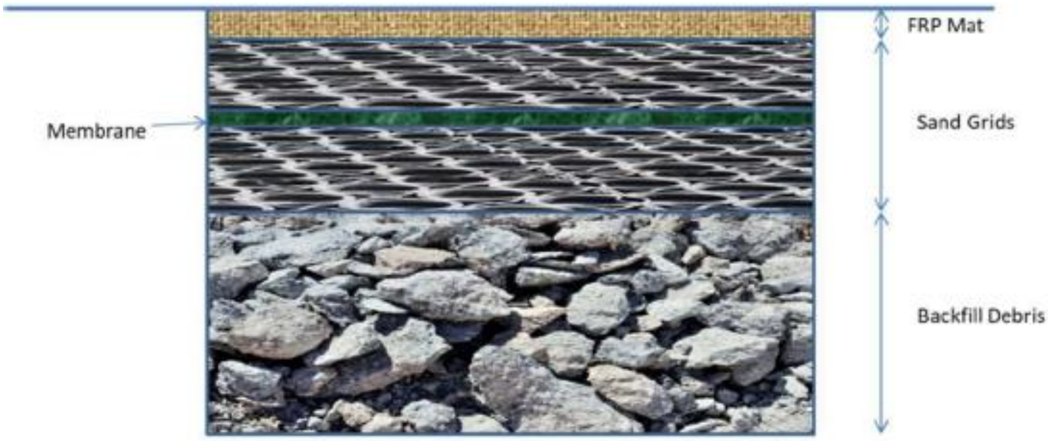


Figure 2.4: RRR by FRP and sand grids

2.1.6 Bolt-together FRP Panels

These panels consist of three plies of fiberglass having polyester resin, basic size is 18ft by 6.67ft and 3/8inch thickness. These panels can easily be transported to the site and then bolted together before placing over the crater to have the crater suitable dimensions. Then anchorage is performed, and the rest of the procedure is like the FRP mat placing procedure.

2.1.7 Crushed Stone

Following steps are usually involved when adopting the crushed stones crater repair method; it is also schematically shown in Figure 2.5.

i. The elevated surface in the pavement is to be removed with the help of a bucket of an excavator or a front-end loader. We can also use a dozer depending upon the surface conditions.
ii. The debris that is extra than 12 inches is to be removed and then it is reduced in size. The pavement is to be broken into smaller parts that would minimize the possibility of spaces and settling issues in the future.
iii. The backfill material is to be placed into the crater.
iv. If there are chances that a settling problem might happen then a membrane fabric should be placed between the different materials.
v. The crater is to be filled and compacted using crushed stone and then the crushed stone is to be compacted using more than four passes of a single drum roller with vibrations.
vi. The compressed crushed stone is to be graded above almost an inch to the surface.
vii. The crushed stone s to be compacted using two passes of a single drum roller with vibrations or if we are using a 10-ton vibratory roller we can give one pass.

At this point, we can consider the repair of crushed stone to be complete. According to the situation and the location or type of aircraft used in the mission, it can be left uncovered r we would need to provide a FOD cover.

Figure 2.5: RRR by crushed stone

2.1.8 AM-2 Mats

AM2 mats are composed of extruded aluminum alloy. AM2 mats consist of aluminum alloy extruded. The mats establish pathways, parking lots, and taxiways for the operation of battlefield aircraft. For approximately 40 years, the extruded aluminum alloy matting AM-2 is stored in the Air Force stock. Once a primary pillar of speedy repair of the runway crater, secondary use of taxiways and the extension of parking spaces were mostly used. If no other procedure is utilized, this is a great option for repairs the runway. For fighter and C-130s, AM-2 mat repair kits are typically suitable but not sufficient for landing strips on jet freight airplanes. The limited anchoring method, narrow pad width (16.5 meters breadth and 23.6 meters long), and jet blast sensitivity from external engines are the limitation of AM2 mats. Taxiways and aprons can be repaired with AM-2 mats if the breakage and sharp turns on the mat are avoided. It is vital to properly drain the foundation and sub-layers. The excess moisture of these layers reduces the carrying capacity and later causes failure of the underlying material. Its process of installation is similar to FRP matting.

2.1.9 Pre-Cast Asphalt Concrete Blocks

This method uses pre-casted and pre-compacted asphalt concrete blocks to repair the craters. Their usual dimensions are 24x24 inches with a thickness of 3-4 inches. The procedure to deploy these blocks is as follows.

i. Backfilling with debris below 18 to 24 inches of the top surface.
ii. Filling with crushed rocks and compaction.
iii. Placing asphalt concrete blocks
iv. Heat blocks with infrared heaters to have a flush repair.

2.2 Gene Expression Programming

2.2.1 Introduction

Computers models are powerful tools in academic and empirical fields for civil engineering problems. In the past decades, artificial intelligence (AI) techniques have attracted researchers' attention in almost every field. These techniques also have been widely highlighted for solving engineering problems. Machine learning systems are powerful tools for the design of computer models. The aim of automation in computer programming to program software itself is pivotal to Machine Learning and Artificial Intelligence and broad are encompassed by machine intelligence (Turning,1948). The main goal of AI and machine learning techniques is to allow machines to exhibit the behaviors of various processes without human interference that could be considered prejudiced. This section gives an overview of the basics of Genetic Algorithms, Genetic Programming, Gene Expression Programming, and recent advancements in this scope.

2.2.2 Genetic Algorithms

John Holland pioneered Genetic Algorithms in the '60s and applied the principle of bio development to computer systems (Holland, 1975). And like all evolutionary computer systems, GA's simplify biological development excessively. In this approach, problems are frequently encoded in fixed-length strings of 0's and 1's and populations (individual or candidate solution) are handled so that a good solution to a certain problem may be developed. Individuals from generation to generation are replicated and selected by fitness. Although the search operators of mutation, crossover, and inversions brought the change in the original Genetic Algorithm, more recent implementations have begun to favor mutation and crossover and thus to reduce inversion of the process (Ferreira, 2001; Ferreira, 2011).

It should be noted that GA's are naked chromosomes or in other words, GA's basis replicators of persons. The GA's chromosomes function as genotypes and phenotypes, like all basic replicators. This means that the selected items and the guardian of the genetic information must be copied and transferred to the next generation at the same time. Therefore, everything in the genome will have an impact on fitness and selection. Compare this scenario the present state of nature in which persons are picked based on the qualities of their bodies alone, in order to clarify the crucial aspect of GA: just the human body and the ability it can achieve is significant in the selection process; the status of the genome does not matter. This dual feature (genotype and phenotype), and its arrangement of structural structure, notably the language of chromosomes and their set length, severely restrict the diversity of activities GA chromosomes can perform. In fact, the chromosomes of GA's are remarkably similar to a basic RNA replicator which likewise shows little structural and functional variation with the linear RNA genome. In the two circumstances, the entire replicator structure dictates the functioning and consequently the individual's fitness. For example, a replication area alone cannot be used in such systems as the answer to the issue; the replicator as a whole is always the solution. These systems are therefore quite restricted.

GA chromosomes are capable of playing a range of tasks because of their dual purpose (genotype and phenotype) and structural arrangement, particularly the simple language and constant length of the chromosomes. Indeed, GA's chromosomes are somewhat similar to basic RNA replicators, which can likewise show a limited structural and functional variation in the linear RNA genome. In the two circumstances, the entire replicator structure affects the individuals functioning and fitness. For example, only a certain component of the replicator cannot be used in such systems as a solution to a problem. The whole replicator is always the solution, nothing more, nothing less. These systems are therefore quite restricted.

2.2.3 Genetic Programming

Genetic Programming was developed by Cramer in 1985 and it was further developed by Koza in 1992. It is used to find alternative fixed-length solutions using nonlinear structures called parse trees of different shapes and sizes. The representation system of Genetic Programming is more versatile as it can use alphabets to create structures as compared to genetic algorithms which use 0's and 1's. On the other hand, Genetic Programming cannot create simple genomes like linear chromosomes of Genetic Algorithms and these nonlinear structures are exact replicators with functions of both phenotype and genotype. The parse tree in Genetic Programming looks like protein molecules in their utilization of more extravagant letters in order and their intricate and interesting progressive representation. These complex replicators reproduce with modification, which is highly constrained in transformative terms, as the transformations occur on the parse tree itself, the modifications are limited. (Ferreira, 2001; Ferreira, 2011)

In Genetic Programming, many types of modification and exchange are not possible because of operating at tree level, as in the case of point modification which is a high performance and simple technique because it can result in structural impracticalities. In overall comparison, the results of any expression protein are substantial protein structures. Even though Genetic Programming does not use linear chromosomes, it has a population of individuals that are selected according to fitness measures and are introduced genetic variations through genetic operators.

There are many Evolutionary Computation Techniques (ECT) that can solve problems automatically without much interference and interaction of advanced structure of the solution, and Genetic Programming is one of them. In other words, GP is a domain-independent and systematic method for machines to automatically solve complex problems that need to be done. GP has been popular since its inception and many people have researched GP. Genetic Programming is progressing very rapidly as more and more practitioners and investigators are discovering new methods and applications.

In Genetic Programming, computer programs are evolved simultaneously and collectively. With every generation of programs, Genetic Programming arbitrarily changes the population of the program. Genetic Programming follows a random natural phenomenon, and results are never guaranteed. However, this essential randomness is the quality of the analysis technique, GP is very successful at evolving unexpected and novel ways of problem-solving. (Poli et al., 2008)

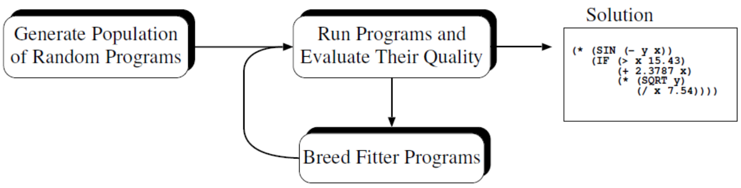


Figure 2.6: Basic flow chart of Genetic Programming using fitness evaluation procedure. (Poli et al., 2008)

These are the basic stages in the GP system. GP can compare various generations of the program with some ideal function and find out the efficiency of the solution. As researchers, we are also interested in the problem-solving capability of the computer program. GP quantifies the comparison and is known as fitness. GP tries to get maximum fitness by breeding fitter programs and iterating the process. The genetic operators have a direct effect on the parse tree and this phenomenon greatly limits the Genetic Programming e.g., mangoes can only be produced on an orange tree using pruning and grafting. Like that, genetic operators should be carefully selected so that the resulting structures are valid. There are three basic operators in Genetic Programming.

Crossover: It is the most frequently used search operator using which new offspring trees are developed by exchanging selected branches between two parent trees. The concept of this operator was to exchange mathematically simpler segments and progress toward complex structures and solutions having bigger building blocks. This technique bears a resemblance to grafting and pruning of trees and has a limited extent. When LISP programs undergo crossover operation, new LISP programs are formed which may are closer to nature.

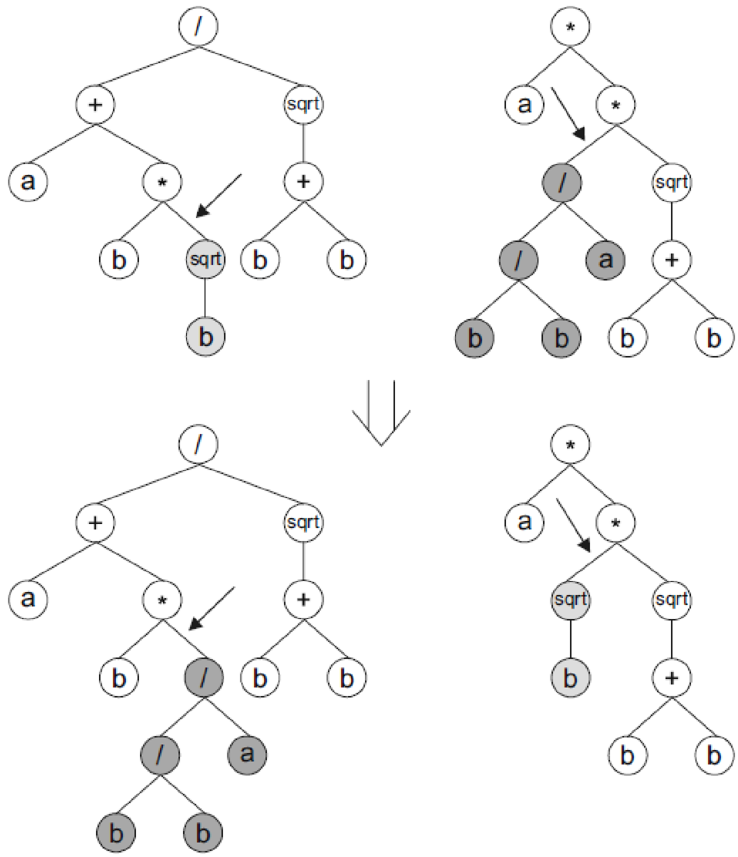


Figure 2.7: Parse Tree Crossover diagram in Genetic Programming. The arrows here show the crossover points. (Ferreira, 2011)

Mutation: It is the second operator of Genetic Programming using which new offspring trees are developed by selecting a node on the parent tree and replacing that with another branch that is randomly selected. It can be seen that the overall shape of the parse tree has not changed by this kind of operator, especially if the nodes that are replaced are a target for mutation. This operator is also different in nature from biological point mutation so that LISP programs are created in the right pattern.

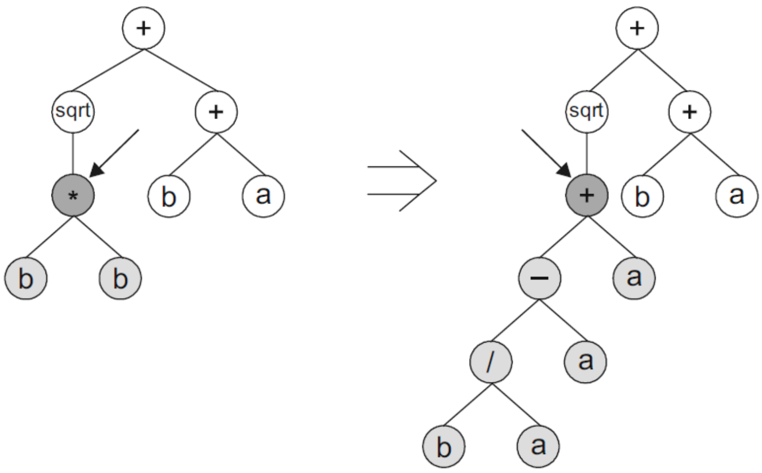


Figure 2.8: Parse Tree Mutation diagram in Genetic Programming. The arrows here show the randomly selected mutation points and branches. (Ferreira, 2011)

Permutation: It is the most conservative operator used in Genetic Programming. During permutation, the arguments of the parse tree are randomly replaced with another such that the structure of the parent tree and offspring tree remains the same.

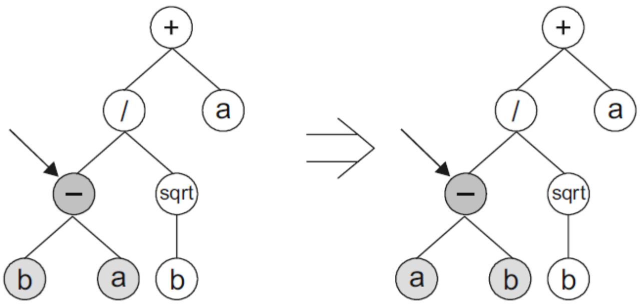


Figure 2.9: Parse Tree Permutation diagram in Genetic Programming. The arrows here show the permutation points. (Ferreira, 2011)

2.2.4 Gene Expression Programming

In 1999, Candida Ferreira invented Gene Expression Programming (Ferreira, 2001). He overcame the inadequacies of Genetic Programming by including both simple, linear chromosomes of fixed lengths that are used in Genetic Algorithms and complex structures of various shapes and sizes that look like parse trees of Genetic Programming. Gene Expression Programming uses expression trees. Expression Trees in Gene Expression Programming are the expressions of fully independent genomes. These complex structures are fully programmed in linear chromosomes of fixed length so it can be accepted that, in GEP, the phenotype and genotype genomes are distinguishable, and the evolutionary phases can be observed in the structure.

Therefore, it can be said that one kind of complex structure can consist of phenotype Gene Expression Programming.

As the expression trees are autonomous genomes and they can consist of only phenotype GEP, another phenomenon can be linked with these concepts i.e., phenotype threshold. It means only slightly modified genomes move on to the next generation. Thus, no more complicated structures must be mutated and replicated, all adjustments taking place in a straightforward linear structure which will eventually evolve into an expression tree. (Ferreira, 2011)

Gene Expression Programming's key insight is the creation of chromosomes that could represent all kinds of parse trees used in Genetic Programming. To read and convey the information encrypted in the chromosomes, a new programming language, Karva was developed.

