International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Nomograms for Strength Properties of HVFAC Concrete Roads

Raja Gopala Raju Veepuri

Research Scholar, Jawaharlal Nehru Technological University, Kakinada, AP, India

Abstract
High Volume Fly Ash Concrete (HVFAC) came into use due to tremendous demand due to urbanization & industrialization. Strength parameters of the HVFAC play a very important role in the design and construction of the concrete members, mainly the Concrete Roads.
The project aims to create Nomograms for the strength parameters of the HVFAC concrete for various water/binder ratios and different concrete ages. These Nomograms are helpful in finding out the unknown parameter by using the nomogram scales, which will be a very simple task even for unskilled labour. An Interesting Aspect of this project is the creation of Nomograms, which are automated and created with Python syntax using open-sourced PyNomo software.
It is worth noting that the equation-fit values and the nomogram values are found to be exactly the same. And they match industry norm values. Hence, these Nomograms are proven to be very accurate and are reliable for industry usage.

Key Words: Nomograms, HVFAC, High Volume Fly Ash Concrete, Compressive strength, Tensile strength, Flexural strength.

1. Introduction

1.1 Challenge of the Day

The concrete industry world is facing heavy demand due to fast-growing infrastructure development, industrialization & urbanization. While making OPC, natural minerals like limestone are depleting day by day, so it has become necessary to search for other pozzolanic materials.
The researchers found that various industrial waste materials like Fly ash, Ground Granulated Blast Furnace Slag, and Copper Slag have pozzolanic and cementitious properties.
Hence, the Need of the day is 'Usage of Waste materials as Resource materials', to preserve the natural minerals for future generations and to protect the globe from pollution, due to mining and heaps of factory wastages.

1.2 Concrete Roads

For the concrete roads used for the transportation of motor vehicles across the world, heavy quantities of cement concrete are required to construct the concrete roads. So, the usage of waste materials such as fly ash is strongly required in making cement-concrete, but not at the cost of concrete quality.
Concrete road is a structure made of cement concrete (PCC or RCC or PSC) surface course with underlying base (DLC- Dry Lean Concrete) and sub-base (GSB- Granular Sub-base or CTSB- Cement treated Sub-base) courses. The surface course PQC (Pavement Quality Concrete) is the stiffest layer which

provides the majority of the strength. The base or sub-base layers are less stiff than the top surface but make important contributions to drainage and frost protection.

1.3 High Volume Fly Ash Concrete (HVFAC)

Fly ash is well accepted as a pozzolanic material that can be used either as a component of blended Portland cements or as a mineral admixture in concrete.

Researches proved that with 50% or more cement replacement of fly ash, it is possible to achieve sustainable, high-performance concrete mixes that show high workability, high ultimate strength, and high durability. Such a type of concrete mix is termed High-Volume Fly Ash Concrete (HVFAC), as per the definition of Malhotra and Mehta [21].

1.3.1 Advantages of HVFAC Concrete against Normal Concrete

- Better surface finish.
- Better later strength gain between 28 days and 90 days or more.
- Easier flowability, pumpability.
- Slower setting time, which is useful for joint cutting and lower power-finishing times for road slabs.
- Better dimensional stability and crack-resistance from thermal shrinkage, and drying shrinkage.
- Better Electrical resistivity and Resistance to chloride ion penetration, after 3 to 6 months of curing, tested as per ASTM: C-202.
- Better durability to Reinforcement corrosion, Alkali-silica expansion and Sulphate attack.
- Best in cost economy due to lower material cost and high favourable lifecycle cost.

1.3.2 Fly Ash Concrete usage in real world

1. Seven-storied building at Park Lane Development at Halifax, Nova Scotia, Canada was built with 55% HVFAC.
2. The State of Wisconsin, USA has been using a 60% Class-F fly ash in concrete mix, since 1989.
3. Sydney construction market has used HVFAC for the Sydney Olympic facilities.
4. The building of National Council for Cement & Building Material (NCCBM) at Ballabhgarh, India still looks fine even after so many years.
5. A building slab with HVFA nano-concrete has been casted in AP, India, by the well-known author-cum-researchers, Mr. Kalidas and Mrs. Bhanumathidas. (Founders of Institute for Solid waste Research and Ecological balance) in 2013.