The foundation of all this innovation is the basic yet revolutionary structure of GEP genes. Not only this structure encodes every imaginable program, but it also facilitates effective development. This adaptable structural arrangement also permits a high-performance collection of genetic operators to find solution space extremely rapidly. As in the case of Gene Expression Programming search operators, they always build a valid structure like complicated mathematical problems, complicated ANN and are hence extremely suitable for developing genetic diversity. GEP has been used for the prediction of compressive strength of foam concrete, compressive strength steel fiber reinforced concrete, moment capacity of ferrocement, shear strength of RC deep beams, flow number of asphalt mixtures, and tunneling. (Gholampour, Gandomi and Ozbakkaloglu, 2017)

The individual structure is picked to reproduce through modification, depending upon both the fitness and luck of the draw. This produces the basic genetic variety which will permit long-term adaptability. During replication of genomes, numerous changes are made in nature like mutation, election, insertion, and others are added after replication, as is the case for homologous recombination and still further mutations. It is therefore not always feasible in nature to recognize when a change has occurred. The fundamental algorithm of Gene Expression Programming can be utilized to address the difficult issues in many disciplines.

This chapter addressed the literature review of the Rapid Runway Repairs (RRR) and Gene Expression Programming (GEP). Here we stated various techniques of RRR being used in past and are in current practice all around the world and also discussed the development of GEP from Genetic Algorithms (GA) and Genetic Programming (GP). In the next chapter, we will discuss the experimental plan and materials to be used for the selected RRR technique based on the literature review.

CHAPTER 3

MATERIAL AND EXPERIMENTAL METHODOLOGY

3.1 Introduction

The first objective of the study was achieved as Rapid Hardening Concrete was selected based on parameters of repair time, cost, and complexity with the help of an extensive literature review. In the construction industry and commercial buildings of highway infrastructure, bridges, dams, and ports, Concrete has been the primary construction material. Concrete is also the priority material for buildings. Concrete is popular because of its economy, its flexibility to adopt different shapes, and its ability to form various wearing structures like slabs, floors, pavements, sideways, etc. Cement, which has become a properly manufactured and treated material, is a major component that makes concretes conceivable.

In the last five decades, there has been an appreciable development in concrete technology, mainly owing to the researcher's interest in supplementary cementing materials, and new generation chemical additives for concrete. With the variety in materials available today, it is possible to design tailored concretes for any type of construction. Another face of progress in concrete technology is that modern researchers now try to investigate concrete from an interdisciplinary point of view, involving chemistry and materials science with civil engineering. These advances have ensured that concrete will remain a material of interest for many decades to come (Wikipedia, 2021).

3.2 Materials

Materials used in the manufacturing of Rapid hardening concrete as well as their characterization are mentioned in the upcoming section followed by a detailed experimental methodology.

3.2.1 Binding Material

Every concrete has a binding material that holds everything together. It is a chemical compound grounded into fine particle sizes and reacts with water or any other chemical to produce adhesive action. It has been used since 6500 BC by Nabatean people who used Clay as binding material and their structures have survived to date. Many other materials have been used like volcanic ash, lime, clay, gypsum, and burnt slabs. (Wikipedia, 2021)

3.2.1.1 Ordinary Portland Cement (OPC)

Portland concrete, which is produced by mixing lime-containing ingredients with clay content, is the largest hydraulic cement in the construction industry. Besides Portland cement, the most popular hydraulic cements include gypsum, ordinary lime, magnesium-based cements, and natural pozzolans. The raw materials are determined carefully to have an exact amount of lime, silica, aluminum oxide, and iron oxide (Nawy, n.d.). As per ASTM C150 Standard, there are 5 general types as explained below:

- Type I: General-purpose cement.
- Type II: This type of cements generates less heat of hydration and has moderate sulfate resistance.
- Type III: This type of cement has high early strength due to the high blain finesse index.
- Type IV: This type of cement has a very low heat of hydration.
- Type V: This type of cement has very high sulfate resistance due to its very low C3A composition.

3.2.1.2 Type III Cement

Type III cement has high early strength. Because it is finer ground and develops strength faster than Type I, the early compressive strength increase is higher. The final strength, however, is not much greater than Type I. All else being equal, Type III cement concrete will have somewhat greater 28-day strengths than concrete made with Type III. (Wang and Ramakrlahnan, 1990)

3.2.1.3 Magnesium Phosphate Cement

The cement has special hydraulic qualities, a regulated fast set, and early development of strength. In recent years there has been extensive study on the development of magnesium-based cements, their strength properties, and their durability. Magnesium Phosphate Cement Mortar quickly produces a prepacked mix of dead burnt Magnesite with fine aggregates when combined with phosphate solution. It hardens quickly and high-strength cement mortar is obtained. It is tough and reliable and can be utilized to restore old concrete pavements. It's highly applicable in places where the operations cannot be withheld from service for a long period. This new cement is a good alternative to expensive synthetic resins with a great potential economic future as compared to those methods that are currently used for rapid runway repairs (Li, Zhang, and Cao, 2014; Mestres and Ginebra, 2011; Seehra, Gupta and Kumar, 1993).

3.2.1.4 High Alumina Cement

Also known as Aluminous Cement or Calcium Aluminate Cement(CAC), High Alumina Cement is comprised of calcium aluminates. Lafarge, the chemical industry in the UK, made high alumina cement for the first time in 1925. It is resistant to corrosive action essential in maritime construction. It acquires high early strength which accelerates the construction process. They are mostly used to produce structural concrete such as precast beams and girders. High alumina cement is obtained by sintering or fusing an alumina and calcareous material mixture in proper proportions and by grinding the resulting material to an extremely fine powder. Mostly Bauxite and Limestone are used for producing high alumina cement. The furnace is charged with these two elements, the oven is ignited with hot air burst with crushed carbon. In general, the fusion process is performed at roughly 1550-1600 ^{o}C in the furnace. The cement is poured in liquid condition into molds and cool down. These casts are crushed and then processed in pipe mills to finesse of around 3000 sq. cm/gm after cooling (Bradbury, Callaway and Double, 1976; Currell et al., 1987; Engineering Notes India, 2017; Hooton, Gillott and Quinn, 2003).

3.2.2 Aggregates

Aggregate is a major component of concrete. Its content makes up to 75% of the total solid volume of concrete and represents up to 80% of the mass. It can be in the form of sand, gravel, crushed stone, slag, and similar materials. The dry density of most common aggregates is 135 to 160 lb/ft3. Aggregates can be made of many different particle sizes. To measure the particle sizes, a dry sample of the aggregate is passed through several standardized sieves starting with the largest openings and using smaller and smaller openings in successive sieves. The grading can then be precisely defined by the total weight passing each sieve. To make consistent concrete batches, the aggregate amount and distribution of particle sizes must be controlled.

3.2.2.1 Fine Aggregates

According to ASTM C778-17 Standard Specification for Standard Sand, If all the particles of the aggregate are smaller than 3/8 in. (9.5 mm), then it is referred to as fine aggregate. Fine aggregate is either natural sand or manufactured sand produced by crushing rock. It fills up the voids between coarse aggregate and cement paste. It helps in the hardening of cement by allowing water to seep through its voids. It minimizes the shrinking and cracking of concrete and economizes concrete by varying its proportion for strength.

3.2.2.2 Coarse Aggregates

According to ASTM C33 Standard Specification for Concrete Aggregates, If most of the particles of the aggregate are larger than about 1/4 in. (6 mm), then it is referred to as coarse aggregate. The material can be gravel or crushed stones. Crushed rock has a sharp, angular texture whereas gravel has round-shaped objects. Some gravel pieces, however, may be crushed to size from large pieces of gravel. They act as the main filler and forms the main bulk mass. Cementitious materials stick to the aggregate's surface to develop as a solid material. It imparts volumetric stability and durability to concrete. It increases crushing strength, resistance to wear and tear, and water tightness of concrete. It also economizes concrete since it is cheaper than cement. Most concrete used in building construction has a maximum aggregate size from 3/4 to 1-1/2 in. The most common aggregates, such as sand, gravel, crushed stone, or crushed slag, make concretes weighing from 135 to 160 lb/ft3. Structural lightweight concrete weighing from 90 to 120 lb/ft3 is made with aggregates of expanded shale, fired clay, slate, or slag.

3.2.3 Water:

It is the most important ingredient of concrete as a binding medium with various chemicals that interacts chemically. To improve workability and compaction, the surface of the aggregates is coated. It also facilitates the spreading of cement over aggregates. Natural portable water without any taste or odor is suitable for concrete. Excessive impurities in the water may affect setting time and compromise other properties as well therefore suspended particles should be less than 2000 ppm. Water should be free of Inorganic salts like Sodium phosphate, sodium borate, sodium iodate, zinc chloride because they act as retarders whereas Calcium chloride acts as an accelerator, and Bicarbonates of sodium and potassium cause rapid setting. According to ASTM C55 Standard Specification for Concrete, a minimum quantity of water should be added for the effective hydration of cement. Water in excess is required to act as a lubricant between aggregates to produce workable and economical concrete. Due to less amount of water, concrete is less workable, and it makes non-uniform mixing due to which it is weaker in strength. Water is also required for curing and aggregate washing.

3.2.4 Admixtures

In addition to cement water and aggregate, artificial or natural ingredients are added to concrete to increase particular properties of concrete during casting, setting, and in its service life. There are a lot of admixtures available that can accelerate or retard the initial setting, increase the strength, increase workability, penetration, and pump ability, increase durability, reduce the heat of hydration, reduce segregation in grouts, control shrinkage, and expansion, make concrete impermeable by decreasing the capillary flow of water, inhibit corrosion, increase resistance to chemical attack, and produce concrete, which is colored, cellular, fungicidal, germicidal, and insecticidal. Here are few admixtures that are used in our study.

3.2.4.1 Accelerators

They reduce the setting time by accelerating the rate of hydration. Many chemical compounds like sulfates (less $CaSO_4$), alkali carbonates aluminates silicates; chlorides of aluminum calcium sodium; sodium and potassium hydroxide, etc. can be used as accelerators. Many compounds can affect the properties of concrete in more than one way like $CaCl_2 < 2\%$ acts accelerator but acts as retarder if $CaCl_2 > 2\%$. They are mostly used to increase the curing rate for high early strength in cold climatic conditions. It is also necessary to match the chemical admixture to the kind and amount of cementitious materials (Currell et al., 1987).

3.2.4.2 Retarders

They increase the setting time by decreasing slows curing rate and retard rate of hydration. With the use of retarders, more free water is available hence the mix is more workable. Many chemical compounds like $CaSO_4$, sugar, starch, cellulose, ammonia and iron chlorides can be used as retarders. They are mostly used to face hot climatic conditions. It is also necessary to match the chemical admixture to the kind and amount of cementitious materials (Currell et al., 1987).

3.2.4.3 High Range Water Reducer

According to ASTM C494, the amount of water needed to make concrete of the appropriate consistency can be reduced by more than 12% with the use of High Range Water Reducing Admixture. It can make concrete highly flowable and cause significant water reduction. HRWR admixtures reduce the water-cement ratio while maintaining a high slump and also reduce the amount of binding material while keeping constant slump and strength. They are more common in places where slump loss is observed frequently, like the batching plant and pouring site are more than 30 min apart so HRWR is added to have significant slump and good quality green concrete. HRWR admixtures can be utilized to attain high-strength concrete, which can help in reducing cross-sections of compression members in high-rise buildings, improve the durability of concrete in aggregated conditions, and several other uses. It is also necessary to match the chemical admixture to the kind and amount of cementitious materials (Currell et al., 1987).

3.2.4.4 Silica Fume

Silica fume is an amorphous solid. It is a non-crystalline polymorphic substance made from silicon dioxide and is also called micro silica. It is an ultra-fine powder that is collected as a byproduct for manufacturing silicon and ferrosilicon alloy and is constituted with less than 1 μm dia and an average of 0.15 μm dia spherical particles. The major application area is high-performance concrete as a pozzolanic material. Concrete made using silica fume has better compressive and flexural strength. This kind of concrete is more durable than normal concrete. Resistance to freezing and thaw and chemical resistivity is also better than normal concrete. There are also fewer chances of bleeding and segregation. The concrete mix is also dense and more consistent.

3.2.4.5 Fly Ash

Fly ash is a heterogenous substance from byproducts created during coal combustion in power plants. It is a fine grey, glassy spherical powder that ascends with flue gases. Pozzolan components react with lime to produce cementitious materials. Fly ash is therefore added to concrete, mines, dams, and landfills. According to ASTM C618, fly ash has been classified into two types based on the type of coal and the forensic analysis i.e., Type C and Type F. Type C fly ash is formed by burning sub-bituminous coals or lignite coal with more than 10% CaO. Type F fly ash is formed by burning bituminous coals or anthracite coal with less than 10% CaO. The typical particle size of fly ash is between 10-100 μm and usually, the particle shape is spherical glassy with tan or grey to black color based on unburnt carbon content. (Hooton, Gillott and Quinn, 2003)

3.3 Experimental Testing

Experimental Testing has been divided into two phases:

- Laboratory Analysis
- Field Testing

3.3.1 Laboratory Analysis

The selected RRR strategy based on technical literature and ground conditions, i.e., Rapid Hardening Concrete will be tested in the lab in this phase. The test method explained in this section will be performed to further optimize the three most appropriate methods for successive field trails.

3.3.1.1 Direct Shear Test / Slant Shear Test

According to ASTM D3080 Standard Test Method for Direct Shear Test of Soils, This test is used to find the shear strength of the soil. We need this test to find the properties of soil in the base, sub-base, and subgrade. The shear strength of soil is an important parameter that shows soil’s maximum resistance to shearing stresses. This test is used to find the angle of internal friction and cohesion of soil, which is required in foundation design, retaining walls, etc. This test may be conducted under three distinct drainage conditions: Consolidated-Undrained, Consolidated-Drained, And

Unconsolidated-Undrained. In general, sandy soils are tested for direct shear in Consolidated-Drained conditions.

For rock and concrete, ASTM D5607 Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force is used. It includes testing for both intact rock strength and sliding friction test, which can be done on uniform specimens or weaker planes, including natural or manufactured joints. For example, the rock concrete interface or the lift line from a concrete pour is an artificial joint. Joints may be open or fully connected or filled with grout, clay, etc. It is possible to test only one joint per specimen, the test is normally carried out with a constant vertical load in an undrained state.

3.3.1.2 Micro Forensic Analysis

Forensic Analysis is a unique methodology for determining the morphological characteristics of concrete. The general techniques used to observe concrete micro-structural behavior during the hydration process include Energy Dispersive Spectroscopy (EDS), X-ray Diffraction Analysis (XRD), and Scanning Electron Microscopy (SEM). These advanced techniques allow us to visualize the precise features of the concrete. The mineral data collected from MSS allow access to the distinctive behavior of concrete and the presence of small compounds inside the hardened concrete and also in aggregate.

3.3.1.3 Crushing Strength of Aggregates

This test is referred to as ASTM C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. It is commonly utilized as a measure of relative quality or fitness of different aggregate sources that have comparable mineral composition. The results do not automatically allow appropriate comparison between the composition, structure, or origin of the rocks. Given the various types of aggregate and their performance history for specified end-uses, assign special care to their performance. There is no consistent relation between percent loss for the same material for the ASTM Test Method C535, which has been established using this testing procedure.

3.3.1.4 Absorption and Specific Gravity of Aggregates

This test is referred to as ASTM C127 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate. This testing procedure includes specific gravity, relative density, and water absorption of aggregates. Specific gravity is a dimensionless quantity and is represented in terms of apparent specific gravity, Oven Dry (OD), and Saturated Surface Dry (SSD). After the aggregate is dried, the OD relative density is calculated. After soaking aggregate in water for a set period, SSD relative density and water absorption are calculated. This testing procedure is not designated for use of lightweight aggregate that conforms to C332 Group 1 specifications.

3.3.1.5 Size of Aggregates

This test is referred to as ASTM D448, Standard Classification for Sizes of Aggregate for Road and Bridge Construction. This classification establishes the designations of aggregate sizes and standard size ranges for mechanical sieve tests of rough aggregates and screening for use in the building and maintenance of various roads and bridges. Standard values are to be considered in SI units this standard does not contain any other measuring units, in the E11 specifications, the size of the sieve is identified by its standard nomenclature. In the parenthesis, the alternative designation is for the information only as is for the information only and is not a separate standard sieve size.

3.3.1.6 California Bearing Ratio Test

This test is referred to as ASTM D1883, Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. This testing technique is used for assessing the potential strength of subgrade, subbase, and base course, including the usage of recycled material for road and airfield pavement. The resulting CBR value for this test is a part of several flexible and rigid pavement design methodologies. The optimal water content of a given compaction effort may be determined at the CBR for applications in which the effect of optimum water content on CBR is minimal. Like in the case of cohesionless and coarse-grained materials or the design process, for the effect of different optimum water content. The minimum percentage of compaction is usually stated as specified dry unit weight.

3.3.1.7 Setting Time Test

This test can be further divided into three sections. For the initial setting time of mortar, ASTM C807 and ASTM 191, Standard Test Method for Time of Setting of Hydraulic Cement Mortar/Cement by Vicat Needle is followed. The setting time of the hydraulic cement mortar using the Vicat needle is determined by this testing method. For a final setting time, ASTM C403, Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance is followed. This test covers the concrete setting time in the form of penetration resistance and is effective for flowable concrete and grouts.

3.3.1.7 Compressive Strength of Concrete

This test is referred to as ASTM C31, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. The importance of compressive strength results must be interpreted with care using this test technique, as strength is not an essential or inherent attribute of concrete created from materials. The values obtained will depend on the specimen size and form, batching, mixing, sample methods, molding and production processes, and the circumstances of age, temperature, and humidity in cure.

3.3.1.8 Split Tensile Strength Test

This test is referred to as ASTM C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. The strength in splitting tensile is often more than direct tensile strength and less than bending strength (modulus of rupture). In designing structural lightweight concrete elements, the splitting tensile strength is utilized to assess the shear strength of the concrete and to measure the reinforcement development length. This test method involves the assessment of the tensile division strength of specimens of cylindrical concrete such as molded cylinders and drilled cores.

3.3.2 Field Testing

The optimized recipes in laboratory experiments will be evaluated under this section, where different field tests will be performed to know the actual behavior in prevailing real field conditions. A list summarizing the proposed field tests to extract the final recipe of RRR satisfying the key performance indicators of repair time, cost, and complexity.

- California bearing ratio test (ASTM D698 and AASHTO T99): To check the bearing capacity of soils/subgrades.
- Standard and modified proctor tests (ASTM D 1557): To check the compaction of soils.
- Dynamic cone penetration Test (ASTM D6851): To check the strength of underling strata.
- Plate loading test (ASTM D1195) To determine the settlement and bearing capacity of pavement.
- Braking Performance Test (ASTM E3188-19 and ASTM E3266-20): To know the aircraft braking performance.
- Pavement friction test (ASTM E1911) and Roughness Test (ASTM E1215): To check the surface frictional properties.
- Roughness Test (ASTM E1215): To check aircraft response to pavement roughness.
- Coefficient of thermal (AASHTO TP60): Coefficient of Thermal Expansion (CTE) pavements

CHAPTER 4

ANALYSIS AND DISCUSSION

4.1 Regression Modelling using Gene Expression Programming:

Due to COVID-19 Situations, we could not perform the experimental strategy explained in Chapter 3, so we are going to develop a novel GEP based predictive model for One-Day Compressive Strength for Rapid Hardening Concrete using GeneXproTools 5.0. To our best knowledge, no detailed study has been conducted that considered Gene Expression Programming for developing a predictive model for Rapid Hardening Concrete. To develop this model, we used Regression Analysis using GEP Algorithms, to predict the One-Day Compressive Strength of Rapid Hardening Concrete.

Regression is used to develop a valid ranking system, to assign probabilities to mode scores, which can be used directly to assess the risk of the financial and insurance applications and to classify prospective marketing operations, and evaluate the risk of disease. The GeneXproTools regression framework uses evolutionary algorithms to combine the canonical regression methods to estimate probabilities for each model score. And when we know the likelihood of an occurrence, we can also forecast categorically in terms of Yes/No or Positive/Negative, for that problem and so assess the confusion matrix for training and validation data. The unique GeneXproTools regression framework provides an extremely robust hybrid framework that fully creates evolutionary strong multivariate nonlinear models, that are supported by classical statistical modeling approaches as well.

We Start analysis in the Run panel to create the regression model after establishing an entirely new run. GeneXproTools enables us to track the evolutionary process by allowing us to access several model fitting charts, including various curve fitting charts, scatter plots, and residual plots. We may then halt the run, by clicking on the Stop button, without the worry of halting evolution prematurely, anytime we see fit because GeneXproTools allows us to further enhance the model using the best model thus far evolving with the seed method. To do so, we click the Run Panel to proceed on the Continue button for finding a better model. This methodology was followed using Gepsoft Tutorials (Gepsoft, n.d.).

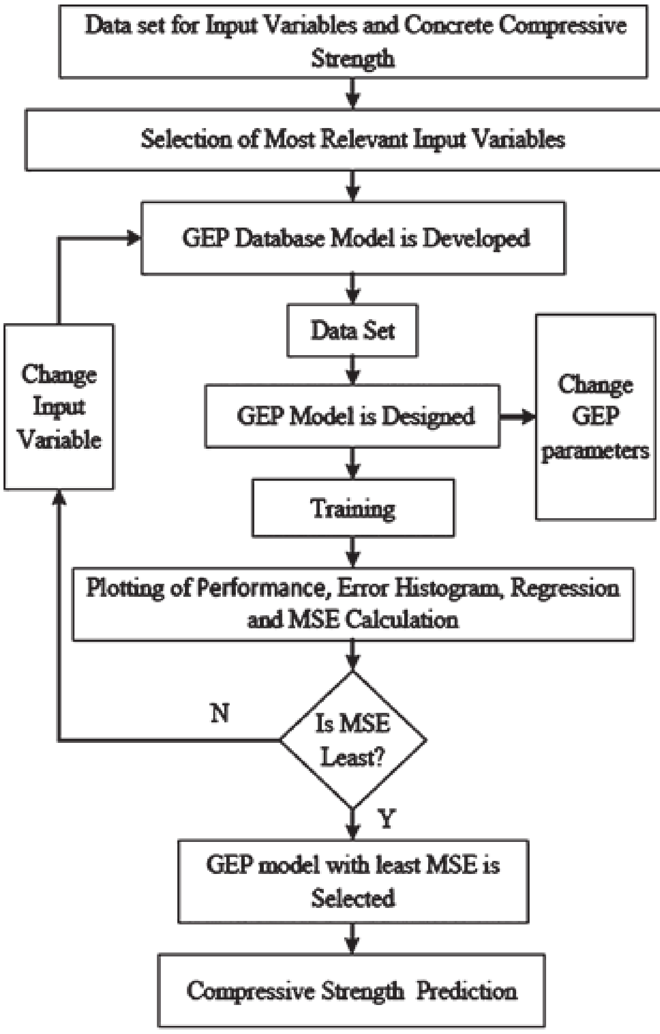


Figure 4.1: Flowchart of Analysis using Gene Expression Programming

4.2 Data

The very first step in developing the regression model was to find data points. This objective was achieved by doing an extensive literature review of the internationally published research studies. The database was gathered from Balaguru and Bhatt, 2000; Cangiano, Meda, and Plizzari, 2009; Domingo and Hirose, 2009; Engineering Notes India, 2017; Ghafoori et al., 2019; Li, Zhang, and Cao, 2014; Modeling Portland Blast-Furnace Slag Cement High-Performance Concrete, 2004; Najm and Balaguru, 2005; Naqash and Reddy, 2020; Popovics, Rajendran and Penko, 1987; Seehra, Gupta and Kumar, 1993; Wu et al., 2019. This database contained 115 different data points of 12 numerical variables and One-Day Compressive Strength values. Various researches show that the performance of the regression models depends upon the ratio of data points and the number of inputs. The ratio is important to check the relation between input variables and the resulting model and should be more than 5 for the ideal model (Frank and Todeschini, 1994).

In our case, the overall ratio of data points to input variables is 9, whereas each variable has 5 datapoints in the database, which fulfills the criteria set by researchers. The data was further divided into training data and validation data randomly by software. Table 1 shows the overview of the variables and their data points.

Sr No.	Description	Remarks
1	Data points	115
2	Total Variables	13
3	Categorical Variables	0
4	Numerical Variables	13
5	Training Data	74% (85)
6	Validating Data	26% (30)
7	Data Shuffling	Random

Table 1: Overview of the data used in the GEP Regression Analysis.

Next, we have the properties of input variables that are ordinary portland cement, magnesium phosphate cement, type 3 cement, high alumina cement, fine aggregate, coarse aggregate, water, super plasticizer, accelerator, retarder, silica fume, and fly ash. These inputs are named from d0 to d11, respectively. The results of this analysis are expected to be in the form of an equation in terms of these input variables and output to be the 1-day compressive strength which is termed as y.

No	Variable	Type	Unit	Min value	Max value	Notation	Frequency
1	OPC Cement	Predictor	(kg/m3)	68	660	d0	69
2	Magnesium Phosphate Cement	Predictor	(kg/m3)	345.5	1701	d1	25
3	Type 3 Cement	Predictor	(kg/m3)	335	522	d2	13
4	High Alumina Cement	Predictor	(kg/m3)	125.3	729	d3	22
5	Fine Aggregate	Predictor	(kg/m3)	186	1750	d4	100
6	Coarse Aggregate	Predictor	(kg/m3)	811	1513	d5	88
7	Water	Predictor	(kg/m3)	34.5	418.6	d6	111
8	HRWR	Predictor	(kg/m3)	1.65	131	d7	68
9	Accelerator	Predictor	(kg/m3)	7.71	12.5	d8	6
10	Retarder	Predictor	(kg/m3)	0.8	86.4	d9	77
11	Silica Fume	Predictor	(kg/m3)	13	59	d10	31
12	FlyAsh	Predictor	(kg/m3)	360	720	d11	6
13	1Day Compressive Strength	Response	Mpa	4.37	92.4	y	115

Table 2: Properties of Input Data Points.

As for the data points, Here is the complete Dataset that was collected from various research papers and used in the regression analysis using GEP algorithms.

OPC	MPC	Type 3 Cement	High Alumina Cement	Fine Aggregate	Coarse Aggregate	Water	HRWR	Accelerator	Retarder	Silica Fume	Flyash	One-day Compressive Strength
Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	Kg/m3	MPa
493.00	0.00	0.00	0.00	670.00	1119.00	168.00	8.90	0.00	2.50	0.00	0.00	30.60
476.00	0.00	0.00	0.00	661.00	1114.00	167.00	8.80	0.00	2.50	15.00	0.00	31.20
461.00	0.00	0.00	0.00	655.00	1113.00	167.00	7.80	0.00	2.50	29.00	0.00	29.00
448.00	0.00	0.00	0.00	652.00	1118.00	168.00	8.90	0.00	2.50	44.00	0.00	25.70
535.00	0.00	0.00	0.00	625.00	1114.00	166.00	8.60	0.00	2.70	0.00	0.00	28.10
519.00	0.00	0.00	0.00	618.00	1113.00	166.00	8.60	0.00	2.70	16.00	0.00	27.40
504.00	0.00	0.00	0.00	614.00	1116.00	167.00	9.70	0.00	2.70	32.00	0.00	38.30
485.00	0.00	0.00	0.00	604.00	1110.00	166.00	9.60	0.00	2.70	48.00	0.00	30.90
591.00	0.00	0.00	0.00	577.00	1118.00	166.00	10.60	0.00	3.00	0.00	0.00	29.20
575.00	0.00	0.00	0.00	572.00	1122.00	167.00	10.70	0.00	3.00	18.00	0.00	32.40
558.00	0.00	0.00	0.00	565.00	1123.00	167.00	11.90	0.00	3.00	36.00	0.00	41.30
539.00	0.00	0.00	0.00	558.00	1121.00	166.00	11.80	0.00	3.00	53.00	0.00	40.60
659.00	0.00	0.00	0.00	517.00	1122.00	165.00	14.50	0.00	3.30	0.00	0.00	34.20
641.00	0.00	0.00	0.00	512.00	1126.00	166.00	13.20	0.00	3.30	20.00	0.00	41.90
615.00	0.00	0.00	0.00	498.00	1114.00	164.00	13.10	0.00	3.30	39.00	0.00	40.40
600.00	0.00	0.00	0.00	496.00	1123.00	166.00	11.90	0.00	3.30	59.00	0.00	34.50
592.00	0.00	0.00	0.00	488.00	1107.00	163.00	11.70	0.00	3.30	59.00	0.00	47.40
635.00	0.00	0.00	0.00	507.00	1115.00	164.00	11.80	0.00	3.30	20.00	0.00	47.50
491.00	0.00	0.00	0.00	667.00	1114.00	167.00	7.80	0.00	2.50	0.00	0.00	29.40
515.00	0.00	0.00	0.00	614.00	1105.00	165.00	8.50	0.00	2.70	16.00	0.00	31.60
447.00	0.00	0.00	0.00	700.00	1163.00	166.00	7.10	0.00	2.20	0.00	0.00	21.20
434.00	0.00	0.00	0.00	696.00	1165.00	166.00	8.10	0.00	2.20	13.00	0.00	31.30
419.00	0.00	0.00	0.00	688.00	1160.00	165.00	7.10	0.00	2.20	27.00	0.00	28.10
408.00	0.00	0.00	0.00	687.00	1168.00	166.00	8.10	0.00	2.20	40.00	0.00	23.20
482.00	0.00	0.00	0.00	662.00	1158.00	164.00	6.70	0.00	2.40	0.00	0.00	23.80
473.00	0.00	0.00	0.00	664.00	1172.00	166.00	8.80	0.00	2.40	15.00	0.00	25.30
452.00	0.00	0.00	0.00	649.00	1155.00	164.00	6.70	0.00	2.40	29.00	0.00	31.50

434.00	0.00	0.00	0.00	640.00	1148.00	163.00	6.70	0.00	2.40	43.00	0.00	27.10
525.00	0.00	0.00	0.00	620.00	1156.00	163.00	8.40	0.00	2.60	0.00	0.00	32.20
512.00	0.00	0.00	0.00	618.00	1163.00	164.00	8.40	0.00	2.60	16.00	0.00	27.90
489.00	0.00	0.00	0.00	603.00	1146.00	162.00	7.30	0.00	2.60	31.00	0.00	30.10
475.00	0.00	0.00	0.00	599.00	1150.00	162.00	8.30	0.00	2.60	47.00	0.00	33.40
582.00	0.00	0.00	0.00	576.00	1165.00	163.00	10.50	0.00	2.90	0.00	0.00	39.00
556.00	0.00	0.00	0.00	561.00	1149.00	161.00	8.00	0.00	2.90	17.00	0.00	34.00
542.00	0.00	0.00	0.00	558.00	1155.00	162.00	8.10	0.00	2.90	35.00	0.00	30.30
533.00	0.00	0.00	0.00	559.00	1173.00	165.00	10.50	0.00	2.90	53.00	0.00	42.20
433.00	0.00	0.00	0.00	638.00	1144.00	162.00	7.60	0.00	2.40	43.00	0.00	32.70
484.00	0.00	0.00	0.00	597.00	1134.00	160.00	9.30	0.00	2.60	31.00	0.00	36.20
556.00	0.00	0.00	0.00	561.00	1149.00	161.00	8.00	0.00	2.90	17.00	0.00	36.50
538.00	0.00	0.00	0.00	554.00	1147.00	161.00	8.00	0.00	2.90	34.00	0.00	34.20
305.00	0.00	0.00	0.00	959.00	900.00	116.00	0.00	0.00	0.00	0.00	0.00	23.60
333.00	0.00	0.00	0.00	974.00	856.00	173.00	0.00	0.00	0.00	0.00	0.00	20.00
360.00	0.00	0.00	0.00	959.00	841.00	188.00	0.00	0.00	0.00	0.00	0.00	21.00
388.00	0.00	0.00	0.00	944.00	826.00	148.00	0.00	0.00	0.00	0.00	0.00	18.20
388.00	0.00	0.00	0.00	944.00	826.00	132.00	0.00	0.00	7.80	0.00	0.00	22.00
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	3.90	0.00	0.00	22.00
333.00	0.00	0.00	0.00	974.00	856.00	59.00	105.00	0.00	0.80	0.00	0.00	13.20
360.00	0.00	0.00	0.00	959.00	841.00	64.00	114.00	0.00	0.90	0.00	0.00	22.00
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	1.00	0.00	0.00	21.70
360.00	0.00	0.00	0.00	959.00	841.00	64.00	114.00	0.00	1.20	0.00	0.00	26.60
305.00	0.00	0.00	0.00	988.00	870.00	54.00	96.00	0.00	1.50	0.00	0.00	18.90
333.00	0.00	0.00	0.00	974.00	856.00	59.00	105.00	0.00	1.70	0.00	0.00	25.50
360.00	0.00	0.00	0.00	959.00	841.00	64.00	114.00	0.00	1.80	0.00	0.00	26.70
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	1.90	0.00	0.00	26.80
416.00	0.00	0.00	0.00	929.00	811.00	73.00	131.00	0.00	2.10	0.00	0.00	27.60
388.00	0.00	0.00	0.00	915.00	915.00	148.00	0.00	0.00	0.00	0.00	0.00	26.00
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	1.90	0.00	0.00	26.00
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	1.20	0.00	0.00	25.20
305.00	0.00	0.00	0.00	988.00	870.00	54.00	96.00	0.00	1.20	0.00	0.00	20.50