1.4 Details of Present Work

The present work consists of formulating Nomograms for the strength parameters i.e., Compressive strength, Tensile strength and Flexural strength at various concrete ages and with different water - binder (w/b) ratios, as mentioned below:

i. different Compressive strength parameters at different ages and different W/B ratios.
ii. different Tensile strength parameters at different ages and different W/B ratios.
iii. different Flexural strength parameters at different ages and different W/B ratios.
iv. different combinations of Compressive strengths, Tensile strengths & Flexural strengths at different ages and different W/B ratios.

2. Literature Survey

2.1 Nomography [10]

2.1.1 Terms related to Nomography

Nomogram

1. Nomogram (Nomograph or Alignment chart or Abac) is a diagram that calculates the result of a mathematical equation in a graphical way.
2. Nomogram consists of a set of numbered scales, usually one for each variable in the formula, arranged so that a straightedge can be placed across the known values to find the unknown value that solves the formula.
3. Since an equation in 2 variables is usually represented by a graph, most nomograms represent formulas that involve 3 or more variables.
4. Cost to produce the nomogram is a sheet of paper. They are fun to design and easy to use.
5. Generally, Nomograms can be prepared by geometrical means as well as by the use of determinants.

Isopleth (Index Line or Straight Edge)
An isopleth is a line that crosses the three scales at values that solve this equation, so if the values of any two of the variables are known, the third variable can be found very easily.

Pivot Line (Reference Line or Blank Scale)
A pivot line is a blank scale that serves as an intermediate turning point for the straight edge. For situations where the sum of more than three functions of single variables, a nomogram with pivot lines can be drawn.

2.1.2 Creation of Nomograms

Nomograms can be created in any of the following ways:

2.1.2.1 Traditional Methods:

1. Drawing geometrically with Scaling modulus (or scaling factor) on paper.
2. Drawing geometrically with the Scaling modulus in AutoCAD.
3. Drawing with the help of Determinants.

2.1.2.2 Non-traditional Method: Creating Nomograms with software programming.

Creating Nomograms with PyNomo Software [1]

1. PyNomo is a powerful open source and free software package for drawing precision Nomograms.
2. PyNomo directly supports 10 types of nomograms based simply on the format of the equation. For these types, there is no need to convert the equation to standard nomographic determinants or use geometric relations.
3. The output is in vector form in a PDF or EPS file. It can be enlarged for printing and still retain its sharpness. For additional artwork, the vector file can be edited in vector form in: Adobe Illustrator, Microsoft Visio, or LaTeX.
4. Text Editors designed for writing and building Python files are: Easy Eclipse and WordPad.

5. PyNomo script allows us to design nearly all nomograms with very little knowledge of algebra, determinants, and logarithms.
6. The underlying typesetting engine used by PyNomo is TeX language.
7. The program script will run in the environment called 'Integrated Development Environment' (IDLE).

2.2 Society for Conservation & Advancement of Nomography

History: In the olden days of ships of wood and men of iron, there was a simple solution to the problem of obtaining results from relationships in equation form. If the equations involved many variables, tables became unwieldy. An implicit solution, or 'working backwards', was almost unthinkable.
It was a task that was easy for professionals and hard for others. Today, pocket calculators and personal computers with spreadsheets are available, but the barrier still exists. Necessity required a simple, elegant solution. In such situations, graphics came to the rescue.

Nomograms: These graphical calculators were invented in 1880 by Philbert Maurice d'Ocagne (1862 – 1938) and used extensively for many years to provide engineers with fast graphical calculations of complicated formulas to a practical precision. Electronic calculators and computers have made nomograms much less common today, but when a quick & handy calculator for a particular formula is needed, then they will be beneficial.

Features: The nomograph is very easy to use. The scales are all labeled so unambiguously that getting the input wrong is impossible. Nomographs have the interesting property of solving equations both explicitly and implicitly. One can find any missing variable or combination of variables by 'working backwards'. That is, instead of proceeding with the first two variables and going left to right across the page, one can start with 'the answer' and work backwards.
Another virtue is the ability to do sensitivity analysis quickly by experimenting with different combinations of variables, holding some fixed and seeing the leeway, with the remaining ones.
Nomograph exactly fits Barbecue Joe's [5] definition of 'Good Engineering': "It's when someone else worked hard so that you don't have to!"