333.00	0.00	0.00	0.00	974.00	856.00	59.00	105.00	0.00	1.30	0.00	0.00	25.80
360.00	0.00	0.00	0.00	959.00	841.00	64.00	114.00	0.00	1.40	0.00	0.00	26.10
388.00	0.00	0.00	0.00	944.00	826.00	68.00	123.00	0.00	1.60	0.00	0.00	24.80
416.00	0.00	0.00	0.00	929.00	811.00	73.00	131.00	0.00	1.70	0.00	0.00	26.40
600.00	0.00	0.00	0.00	1750.00	0.00	162.00	16.00	0.00	0.00	0.00	0.00	80.00
660.00	0.00	0.00	0.00	1674.00	0.00	165.00	17.00	0.00	0.00	0.00	0.00	45.00
360.00	0.00	0.00	0.00	200.00	1428.00	144.00	8.00	0.00	0.00	0.00	0.00	15.00
340.00	0.00	0.00	0.00	186.00	1498.00	170.00	6.30	0.00	0.00	0.00	0.00	5.00
320.00	0.00	0.00	0.00	233.00	1513.00	192.00	4.00	0.00	0.00	0.00	0.00	5.00
0.00	1620.00	0.00	0.00	0.00	0.00	180.00	0.00	0.00	0.00	0.00	0.00	49.03
0.00	1656.00	0.00	0.00	0.00	0.00	144.00	0.00	0.00	0.00	0.00	0.00	83.66
0.00	1701.00	0.00	0.00	0.00	0.00	99.00	0.00	0.00	0.00	0.00	0.00	82.34
0.00	1620.00	0.00	0.00	0.00	0.00	180.00	0.00	0.00	0.00	0.00	0.00	45.10
0.00	1656.00	0.00	0.00	0.00	0.00	144.00	0.00	0.00	0.00	0.00	0.00	62.62
0.00	1701.00	0.00	0.00	0.00	0.00	99.00	0.00	0.00	0.00	0.00	0.00	61.38
0.00	863.64	0.00	0.00	863.64	0.00	86.36	0.00	0.00	17.27	0.00	0.00	42.17
0.00	575.76	0.00	0.00	1151.52	0.00	57.58	0.00	0.00	11.52	0.00	0.00	53.74
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	8.64	0.00	0.00	53.06
0.00	345.45	0.00	0.00	1381.82	0.00	34.55	0.00	0.00	6.91	0.00	0.00	24.71
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	8.64	0.00	0.00	34.33
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	8.64	0.00	0.00	37.07
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	21.59	0.00	0.00	32.27
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	43.18	0.00	0.00	30.79
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	64.77	0.00	0.00	30.21
0.00	431.82	0.00	0.00	1295.45	0.00	43.18	0.00	0.00	86.36	0.00	0.00	25.11
0.00	960.00	0.00	240.00	0.00	0.00	192.00	0.00	0.00	48.00	0.00	360.00	28.42
0.00	917.20	0.00	183.44	0.00	0.00	275.16	0.00	0.00	64.20	0.00	360.00	17.58
0.00	885.25	0.00	147.54	0.00	0.00	354.10	0.00	0.00	53.11	0.00	360.00	9.23
0.00	751.74	0.00	125.29	0.00	0.00	150.35	0.00	0.00	52.62	0.00	720.00	13.72
0.00	670.81	0.00	167.70	0.00	0.00	201.24	0.00	0.00	40.25	0.00	720.00	16.38
0.00	654.55	0.00	130.91	0.00	0.00	261.82	0.00	0.00	32.73	0.00	720.00	4.37
0.00	1232.88	0.00	246.58	0.00	0.00	246.58	0.00	0.00	73.97	0.00	0.00	39.30

0.00	1186.81	0.00	197.80	0.00	0.00	356.04	0.00	0.00	59.34	0.00	0.00	13.72
0.00	1046.51	0.00	261.63	0.00	0.00	418.60	0.00	0.00	73.26	0.00	0.00	15.50
0.00	0.00	0.00	729.48	583.59	875.38	211.55	0.00	0.00	0.00	0.00	0.00	91.00
0.00	0.00	0.00	551.72	662.07	993.10	193.10	0.00	0.00	0.00	0.00	0.00	84.20
0.00	0.00	0.00	440.37	704.59	1056.88	198.17	0.00	0.00	0.00	0.00	0.00	72.10
0.00	0.00	0.00	305.73	758.22	1137.32	198.73	0.00	0.00	0.00	0.00	0.00	42.80
0.00	0.00	0.00	705.88	592.94	889.41	211.76	0.00	0.00	0.00	0.00	0.00	92.40
0.00	0.00	0.00	551.72	662.08	993.12	193.10	0.00	0.00	0.00	0.00	0.00	80.70
0.00	0.00	0.00	440.37	704.59	1056.88	198.17	0.00	0.00	0.00	0.00	0.00	68.70
0.00	0.00	0.00	305.73	758.22	1137.32	198.73	0.00	0.00	0.00	0.00	0.00	37.20
0.00	0.00	0.00	268.16	772.29	1158.44	201.12	0.00	0.00	0.00	0.00	0.00	24.50
0.00	0.00	385.00	173.25	677.60	1016.40	0.00	0.00	0.00	0.00	0.00	0.00	21.00
0.00	0.00	385.00	173.25	677.60	1016.40	0.00	0.00	0.00	0.00	0.00	0.00	23.00
0.00	0.00	335.00	184.25	777.20	1165.80	0.00	0.00	0.00	0.00	0.00	0.00	16.50
0.00	0.00	335.00	184.25	777.20	1165.80	0.00	0.00	0.00	0.00	0.00	0.00	19.50
0.00	0.00	386.00	0.00	898.00	1097.00	135.10	1.65	7.71	0.00	0.00	0.00	40.00
0.00	0.00	388.00	0.00	802.00	1002.00	190.00	0.00	0.00	0.00	0.00	0.00	12.82
0.00	0.00	422.00	0.00	773.00	1002.00	190.00	0.00	0.00	0.00	0.00	0.00	14.80
0.00	0.00	463.00	0.00	737.00	1002.00	190.00	0.00	0.00	0.00	0.00	0.00	21.83
0.00	0.00	445.00	0.00	848.00	1037.00	155.75	1.65	8.90	0.00	0.00	0.00	56.00
0.00	0.00	522.00	0.00	618.00	1008.00	177.48	1.65	12.53	0.00	0.00	0.00	36.50
0.00	0.00	522.00	0.00	588.00	942.00	167.04	2.65	12.53	0.00	0.00	0.00	38.70
0.00	0.00	522.00	0.00	540.00	990.00	177.48	2.65	12.53	0.00	0.00	0.00	39.00
0.00	0.00	522.00	0.00	540.00	1032.00	167.04	2.65	12.53	0.00	0.00	0.00	37.00

Table 3: Input Data used for Regression Analysis using GEP Algorithms.

4.3 Importing Data to GeneXproTools:

The next stage is quite simple. We obtained student license GeneXproTools 5.0. A new project is started with Regression Analysis type and data source as Excel Database. There are a lot of other options available in the Run Category like classification, Function finding (regression), logistic regression, time series prediction, and logic synthesis.

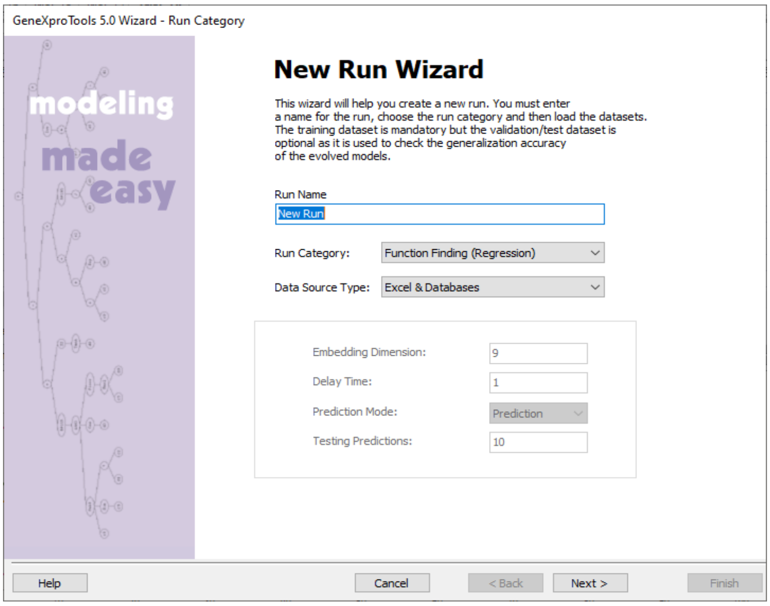


Figure 4.2: New Run Wizard in GeneXproTools

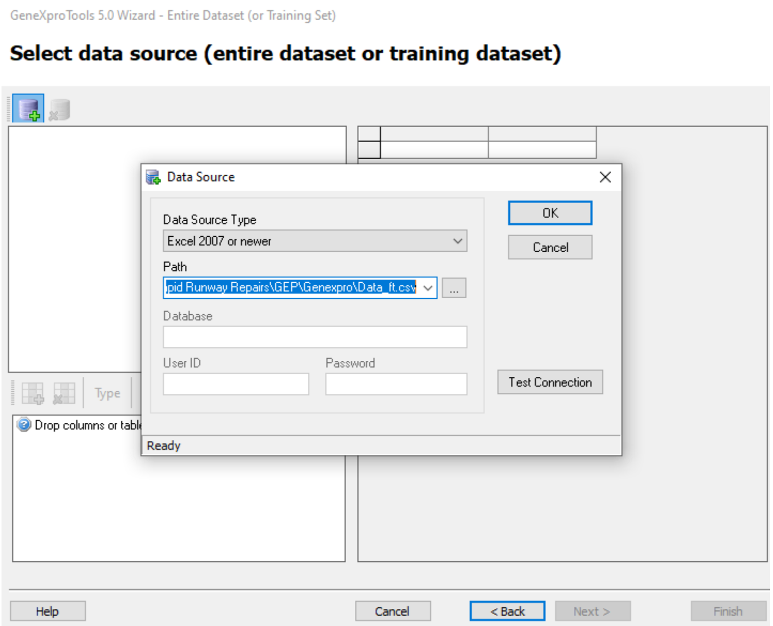


Figure 4.3: Selecting Data Wizard in GeneXproTools

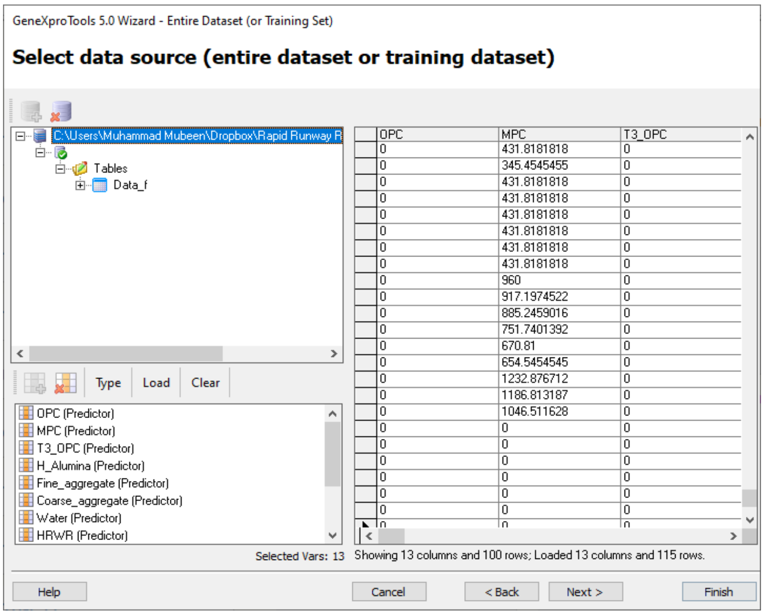
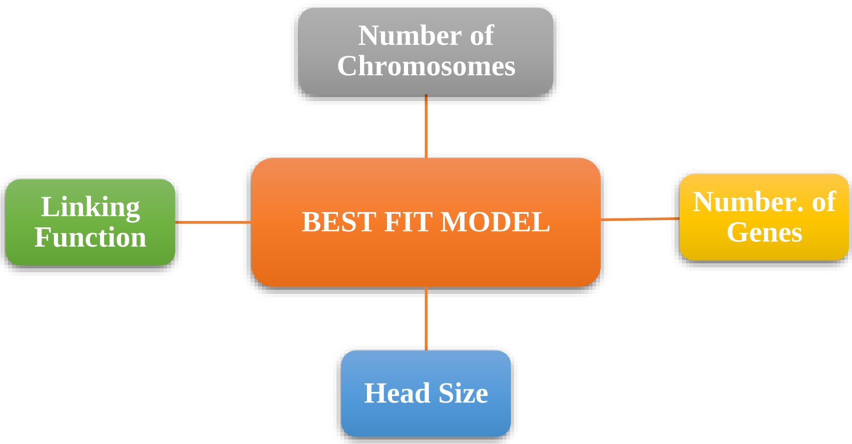


Figure 4.4: Importing Data Wizard in GeneXproTools

The imported data is then divided into training data and validation data automatically. As we have set the proportion of 75% and 25% data to be classified anonymously. In this case, it can be seen in Figure 4.4 that the system has selected 100 rows from a total of 115 rows of data as training data, but the percentage of data was changed from the system to 80 and 35 data points as training data and validation data points, respectively.

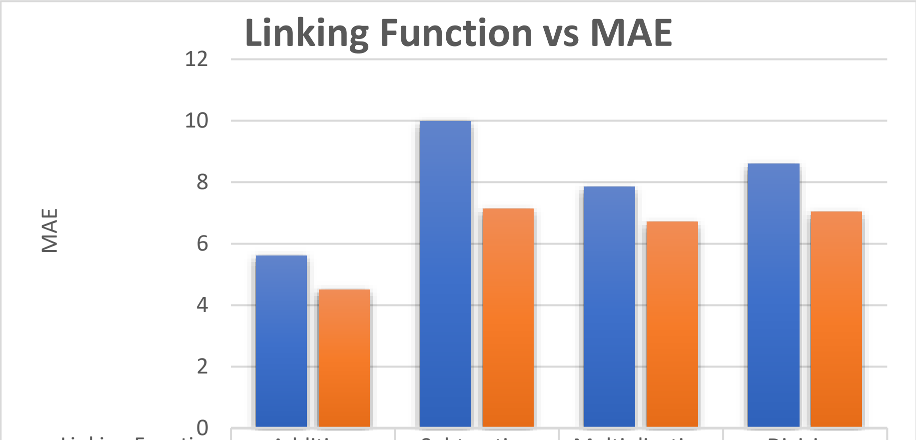
4.4 Model Parameters

In order to select the best model to predict One-Day Compressive Strength, a trial-and-error approach was used. Following four important features of Gene Expression Programming configuration were investigated with a wide range of combinations and one final set of parameters was developed to be used in the GEP regression analysis.



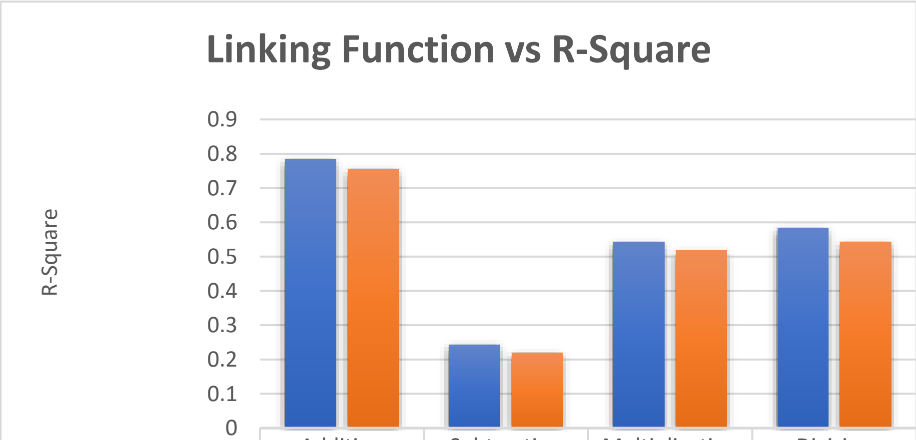
4.4.1 Linking Function

While keeping the other features constant, the best linking function was determined in terms of maximum Coefficient of Determination (R-square) and minimum Mean Absolute Error (MAE) in the model. This graph shows the performance of different GEP models with different linking functions. The maximum value of R-square and min MAE for the data and utilization of all input variables was obtained when the linking function was the addition.



Linking Function	Addition	Subtraction	Multiplication	Division
MAE Training	5.612775636	9.980056263	7.849805891	8.597509653
MAE Validation	4.508844116	7.137089995	6.714568617	7.035309077

Figure 4.5: Graph Between Linking Function and Mean Absolute Error.



Linking Function	Addition	Subtraction	Multiplication	Division
R-Square Training	0.784112056	0.243145977	0.542639571	0.584089685
R-Square Validation	0.754910474	0.218697349	0.517251888	0.542680586

Figure 4.6: Graph Between Linking Function and Coefficient of determination (R-Squared).

4.4.2 Number of Chromosomes

While keeping the other features constant, the best number of chromosomes was determined in terms of maximum Coefficient of Determination (R-square) and minimum Mean Absolute Error (MAE) in the model. This graph shows the performance of different GEP models with different numbers of chromosomes. The maximum value of R-square and min MAE for the data and utilization of all input variables was obtained when the number of chromosomes was 30.

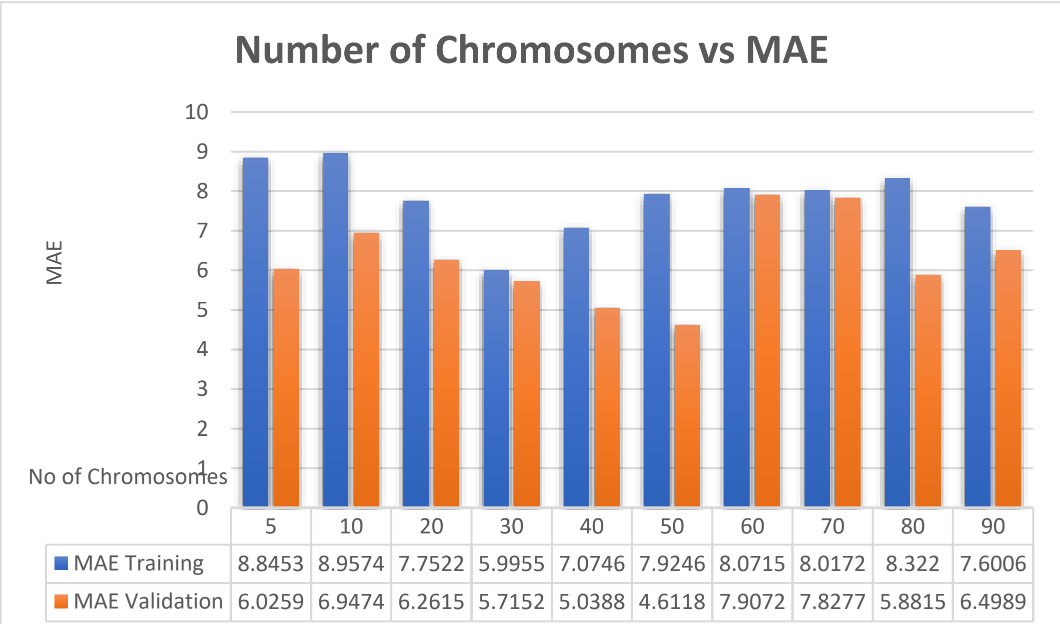


Figure 4.7: Graph Between Number of Chromosomes and Mean Absolute Error.

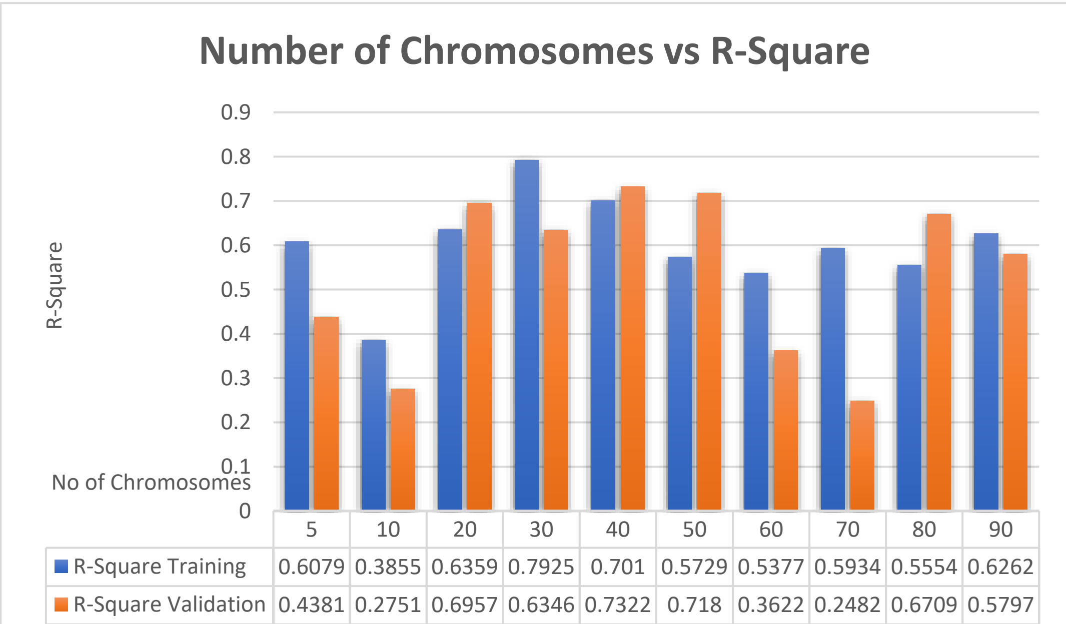
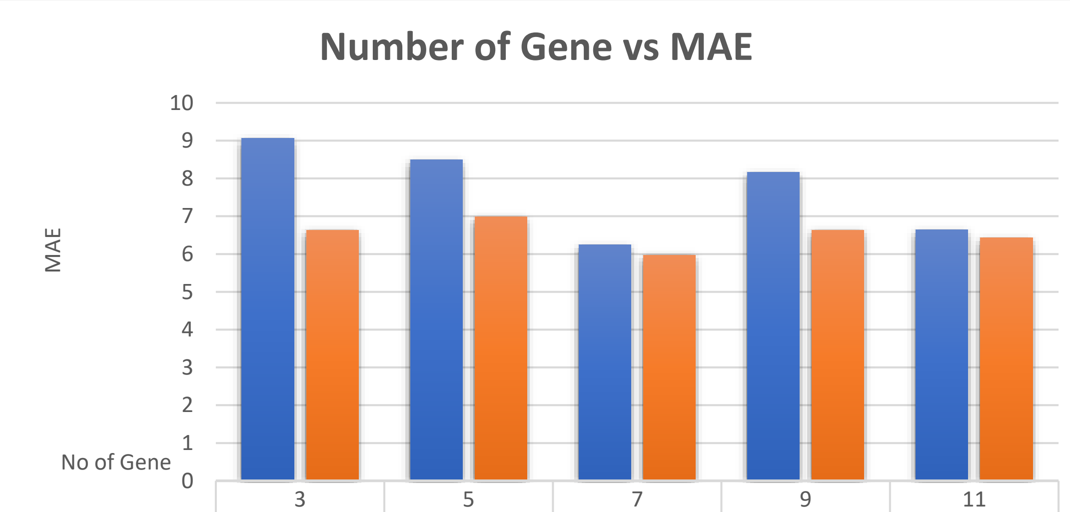


Figure 4.8: Graph Between Number of Chromosomes and Coefficient of determination (R-Squared).

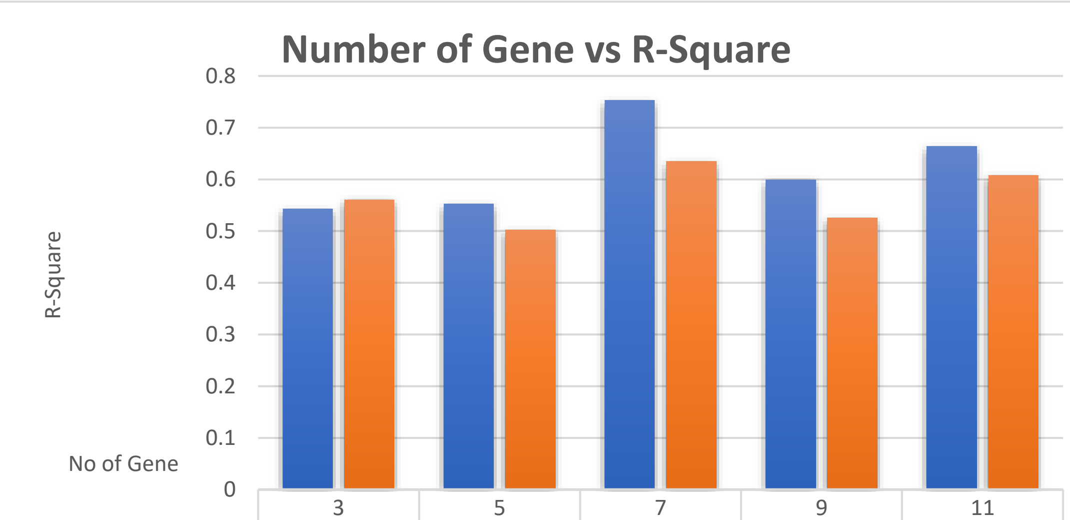
4.4.3 Number of Genes

While keeping the other features constant, the best number of Genes were determined in terms of maximum Coefficient of Determination (R-square) and minimum Mean Absolute Error (MAE) in the model. This graph shows the performance of different GEP models with different numbers of Genes. The maximum value of R-square and min MAE for the data and utilization of all input variables was obtained when the number of Genes was 7.



No of Gene	3	5	7	9	11
MAE Training	9.065410671	8.49563508	6.243896441	8.163407012	6.640563359
MAE Validation	6.631638116	6.981301957	5.972767799	6.634281402	6.42677398

Figure 4.9: Graph Between Number of Genes and Mean Absolute Error.



No of Gene	3	5	7	9	11
R-Square Training	0.542846144	0.552595172	0.75291926	0.599230667	0.663649582
R-Square Validation	0.560533476	0.502152617	0.634322192	0.525597783	0.607741845

Figure 4.10: Graph Between Number of Genes and Coefficient of determination (R-Squared).

4.4.4 Head Size

While keeping the other features constant, the best head size was determined in terms of maximum Coefficient of Determination (R-square) and minimum Mean Absolute Error (MAE) in the model. This graph shows the performance of different GEP models with different head sizes. The maximum value of R-square and min MAE for the data and utilization of all input variables was obtained when the head size was 13.

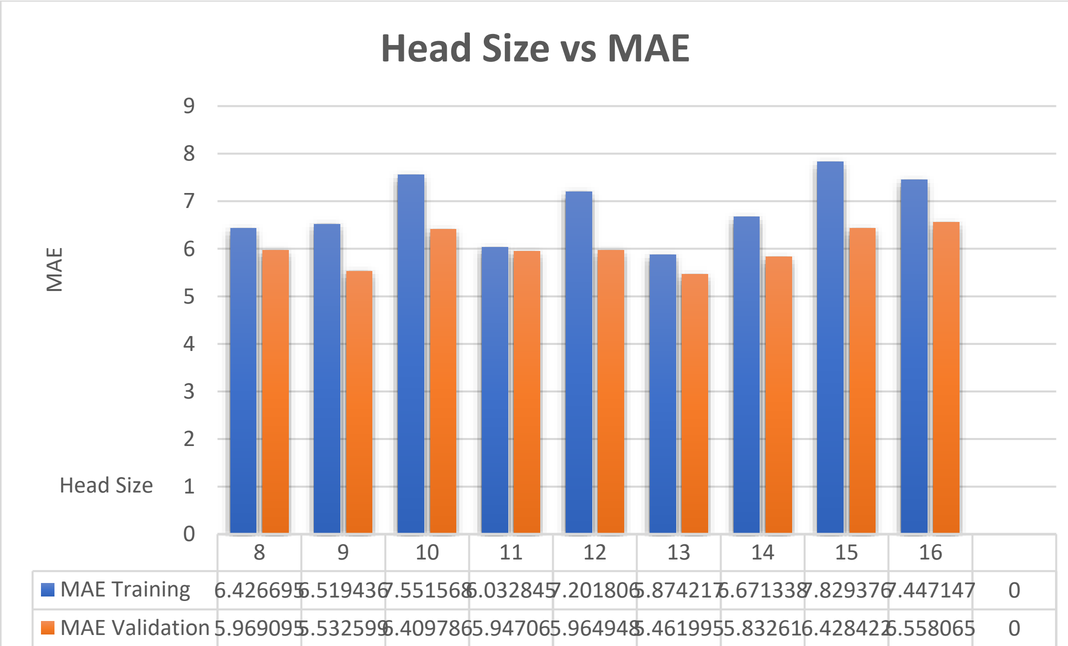


Figure 4.11: Graph Between Head Size and Mean Absolute Error.

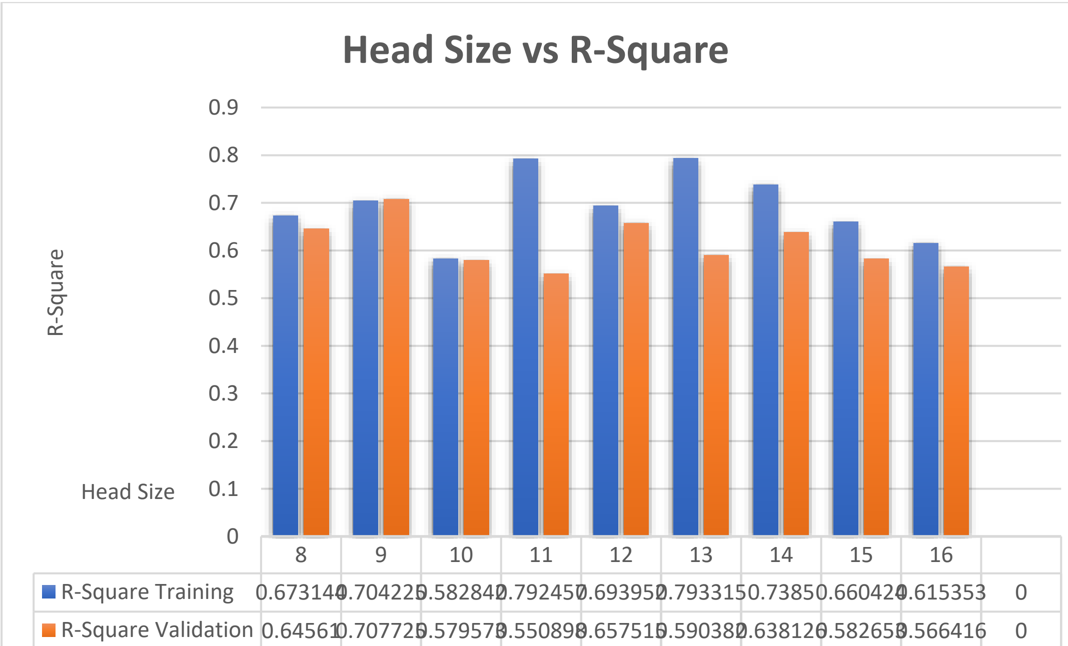


Figure 4.12: Graph Between Head Size and Coefficient of determination (R-Squared).

With the comparison of Head Size, our parameters for the best model are finalized and are shown in table 4. The number of chromosomes for the best model we selected 35; the number of genes was set to 7; head size was set to 13 and linking function was set as Addition with fitness function as Mean Absolute Error. Other properties were selected by GeneXproTools itself. The best results were observed at 14265th generation. The model was continued but the results deviated from desired values.

General Settings		
Chromosomes:		35
Genes:		07
Head Size:		13
Tail Size:		14
Dc Size:		14
Gene Size:		41
Linking Function:		Addition
Fitness Function:		MAE
Statistics		
Program Size		113
Literals		38
Up/Down Accuracy	(Training)	61.9%
Up/Down Error	(Training)	38.1%
Up/Down Hits	(Training)	52
Up/Down Errors	(Training)	32
Up/Down Accuracy	(Validation)	65.52%
Up/Down Error	(Validation)	34.48%
Up/Down Hits	(Validation)	19
Up/Down Errors	(Validation)	10

Table 4: General Setting and Properties of the GEP regression model.