Limitations: The disadvantage of nomographs is that their precision depends upon the precision of the data considered for making the nomogram, which is quite obvious. In fact, the calculation is almost instantaneous, much like a "graphical table lookup." All we have to be able to do is visually interpolate a scale.

PyNomo: Leif Roschier created a tool that enables us to construct Nomographs programmatically. There is a complete system for creating nomographs, including automatically scaling the representation to maximize the allowable precision. The programming consists of adapting some standard Python scripts. It is available as open source, licensed under the GNU GPL Version 3. PyNomo is very valuable both as a rapid prototyping tool and as a means of producing final production-quality nomographs.

2.3 Mark Howison [7]

Nomograms graphically encode mathematical relationships between multiple parameters. Historically, nomograms enjoyed wide use as analog computation devices but fell out of favor with the advent of powerful calculators, computers, and related software.

Because nomograms have, in many cases, been made obsolete by technological advances in computing and modeling, there is a small amount of recent work on the topic. A Python library called PyNomo uses TeX to construct nomograms of 3-parameter functions from a user-programmed Python file.

Historically, nomograms have not only been constructed geometrically from mathematical equations [8], but also empirically from data [9].

2.4 Ron Doerfler [10]

Nomography, a forgotten art, is the graphical representation of mathematical relationships or laws (the Greek word for law is nomos). These graphs are variously called Nomograms, Nomographs, Alignment charts, and Abacs.

Today, the use of nomograms seems scattered in the quick and easy calculations of hit strength, etc., in strategic war gaming. There are many simple nomograms that exist for doctors to quickly assess attributes and probabilities.

Ron Doerfler [11]

PyNomo is a powerful & free software package for drawing precision Nomograms. It is written by Leif Roschier, and it provides a solution to one of the most vexing problems in nomography. The output is in vector form in a PDF or EPS file, so it can be enlarged for printing and still retain its sharpness. If additional artwork is desired, the vector file can be edited in vector form, say in Adobe Illustrator, Microsoft Visio, or LaTeX.

PyNomo directly supports 10 basic types of nomograms as shown in Table 1, based simply on the format of the equation, so for these types, there is no need to convert the equation to the standard nomographic determinant or use geometric relations.

Table 1: Types of Nomograms supported by PyNomo

Type	Form of Equation	Form of Nomogram
Type-1	$f_1(u_1) + f_2(u_2) + f_3(u_3) = 0$	3 Parallel Scales
Type-2	$f_1(u_1) = f_2(u_2) \times f_3(u_3)$ or $f_3(u_3) = f_1(u_1) \times f_2(u_2)$	N or Z
Type-3	$f_1(u_1) + f_2(u_2) + \ldots\ldots + f_n(u_n) = 0$	Compound Parallel Scales
	$f_1(u_1) + f_2(u_2) + f_3(u_3) = 0$ and $f_3(u_3) + f_4(u_4) + f_5(u_5) = 0$	3-Parallel Scales Compounded
Type-4	$\frac{f1(u1)}{f2(u2)} = \frac{f3(u3)}{f4(u4)}$	Proportion

Type	Form of Equation	Form of Nomogram
Type-5	$f_1(v) = f_2(x, u)$	Contour
Type-6	u = u	Ladder
Type-7	$\frac{1}{f3(u3)} = \frac{1}{f1(u1)} + \frac{1}{f2(u2)}$	Reciprocal / Angle
Type-8	y = f (u)	Single Scale
Type-9	Determinant	General Nomogram
Type-10	$f_1(u) + f_2(v)\, f_3(w) + f_4(x) = 0$	One Curved Line

2.5 J. Morasco, R. Doerfler & Roschier [12]

A nomogram is a graphical calculating device, a 2-dimensional diagram designed to allow the approximate graphical computation of a function. They provide engineers with fast graphical calculations of complicated formulas to practical precision. Each variable is marked along a scale, and a line drawn through the known scale, values will cross the value of the unknown variable.

Nomograms serve a dual purpose:

1. They allow fast computation answers in the form of unambiguous numbers.
2. And at the same time, they provide tremendous insight through the relationship of various scales, their labelling, limits, and gradations.