4.5 Design Process

After assigning the optimized parameters to the new model, the next step is to run the analysis, the analysis is repeated unless desired fitness parameters are observed. Figure 4.13 shows the run panel of GeneXproTools. Simply, we develop a good GEP regression model with GeneXproTools. A text file or Excel/Database file is used to import data to the system, GeneXproTools displays run panel instantly. This is achievable because GeneXproTools features default pre-set settings and data pre-processing (using categorical variables and missing values), which perform extremely well with practically any situation. Later we learn how to pick some of the most basic settings to explore all the options in the application, but we may construct a highly intricate and accurate model with just one click.

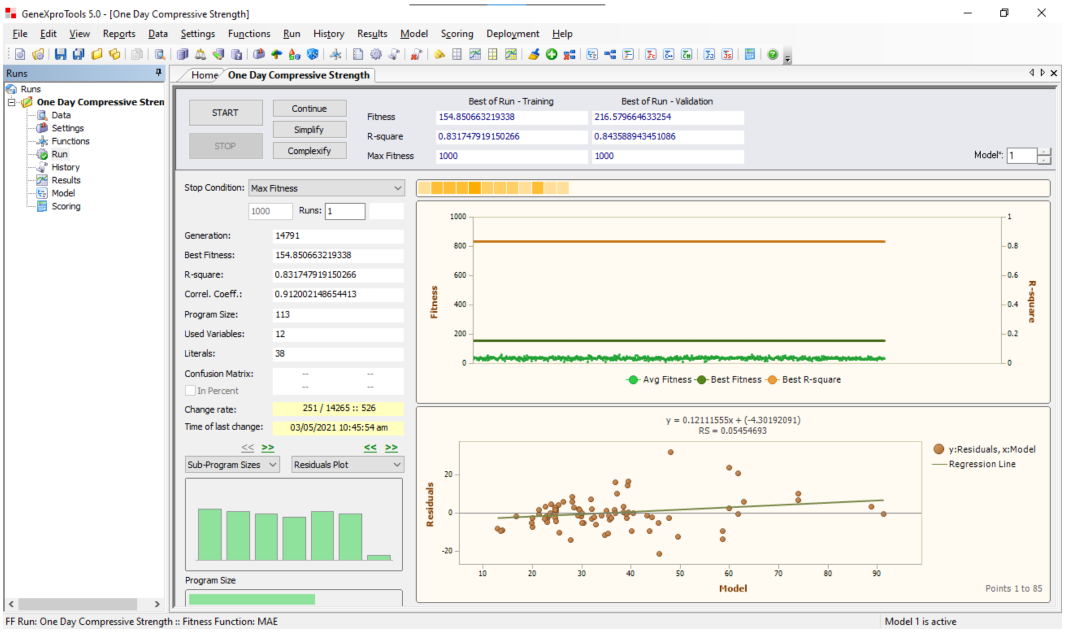


Figure 4.13: Run panel in GeneXproTools 5.0

The original design process can be evaluated and visualized by using the help of real-time monitoring of various charts for the model and different statistics that we can see in the Run panel, for example, various curve fitting chats, plots of the residuals, scatter plots, the coefficient of correlation and the R-square, while we create the model by learning its algorithm. The correlation between the target and the model output can be measured using either R-square or the correlation coefficient.

4.6 Fitness Measures for Regression

A good regression model leads to anticipated values around the data values observed. If there is no use of informative predictor variables, the mean model which employs the means for each estimated value will usually be utilized. Therefore, the fitness of the suggested regression model should be better than the fitness of the mean model. In Ordinary Least Squares (OLS) regression, three statistics are used to assess the model fitness:

- Root Mean Square Error
- Coefficient of Determination (R-Squared)
- Overall F-Test

These three fitness measures are based on two sums of squares, i.e., Sum of Square Error (SSE) and Sums of Squares Total (SST). SST shows the difference between the mean and the data whereas the SSE measures the difference between the expected values of the model and the data. Various combinations of both numbers offer various information on how the regression model is as compared to the mean model.

4.6.1 R-Squared

The square Pearson product-moment correlation coefficient is referred to as R-Squared Value. It is composed of a dimensionless index ranging from -1 to 1. GeneXproTools constantly updates the R-square in the evolutionary dynamic chart between the model output and the actual values and displays them on the Run Panel. For an individual model, the R_i Pearson product-moment correlation coefficient is assessed using equation 1

$$R^2 = \left(\frac{\sum_{i=1}^{n} (pi - \bar{p})(ai - \bar{a})}{\sqrt{\sum_{i=1}^{n} (pi - \bar{p})^2 \ \sum_{i=1}^{n} (ai - \bar{a})^2}} \right)^2 \quad (1)$$

4.6.2 Root Mean Square Error

The standard deviation of the residuals is defined as the Root Mean Square Error (RMSE) and can also be named as prediction errors. Residuals indicate how far away the data points are from the regression line and RMSE indicates how to spread out these residuals are. In other words, it shows how concentrated the data is around the best fit line. In climatology, forecasting, and regression analysis, root mean square error is frequently used to validate experimental results. Root Mean Square Error (RMSE) can be assessed using equation 2.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (ai - pi)^2} \quad (2)$$

4.6.3 Overall F-Test

F-test is used to evaluate the null hypothesis if every regression coefficient is zero versus the opposite of that, at least one regression model is not zero. Also, R-square equal to zero is the equivalent null hypothesis. A significant F-test indicates that the observed R-square values are reliable and are not the result of abnormalities. As a result, the F-test check if the relationship between the response variable and the set of functions is statistically consistent and can be beneficial when modeling or classification is a research objective.

There are many other fitness functions available in GeneXproTools like Pearson Correlation Coefficient. Mean Squared Error. Relative Absolute Error. Mean Absolute Error. Relative Squared Error. Root Relative Squared Error. Up/Down Accuracy. and Up/Down Error. For regression problems, we have access to a total of 49 built-in fitness functions in the fitness function tab of the settings panel. Most of them have multiple objectives, such as the use of different reference simple models, lower and upper limits for results of the models, the parsimony pressure, variable pressure, and more. In addition, we may develop and explore the solution space using our customized fitness functions. By selecting the Custom fitness editor button, we can open and write JavaScript the code for our fitness function.

4.7 Variable Importance

Variable importance analysis is a methodology for evaluating the relevance of input variables for complex interactions to improve the interpretability and computational efficiency of the GEP regression model. This process is significantly more complex when classifying issues with imbalanced datasets. It is an important task with the major objective of improving model interpretability, optimizing data storage, reducing computing costs, and providing a lower number of significant variables without any loss of explaining predictions.

In Figure 4.14, the variable importance of our model variables has been displayed. It shows that among all input variables, the amount of Magnesium Phosphate Cement and High Alumina Cement has a higher impact on the Compressive Strength i.e., 29.39% and 29.05% respectively, while the impact of Fine aggregate, Coarse aggregate, and HRWR is mild which is 9.9%, 10.6%, and 7.5% respectively. The remaining input variables like OPC, Type 3 Cement, Accelerator, Retarder, and Silica Fume have a low impact on the One-Day Compressive Strength of Rapid Hardening Concrete.

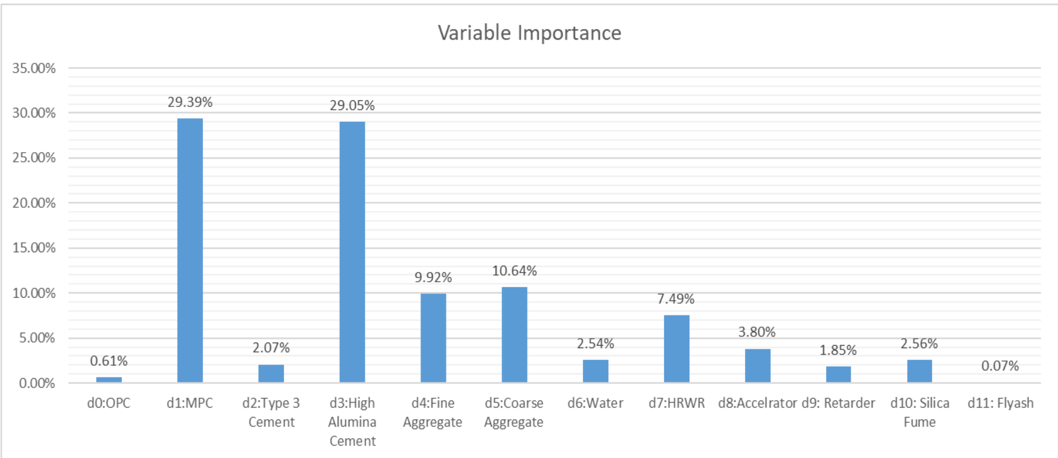


Figure 4.14: Variable importance of the model variables

4.8 Model Testing and Evaluation

We can assess the model by utilizing various charts and other fitness measures in the results panel like Root Mean Squared Error and Mean Absolute Error. We can also examine in the result panel how our model generalizes to a new dataset by assessing how well it performs in the validation run.

4.9 Results

After many trials on GeneXproTools, we finally got our best model. For training data, this model had R-Squared values of 0.832, Mean Absolute Error of 5.45, and Root Mean Square Error of 8.04. Similarly, for validation data, this model had R-Squared values of 0.844, Mean Absolute Error of 3.62, and Root Mean Square Error of 4.99. As for the comparative study, we compared our values with (Mousavi et al., 2012), and (Azim et al., 2020). Our R-Square and error values are sufficiently good, R-squared value above 0.8 is adequate (Gandomi et al., 2011).

Properties		1Day Strength of Our GEP Model	Mousavi et al., 2012	Azim et al., 2020
R-Squared	Training	0.832	0.907	0.83
	Validation	0.844	0.914	0.85
RMSE	Training	8.04	-	6.67
	Validation	4.99	-	4.57
MAE	Training	5.45	5.202	-
	Validation	3.62	5.197	-

Table 5: Comparison of Our Results with (Mousavi et al., 2012), and (Azim et al., 2020).

The results shown here are comparatively good and can be improved with experimental testing. This shows that our model is capable of producing accurate results in the pre-planning and predesigning phase of the study in Rapid Runway Repairs. With our GEP regression model, we can create a cost-effective and efficient mix design that could achieve sufficient compressive strength in very little time and effort. This code can also be developed in Excel VBA for everyday use in engineering design practices and other related fields.

Here are a few of the charts showing various properties of the model and target for both training data and validation data. The first ones are Curve Fitting Charts. We can see in these charts that the target plots are significantly close to the model plot. This shows the efficiency of the GEP regression model and the results will be precise and accurate. The model can be improved by increasing the number of data points and refining modeling parameters.

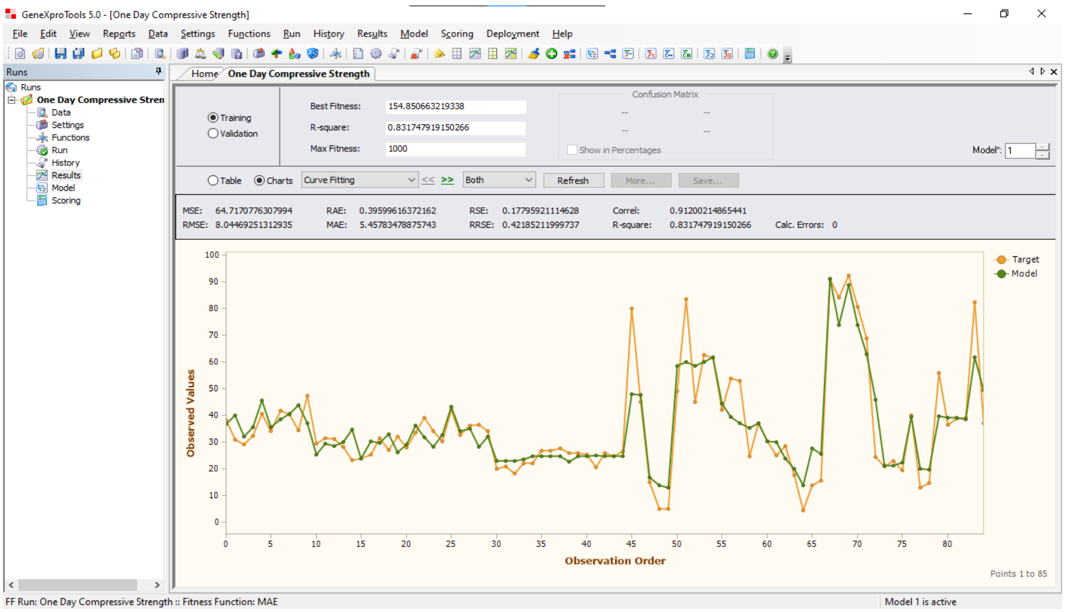


Figure 4.15: Results panel in GeneXproTools 5.0 displaying Curve fitting chart for Training Data

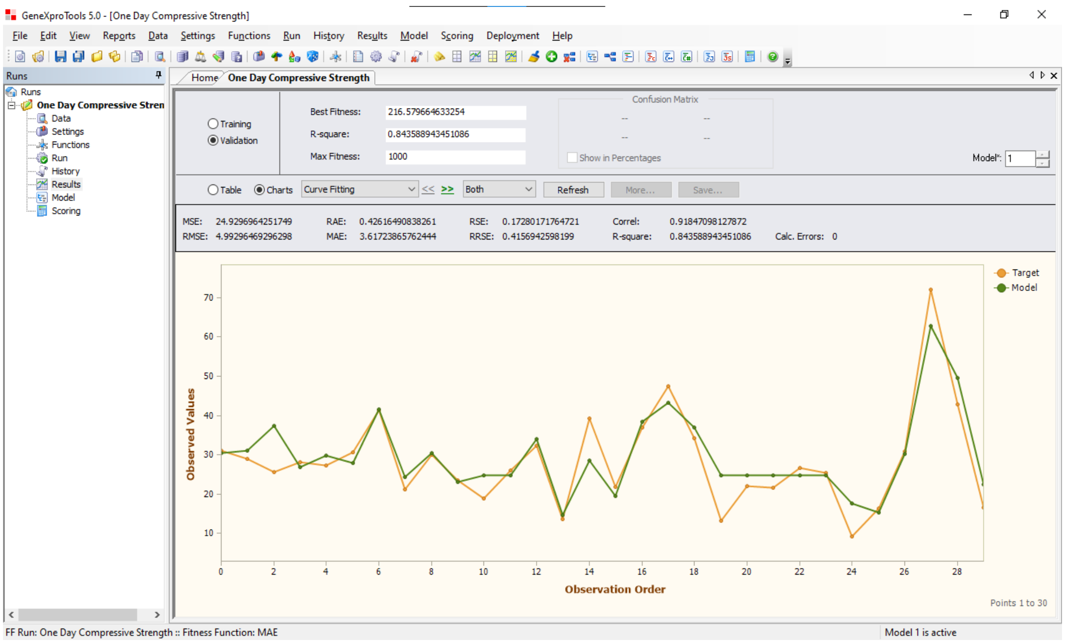


Figure 4.16: Curve fitting chart for Validation Data

Stacked Distribution charts are displayed here in which we can observe that the points are distributed unevenly as we move across the chart from left to right and are clustered on the left side. It shows that a variety of input model cases and a few of them have more data points than other e.g. the data points for OPC Concrete were more than other types of concrete and its strength development is different from other types of Rapid Hardening Concrete studied in GEP based Regression model.