As the mathematician & computer scientist Richard Hamming remarked: ‘The purpose of computing is insight, not numbers.’

2.6 Applications of Nomograms:

- Ballistic calculations: prior to fire control systems, where time calculation is critical.
- Medical diagnostics.
- Chemistry & Chemical engineering: to encapsulate both physical relationships & empirical data for specific compounds.
- Machine shop calculations: to convert blueprint dimensions and perform calculations based on material dimensions & properties.
- Statistics: for complicated calculations of properties of distributions and operations research & design of acceptance tests for Quality control.
- Aeronautics: in cockpits of aircraft, as a navigation & flight control aid.
- Engineering works: Electrical design of filters & transmission lines, Mechanical calculations of stress & loading, Optical calculations, etc.
- Operations Research: to obtain results in a variety of optimization problems.
- In this project, Nomograms have been prepared for the strength parameters of fly ash concrete for the Road engineering field, which may be the first of its kind.

3. Pre-Project Phase of the Thesis

3.1 Experimental Data Used for the Thesis [27]

The values of Compressive strengths, Tensile strengths, and Flexural strengths at different w/b ratios and different ages were collected, for commencing this project. The collected data is presented in the following tables Table 2, Table 3, and Table 4.

Table 2: Compressive Strengths - for different W/B Ratios & Ages

S. No.	w/b Ratio	**Compressive Strength** (MPa)			
		28 days	**90 days**	**180 days**	**360 days**
	W/B	**C28**	**C90**	**C180**	**C360**
1	0.55	35.15	46.21	53.63	63.27
2	0.5	39.19	53.54	58.64	71.29
3	0.45	44.5	58.39	63.39	80.54
4	0.4	55.8	72.54	78.12	89.28
5	0.36	62.66	81.54	83.96	95.16
6	0.32	66.4	87.25	89.17	99.89
7	0.3	68.19	96.39	100.39	106.28
8	0.27	70.66	100.51	110.72	114.27

Table 3: Tensile Strengths - for different W/B Ratios & Ages

S. No.	w/b Ratio	**Tensile Strength** (MPa)			
		28 days	**90 days**	**180 days**	**360 days**
	W/B	**T28**	**T90**	**T180**	**T360**
1	0.55	4.18	5.51	6.44	7.31
2	0.5	4.9	6.55	7.24	8.42
3	0.45	5.76	7.26	7.53	9.05
4	0.4	6.99	9.13	9.95	10.19
5	0.36	7.6	10.17	10.69	11.21
6	0.32	8.44	10.39	11.36	12.18
7	0.3	8.14	12.98	11.39	12.92
8	0.27	9.08	12.54	12.67	13.67

Table 4: Flexural Strengths - for different W/B Ratios & Ages

S. No.	w/b Ratio	**Flexural Strength** (MPa)			
		28 days	**90 days**	**180 days**	**360 days**
	W/B	**F28**	**F90**	**F180**	**F360**
1	0.55	4.16	4.7	5.24	6.3
2	0.5	4.26	5.17	6.46	7.1
3	0.45	4.34	5.43	6.6	7.7
4	0.4	4.42	5.62	6.77	8.2

5	0.36	4.61	5.74	6.89	8.28
6	0.3	5.07	5.87	7.04	8.46
7	0.27	5.42	6.22	7.46	8.96

3.2 Variables Considered for Equation Formulation

Table 5: Variables in the Equations

Variable	Description of Variable	Unit
W/B	Water - Binder Ratio	Constant
C28	Compressive Strength at 28 days	MPa
C90	Compressive Strength at 90 days	MPa
C180	Compressive Strength at 180 days	MPa
C360	Compressive Strength at 360 days	MPa
T28	Tensile Strength at 28 days	MPa
T90	Tensile Strength at 90 days	MPa
T180	Tensile Strength at 180 days	MPa
T360	Tensile Strength at 360 days	MPa
F28	Flexural Strength at 28 days	MPa
F90	Flexural Strength at 90 days	MPa
F180	Flexural Strength at 180 days	MPa
F360	Flexural Strength at 360 days	MPa

3.3 Formulated Equations [28]

The author has created the following 62 model equations with 3 strength parameters, Concrete age & w/b ratio as variables for the project, based on Regression analysis.