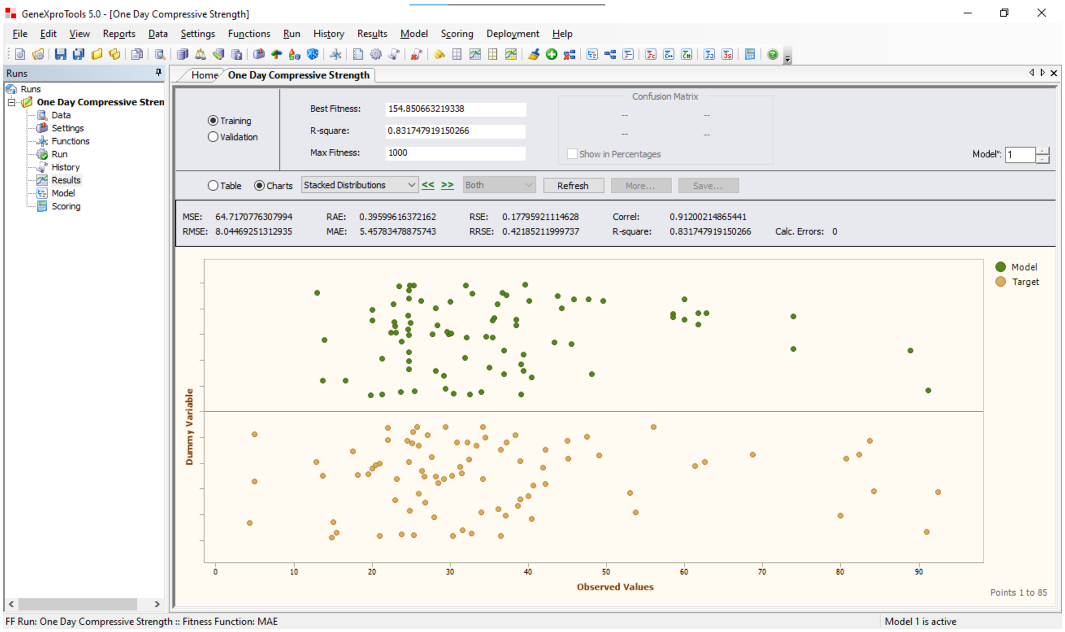


Figure 4.17: Stacked Distribution chart for Training Data

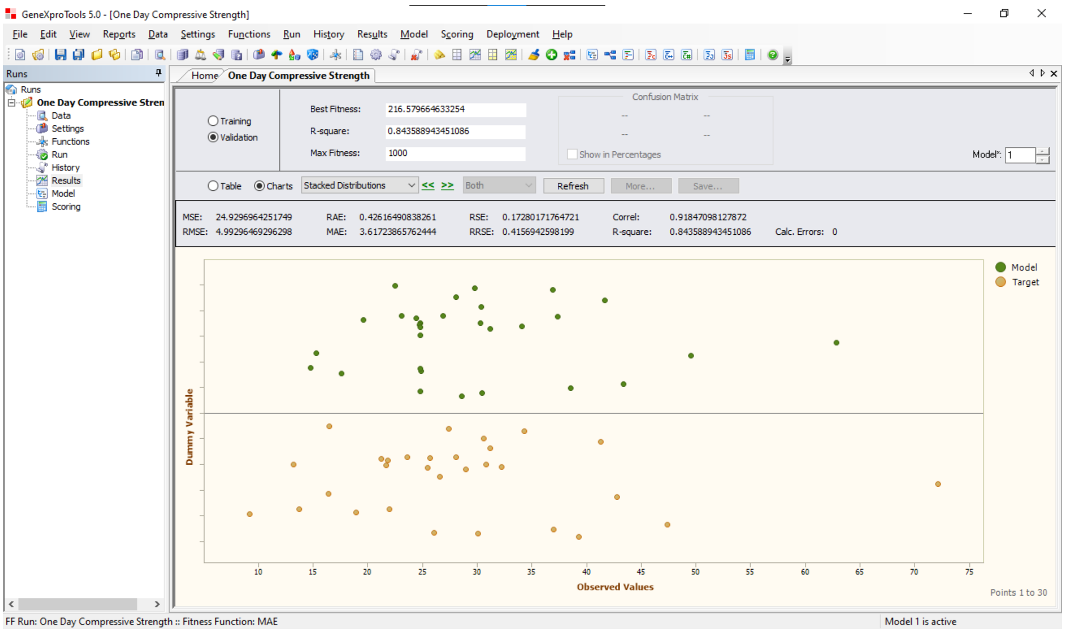


Figure 4.18: Stacked Distribution chart for Validation Data

Next is the Scatter plot of the GEP regression model. It has Modal values on X-Axis and Target values on Y-Axis. It is observable that the data points are located very close to the regression line and the line also has a slope of 1.0194 for Training Data and 1.0016 for validation data. It has been suggested by Golbraikh and Tropsha, 2002, that the slope of the regression line of a good regression model should be approximately equal to 1 which is true for our model.

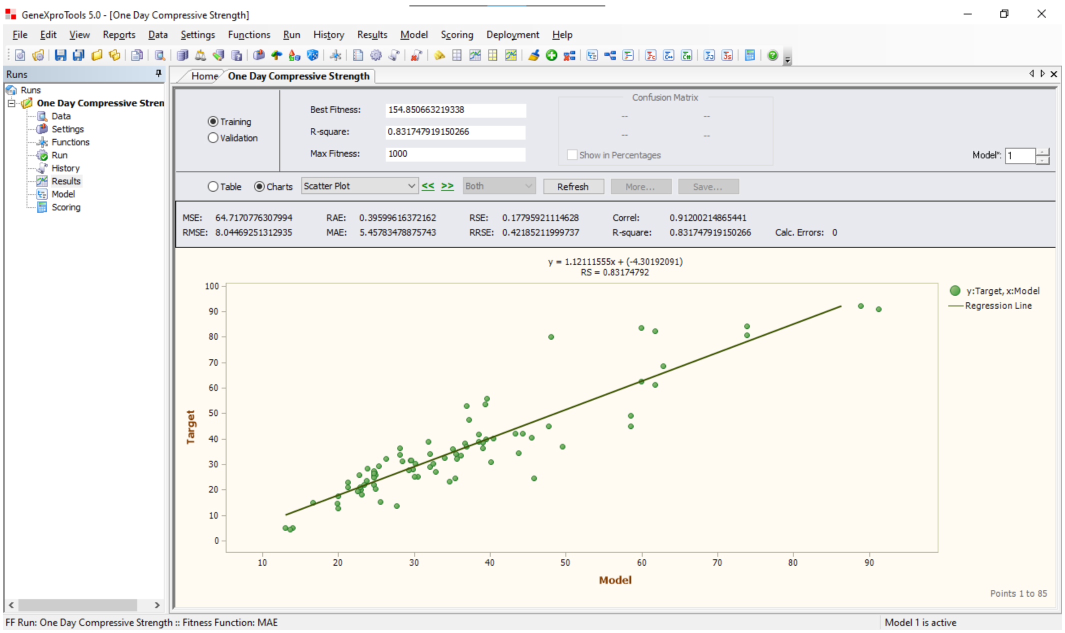


Figure 4.19: Scatter Plot for Training Data

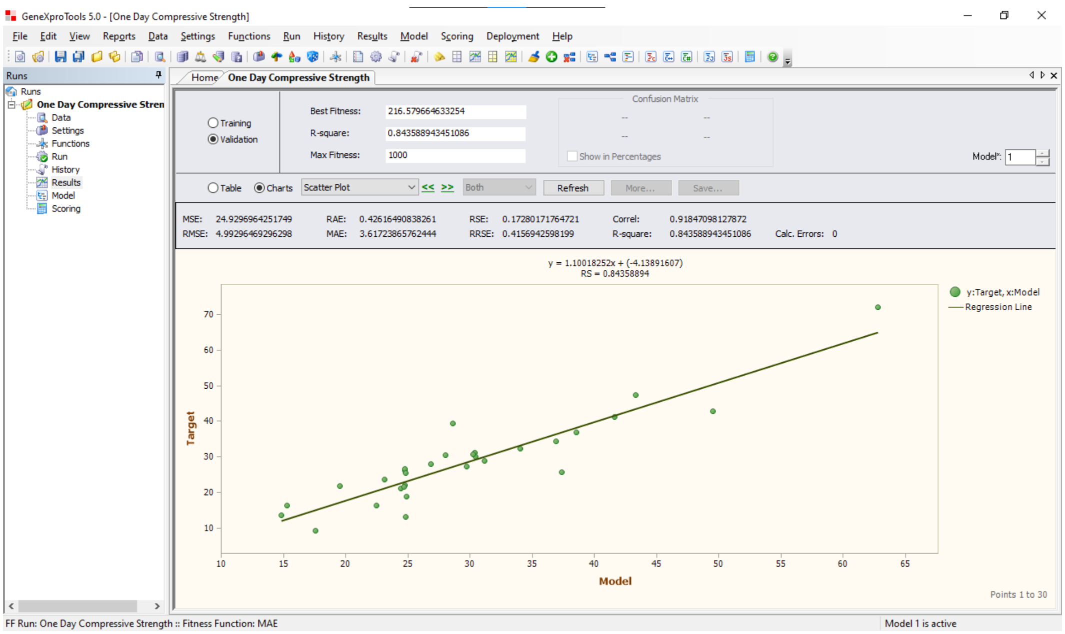


Figure 4.20: Scatter Plot for Validation Data

A residual plot is a representation of how far away the data points from the regression line are. Since the regression plot cannot show the comparison of individual errors in the data points, the residual plot shows that on a vertical scale. The highest residual value of training data is ~30 whereas for validation data it is ~12. We can also see that the values are spread across the horizontal axis for both training data and validation data. It shows that the data partitioning into training data and validation data is reliable.

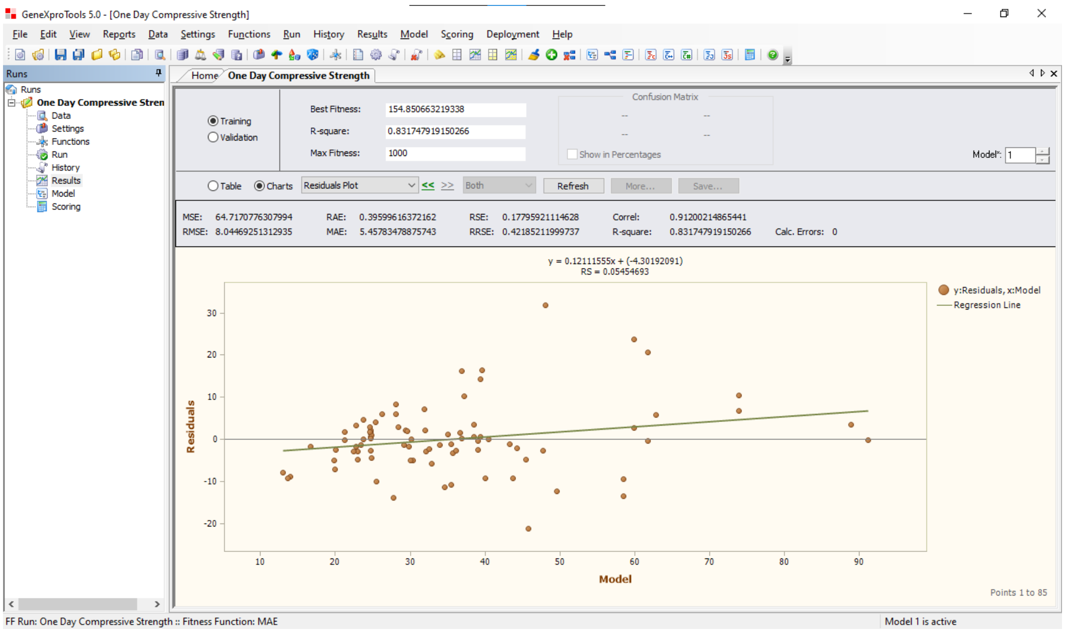


Figure 4.21: Residual plot for Training Data

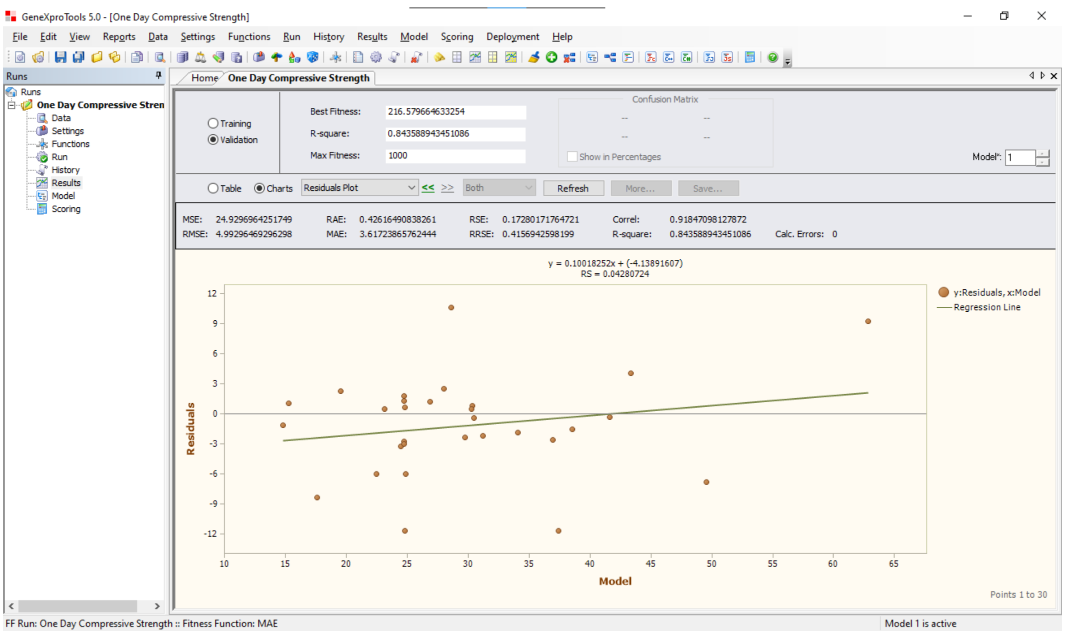


Figure 4.22: Residual plot for Validation Data

4.10 Generating Model Code

We can examine and observe the model code in our preferred programming language and also in the form of an expression tree and different charts in the model tab. GeneXproTools has 17 preprogrammed programming languages for the GEP regression models. The grammars in the system create code in several programming languages such as Ada, C, C++, C#, Excel VBA, Java, MATLAB, PHP, Python, R, VB.NET, etc. However, above all GeneXproTools also allows users to add their programming language, which can be simply developed using one of the existing grammars.

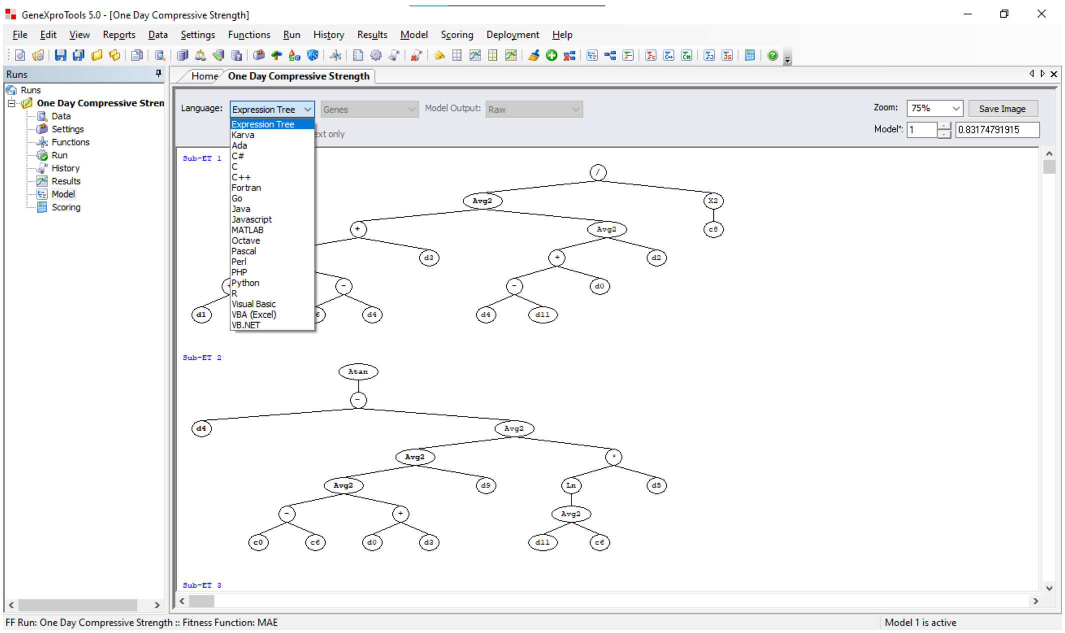


Figure 4.23: Model Panel used to generate expression tree diagram and code in various programming languages

4.11 Generating Model Equation using Expression Tree

As it was explained earlier, the expression trees are connected with linking function found using trial and error approach and all expression trees have nodes and stem that made up of various mathematical functions, variables, and constants. Figure 4.24, Figure 4.25, and Figure 4.26 show the expression tree of our GEP regression model, and their mathematical equations are represented from Eq. 3 to Eq. 11. The equations formed are in 7 parts as no. of genes were set as 7 in section 4.4.3, added due to linking function of Addition in section 4.4.1, to give a final compressive strength equation. This model helps in identifying the behavior of various RHC constituents and predicts the compressive strength as their amount changes in the mix design. With this prediction, Rapid Runway Repairs can be effectively improved when using the RHC Repair Method with a wide range of cementitious materials.