3.3.1 Model Equations for Compressive Strengths, W/B & Age:

1	C28 versus W/B	C28 = 110 - 139 W/B
2	C90 vs. W/B	C90 = 154 - 201 W/B
3	C180 vs. W/B	C180 = 158 - 199 W/B
4	C360 vs. W/B	C360 = 159 - 174 W/B
5	C90 vs. C28	C90 = -4.89 + 1.44 C28
6	C180 vs. C28	C180 = 1.78 + 1.41 C28
7	C360 vs. C28	C360 = 22.1 + 1.23 C28
8	C90 vs. C28, W/B	C90 = 94.8 + 0.538 C28 - 127 W/B
9	C180 vs. C90, C28	C180 = 9.53 + 1.58 C90 - 0.863 C28
10	C180 vs. C90, C28, W/B	C180 = 10.5 + 1.58 C90 - 0.868 C28 - 1.3 W/B
11	C360 vs. C180, C90, C28	C360 = 21.2 + 0.506 C180 + 0.015 C90 + 0.493 C28
12	C360 vs. C180, C90, C28, W/B	C360= 160 + 0.499 C180 - 0.464 C90 - 0.08 C28 - 179 W/B

3.3.2 Model Equations for Tensile Strengths, W/B & Age:

1	T28 vs. W/B	T28 = 13.8 - 17.6 W/B
2	T90 vs. W/B	T90 = 19.8 - 26.7 W/B
3	T180 vs. W/B	T180 = 18.6 - 22.6 W/B
4	T360 vs. W/B	T360 = 19.5 - 22.6 W/B
5	T90 vs. T28	T90 = -0.78 + 1.47 T28
6	T180 vs. T28	T180 = 0.806 + 1.29 T28
7	T360 vs. T28	T360 = 1.96 + 1.26 T28
8	T90 vs. T28, W/B	T90 = 46.7 - 1.95 T28 - 60.9 W/B
9	T180 vs. T90, T28	T180 = 0.932 + 0.163 T90 + 1.05 T28
10	T180 vs. T90, T28, W/B	T180 = -29.6 + 0.636 T90 + 2.57 T28 + 39.7 W/B
11	T360 vs. T180, T90, T28	T360 = 2.37 - 0.083 T180 + 0.434 T90 + 0.726 T28
12	T360 vs. T180, T90, T28, W/B	T360= 47.8 + 1.03 T180 - 0.468 T90 - 2.77 T28 - 60.4 W/B

3.3.3 Model Equations for Flexural Strengths, W/B & Age:

1	F28 vs. W/B	F28 = 6.32 - 4.22 W/B
2	F90 vs. W/B	F90 = 7.44 - 4.70 W/B
3	F180 vs. W/B	F180 = 9.10 - 6.10 W/B
4	F360 vs. W/B	F360 = 11.3 - 8.49 W/B
5	F90 vs. F28	F90 = 1.20 + 0.941 F28
6	F180 vs. F28	F180 = 1.23 + 1.17 F28
7	F360 vs. F28	F360 = 0.37 + 1.62 F28
8	F90 vs. F28, W/B	F90 = 8.58 - 0.182 F28 - 5.46 W/B
9	F180 vs. F90, F28	F180 = -0.869 + 1.75 F90 - 0.473 F28
10	F180 vs. F90, F28, W/B	F180 = -7.81 + 2.41 F90 - 0.157 F28 + 4.56 W/B
11	F360 vs. F180, F90, F28	F360 = -2.48 - 0.357 F180 + 2.74 F90 - 0.538 F28
12	F360 vs. F180, F90, F28, W/B	F360= 0.9 - 0.227 F180 + 2.21 F90 - 0.625 F28 - 2.14 W/B

3.3.4 Model Equations for the Combined Parameters:

1	T28 vs. C28	T28 = -0.064 + 0.126 C28
2	T90 vs. C28	T90 = -1.18 + 0.190 C28
3	T180 vs. C28	T180 = 0.641 + 0.163 C28
4	T360 vs. C28	T360 = 1.80 + 0.159 C28
5	T90 vs. C90	T90 = -0.626 + 0.133 C90
6	T180 vs. C180	T180 = 0.859 + 0.110 C180
7	T360 vs. C360	T360 = -0.973 + 0.129 C360
8	T28 vs. F28	T28 = -9.47 + 3.50 F28
9	T90 vs. F90	T90 = -20.9 + 5.43 F90
10	T180 vs. F180	T180 = -9.95 + 2.92 F180

11	T360 vs. F360	T360 = -8.72 + 2.43 F360
12	F28 vs. C28	F28 = 3.03 + 0.0294 C28
13	F90 vs. C28	F90 = 3.77 + 0.0329 C28
14	F180 vs. C28	F180 = 4.39 + 0.0419 C28
15	F360 vs. C28	F360 = 4.63 + 0.0600 C28
16	F90 vs. C90	F90 = 3.93 + 0.0221 C90
17	F180 vs. C180	F180 = 4.51 + 0.0271 C180
18	F360 vs. C360	F360 = 3.66 + 0.0474 C360
19	T28 vs. C28, F28	T28 = -1.25 + 0.112 C28 + 0.413 F28
20	T28 vs. C28, F28, W/B	T28 = 9.76 + 0.0433 C28 - 0.136 F28 - 11.9 W/B
21	T90 vs. C90, F90	T90 = 2.25 + 0.154 C90 - 0.771 F90
22	T90 vs. C90, F90, W/B	T90 = 31.1 + 0.0648 C90 - 2.79 F90 - 27.7 W/B
23	T180 vs. C180, F180	T180 = -0.83 + 0.097 C180 + 0.398 F180
24	T180 vs. C180, F180, W/B	T180 = 8.0 + 0.0629 C180 + 0.043 F180 - 9.3 W/B
25	T360 vs. C360, F360	T360 = 1.83 + 0.162 C360 - 0.739 F360
26	T360 vs. C360, F360, W/B	T360 = 15.3 + 0.0848 C360 - 0.826 F360 - 14.6 W/B

4. Creation of Nomograms for Strength Parameters

4.1 Methods of Nomogram creation

4.1.1 The general traditional methods of Nomogram creation are:

1. Drawing geometrically with Scaling modulus (or scaling factor), on paper.
2. Drawing geometrically with the Scaling modulus in AutoCAD.
3. Drawing with the help of Determinants.

4.1.2 But in this project, Nomograms are created by a non-traditional method, i.e., automating the creation of Nomograms with software programs.

4.2 Creating Nomograms with PyNomo Software Programs

Software programs are written in the Python language of PyNomo software, which is a free software package for drawing precision Nomograms. The output is in vector form in a PDF file.

4.3 Creating Nomograms for Different Number of Variables (Table 5)

1 **For 2 variables:** Single-scale Nomograms are developed, with the equations of the form y = f(u), by writing Type8-Sample.py PyNomo programs.

2 **For 3 variables:** 3- parallel scale Nomograms are developed, with the equations of the form $f_1(u_1) + f_2(u_2) + f_3(u_3) = 0$, by writing Type1-Isopleth.py PyNomo programs.

3 **For 4 variables:** Compound parallel scale Nomograms are developed, with the equations of the form

$f_1(u_1) + f_2(u_2) + \ldots + f_n(u_n) = 0$, by writing Type3-Dualscale.py PyNomo programs.

4 **For 5 variables:** Compound parallel scales Nomograms are developed, with the equations of the form $f_1(u_1) + f_2(u_2) +\ldots + f_n(u_n) = 0$, by writing Type3-Dualscale.py PyNomo programs.

4.4 PyNomo Software Programs for Nomograms [1, 2]

The author has created 62 software programs written & executed for Model equations using a Python script with PyNomo open-source software, resulting in the 62 Nomograms as outputs.

But due to space constraints in the journal, only a few of the programs are provided in the paper in Appendix-A.