4.11.1 Sub Expression Trees

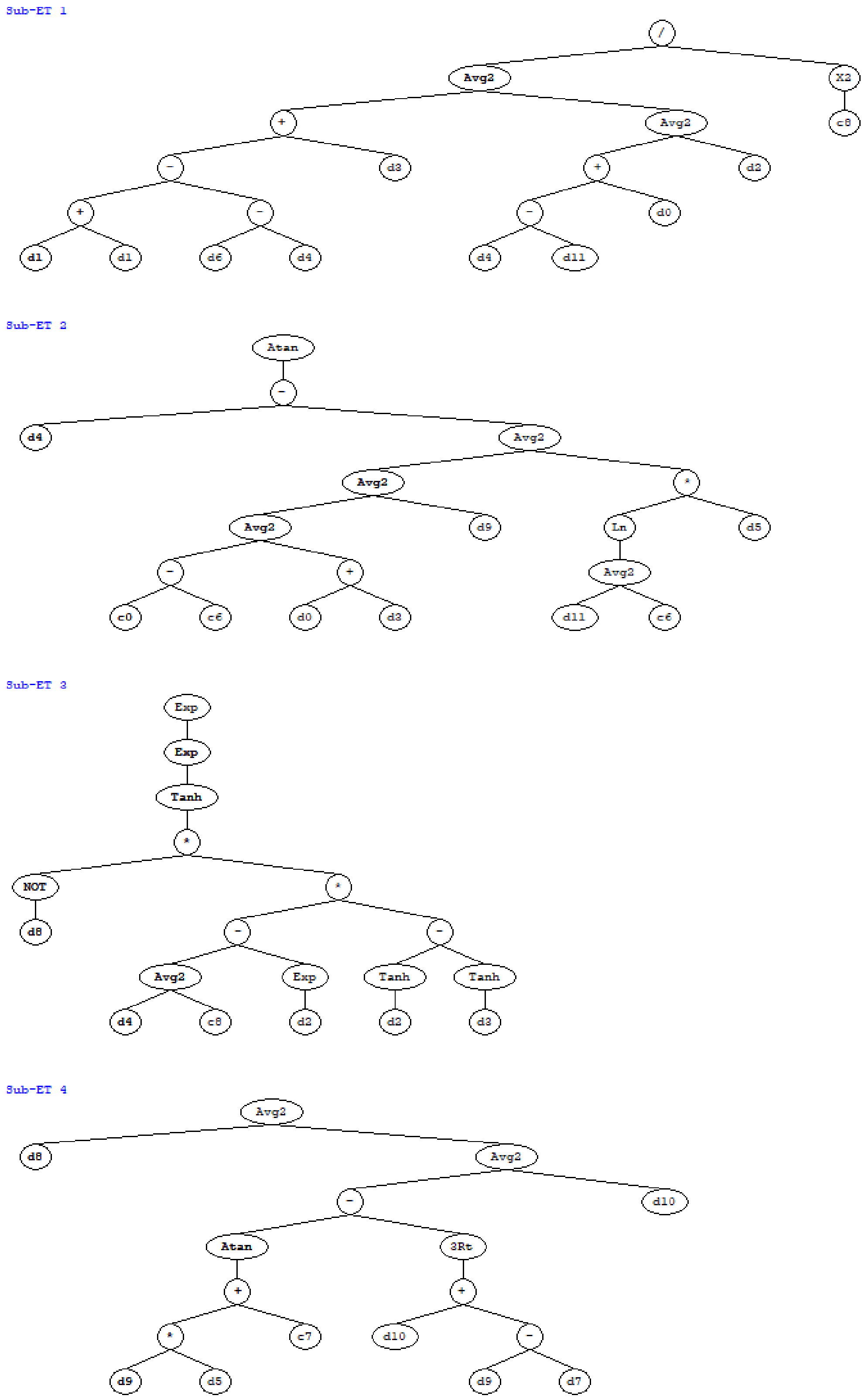


Figure 4.24: Sub Expression Trees #1 - #4

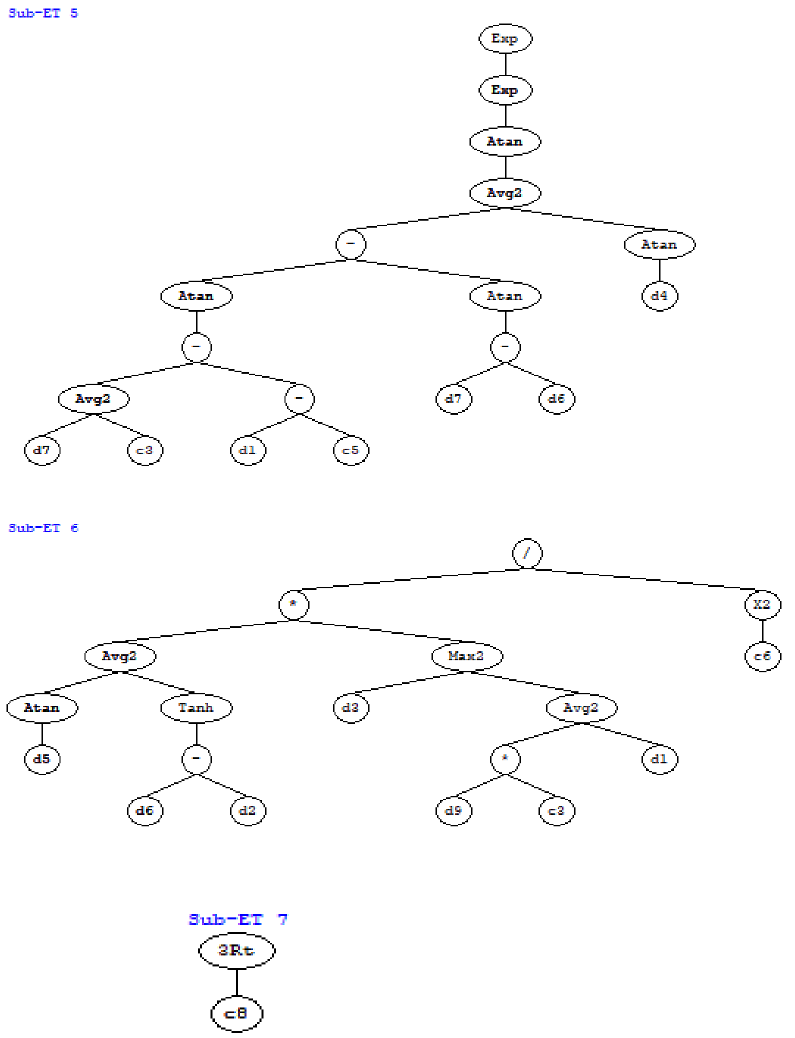


Figure 4.25: Sub Expression Trees #5 - #7

4.11.2 Equations:

$$f'c\ (MPa) = y1 + \tan^{-1} y2 + e^{y3} + y4 + e^{y5} + y6 + y7 \tag{4}$$

$$y1 = \frac{\left(\left(\left(d(1) + d(1)\right) - \left(d(6) - d(4)\right)\right) + d(3)\right) + \left(\frac{\left(\left(d(4) - d(11)\right) + d(0)\right) + d(2)}{2.0}\right)}{2 * G1C8^2} \tag{5}$$

$$y2 = d(4) - \left(\frac{\left(\frac{(G2C0 - G2C6) + \left(d(0) + d(3)\right)}{2.0}\right) + d(9)}{4.0}\right) + \left(ln\left(\left(\frac{d(11) + G2C6}{2.0}\right)\right) * \frac{d(5)}{2}\right) \tag{6}$$

$$y3 = e^{\tanh\left(\left(\left(1.0 - d(8)\right)\left(\left(\left(\frac{d(4)+G3C8}{2}.0\right) - e^{\left(d(2)\right)}\right)\left(\tanh\left(d(2)\right) - \tanh\left(d(3)\right)\right)\right)\right)\right)} \tag{7}$$

$$y4 = \frac{d(8)}{2} + \frac{\left(\tan^{-1}\left(\left(\left(d(9) * d(5)\right) + G4C7\right)\right) - \left(\sqrt[3]{\left|d(10) + \left(d(9) - d(7)\right)\right|}\right)\right) + d(10)}{4} \quad (8)$$

$$y5 = e^{\tan^{-1}\left(\frac{\left(\tan^{-1}\left(\left(\left(\frac{d(7)+G5C3}{2.0}\right)-\left(d(1)-G5C5\right)\right)\right)-\tan^{-1}\left(\left(d(7)-d(6)\right)\right)\right)+\tan^{-1}\left(d(4)\right)}{2.0}\right)} \quad (9)$$

$$y6 = \left(\frac{\tan^{-1}\left(d(5)\right) + \tanh\left(\left(d(6) - d(2)\right)\right)}{2.0 * G6C6^2}\right) * \max\left(d(3), \left(\frac{\left(d(9) * G6C3\right) + d(1)}{2.0}\right)\right) \quad (10)$$

$$y7 = \sqrt[3]{|G7C8|} \quad (11)$$

Where constants are:
G1C8 = 8.45322153386029; G2C0 = -5.18397981200598
G2C6 = 4.27228217413862; G3C8 = 158.834498123112
G4C7 = -51.7040633559211 G5C3 = 7.7206952312418
G5C5 = -8.47165661821192; G6C6 = -3.66130558183538
G6C3 = -11.0020787468171; G7C8 = 1.01168858912931

These are the constants predicted by GEP to balance the equations to fit for the compressive strength regression model.

4.11.3 MATLAB Code:

MATLAB code is as follows:

```
%------------------------------------------------------------------
% Regression model generated by GeneXproTools 5.0 on 03/05/2021
% GEP File: C:\Users\Muhammad Mubeen\Dropbox\Rapid Runway
Repairs\GEP\Genexpro\One_day_comressive_strength.gep
% Training Records:  85
% Validation Records:   30
% Fitness Function:  MAE
% Training Fitness:  154.850663219338
% Training R-square: 0.831747919150266
% Validation Fitness:   216.579664633254
% Validation R-square:  0.843588943451085
%------------------------------------------------------------------
function result = gepModel(d)

G1C8 = 8.45322153386029;
G2C0 = -5.18397981200598;
G2C6 = 4.27228217413862;
G3C8 = 158.834498123112;
G4C7 = -51.7040633559211;
G5C3 = 7.7206952312418;
G5C5 = -8.47165661821192;
G6C6 = -3.66130558183538;
G6C3 = -11.0020787468171;
G7C8 = 1.01168858912931;
```

```
d(1)=input('Amount of OPC=');
d(2)=input('Amount of MPC=');
d(3)=input('Amount of Type III Cement=');
d(4)=input('Amount of HAC=');
d(5)=input('Amount of Fine Aggregates=');
d(6)=input('Amount of Coarse Aggregates=');
d(7)=input('Amount of Water=');
d(8)=input('Amount of HRWR=');
d(9)=input('Amount of Accelerator=');
d(10)=input('Amount of Reducer=');
d(11)=input('Amount of Silica Fume=');
d(12)=input('Amount of Fly Ash=');

y = 0.0;

y = ((((((d(2)+d(2))-(d(7)-d(5)))+d(4))+((((d(5)-
d(12))+d(1))+d(3))/2.0))/2.0)/(G1C8^2));
y = y + atan((d(5)-((((((G2C0-G2C6)+(d(1)+d(4)))/2.0)+d(10))/2.0)
+(reallog(((d(12)+G2C6)/2.0))*d(6)))/2.0)));
y = y + exp(exp(tanh(((1.0-d(9))*((((d(5)+G3C8)/2.0)-
exp(d(3)))*(tanh(d(3))-tanh(d(4))))))));
y = y + ((d(9)+(((atan(((d(10)*d(6))+G4C7))-gep3Rt((d(11)+(d(10)-
d(8)))))+d(11))/2.0))/2.0);
y = y + exp(exp(atan((((atan((((d(8)+G5C3)/2.0)-(d(2)-G5C5)))-
atan((d(8)-d(7))))+atan(d(5)))/2.0))));
y = y + ((((atan(d(6))+tanh((d(7)-
d(3))))/2.0)*max(d(4),(((d(10)*G6C3)+d(2))/2.0)))/(G6C6^2));
y = y + gep3Rt(G7C8);

result = y;

function result = gep3Rt(x)
if (x < 0.0),
    result = -((-x)^(1.0/3.0));
else
    result = x^(1.0/3.0);
end
```

4.12 Summary

The technique has many benefits as we have the option to pause or stop the process at any interval and then we can take a good look at the changed model. For example, the mathematical representation of the evolved model can be analyzed, how did it perform during the validation, the necessary statistics can be evaluated and to check its accuracy the measures of fit can be used, it can be seen how it does on another test set, etc. Then the adjustment of few factors can be done, like, a changed fitness function can be chosen, expansion of function set can be done, a neutral gene can be added, pressure can be applied to make the structure simple, the training set used to refresh the model can be changed, etc. and these new conditions can be explored for further improvements. This process can be repeated for as long as one wants or there is complete satisfaction for the model.

CHAPTER 5

CONCLUSIONS

In this study, Gene Expression Programming (GEP), a tougher and more versatile version of Genetic Programming (GP), was used to predict One-Day Compressive Strength of Rapid Hardening Concrete mixes. For anticipating compressive strength, a precise and accurate empirical model was made in GeneXproTools 5. A huge array of data from previously published compressive strength test results of Rapid Hardening Concrete (RHC), were involved in developing the prediction model. The GEP model has the ability to predict the compressive strength of Rapid Hardening Concrete mixes. Among all input variables, the amount of Magnesium Phosphate Cement and High Alumina Cement have higher impact on the Compressive Strength i.e., 29.39% and 29.05% respectively, while the impact of Fine aggregate, Coarse aggregate and HRWR is moderate, which is 10.5%, 9.95% and 7.5% respectively. The remaining input variables like OPC, Type 3 Cement, Accelerator, Retarder and Silica Fume have low impact on the compressive strength. The validity of the model is tested for a part of test results beyond the training data domain using the validation dataset. In the validation phase, the model's efficiency for its intended application becomes evident that it can provide accurate strength estimation of Rapid Hardening Concrete mixes. In addition, the GEP prediction model also delivers efficient satisfaction of the conditions of different criteria involved in its external validation. The GEP model was also evaluated against other multivariable linear and nonlinear regression models available in the literature. As a result of nonlinearity in compressive strength behavior, the regression model created using GEP algorithms demonstrates better results as compared to other machine learning and regression models. The proposed model also integrates the effect of numerous significant factors representing the One-Day Compressive Strength behavior. Via the derived model, the One-Day Compressive Strength can be simply estimated from the RHC mixture's basic properties. As a result, the need for sophisticated and time-consuming laboratory tests can be omitted. This point is one of the main advantages of using the GEP model. The derived models can be used in the practical pre-planning phase and pre-design phase in terms of a wide range of cementitious materials, admixtures, and additives for Rapid Runway Repairs.

RECOMMENDATIONS

This research study can be used for the preliminary design of Rapid Hardening Concrete using General Purpose OPC, Type III OPC, MPC, High Alumina Cement to be used in Rapid Runway Repairs.

A similar study should be conducted with other design parameters like initial setting time, final setting time, slump, One-hour compressive strength, two-hour compressive strength, four-hour compressive strength, thermal conductivity, surface friction, etc.

Experimental studies can be conducted to evaluate the proposed Regression Model created using Gene Expression Programming Algorithms, for One-Day Compressive Strength of Rapid Hardening Concrete

The proposed model can be improved by adding and refining the database used in this study to make the GEP based regression model, and by changing the various modeling parameters in the analysis portion like linking functions, the number of heads, genes, chromosomes, etc.

A comparison of compressive strength and setting time models of different Machine Learning techniques to be performed in future studies (linear regression, non-linear regression, logistic regression, etc.).

In our model, GEP also established a relationship between the materials that were not in the input dataset at once, therefore, further studies can be conducted to study the accuracy of the relationship when different rapid hardening cements are combined.

CONSTRAINTS

Due to the reshuffling of groups consisting of day-scholars and hostelites, this project was assigned to us in January 2021, therefore the Time to complete our study was our main concern.

In such a short period, especially in the event of COVID Lockdown, Material could not be procured (local and imported both).

Due to COVID Lockdown, BS Students were not allowed to visit NUST for Lab testing, only PG Students were allowed in Labs

Data acquisition for GEP is also a difficult task in this study, to gather only relevant data out of hundreds of research papers. Also, there are no other Machine Learning studies available on Rapid Hardening Concrete.

As GEP works on natural algorithms, the results are always uncertain and unpredictable. It takes a lot of trials to get a desirable model using GEP. It took us more than two weeks to get this final model.

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