4.4.1 Programs for Compressive Strengths, W/B & Age

Eq.1. Program for the variables C28 and W/B

```
### Type8-Sample.py ###
from pynomo.nomographer import *
C28_params={
'tag':'myscale',
'u_min':30,
'u_max':75,
'function':lambda u:u,
'title':r'C28',
'title_x_shift':-0.5,
'tick_levels':4,
'tick_text_levels':3,
'tick_side':'left',}
block_1_params={
'block_type':'type_8',
'f_params':C28_params,
}
WB_params={
'tag':'myscale',
'u_min':0.25,
'u_max':0.6,
'function':lambda u:(110-u)/139,
'align_func':lambda u:(110-139*u),
'title':r'W/B',
'title_x_shift':0.5,
'tick_levels':4,
'tick_text_levels':2,
'tick_side':'right',}
block_2_params={
'block_type':'type_8',
'f_params':WB_params,
```

```
}
main_params={
'filename':'C28-WB.pdf',
'paper_height':20.0,
'paper_width':10.0,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $C28=110-139 \times W/B$',}
Nomographer(main_params)
```

4.4.2 Programs for Tensile Strengths, W/B & Age

Eq. 13. Program for the variables T28 and W/B

```
### Type8-Sample.py ###
from pynomo.nomographer import *
T28_params={
'tag':'myscale',
'u_min':3.5,
'u_max':9.5,
'function':lambda u:u,
'title':r'T28',
'title_x_shift':-0.5,
'tick_levels':4,
'tick_text_levels':3,
'tick_side':'left',
}
block_1_params={
'block_type':'type_8',
'f_params':T28_params,
}
WB_params={
'tag':'myscale',
'u_min':0.25,
'u_max':0.6,
'function':lambda u:(13.8-u)/17.6,
'align_func':lambda u:(13.8-17.6*u),
'title':r'W/B',
'title_x_shift':0.5,
'tick_levels':4,
'tick_text_levels':3,
'tick_side':'right',
```

```
}
block_2_params={
'block_type':'type_8',
'f_params':WB_params,
}
main_params={
'filename':'T28-WB.pdf',
'paper_height':20.0,
'paper_width':10,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $T28=13.8-17.6 \times W/B$',
}
Nomographer(main_params)
```

4.4.3 Programs for Flexural Strengths, W/B & Age

Eq. 25. Program for the variables F28 and W/B

```
### Type8-Sample.py ###
from pynomo.nomographer import *
F28_params={
'tag':'myscale',
'u_min':3.8,
'u_max':5.5,
'function':lambda u:u,
'title':r'F28',
'title_x_shift':-0.5,
'tick_levels':3,
'tick_text_levels':2,
'tick_side':'left',
}
block_1_params={
'block_type':'type_8',
'f_params':F28_params,
}
WB_params={
'tag':'myscale',
'u_min':0.2,
'u_max':0.6,
'function':lambda u:(6.32-u)/4.22,
'align_func':lambda u:(6.32-4.22*u),
```

```
'title':r'W/B',
'title_x_shift':0.5,
'tick_levels':4,
'tick_text_levels':3,
'tick_side':'right',
}
block_2_params={
'block_type':'type_8',
'f_params':WB_params,
}
main_params={
'filename':'F28-WB.pdf',
'paper_height':20.0,
'paper_width':10,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $F28=6.32-4.22 \times W/B$',
}
Nomographer(main_params)
```

4.4.4 Programs for all strengths, W/B & Age

Eq. 37. Program for the variables T28 and C28

```
### Type8-Sample.py ###
from pynomo.nomographer import *
T28_params={
'tag':'myscale',
'u_min':4,
'u_max':9.5,
'function':lambda u:u,
'title':r'T28',
'title_x_shift':-0.5,
'tick_levels':4,
'tick_text_levels':2,
'tick_side':'left',
}
block_1_params={
'block_type':'type_8',
'f_params':T28_params,
}
C28_params={
```

```
'tag':'myscale',
'u_min':33,
'u_max':75,
'function':lambda u:(u+0.064)/0.126,
'align_func':lambda u:(0.126*u-0.064),
'title':r'C28',
'title_x_shift':0.5,
'tick_levels':4,
'tick_text_levels':2,
'tick_side':'right',
}
block_2_params={
'block_type':'type_8',
'f_params':C28_params,
}
main_params={
'filename':'T28-C28.pdf',
'paper_height':20.0,
'paper_width':10,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $T28=-0.064+0.126 \times C28$',
}
Nomographer(main_params)
```

Eq. 44. Program for the variables T28 and F28

```
### Type8-Sample.py ###
from pynomo.nomographer import *
T28_params={
'tag':'myscale',
'u_min':4.5,
'u_max':10,
'function':lambda u:u,
'title':r'T28',
'title_x_shift':-0.5,
'tick_levels':4,
'tick_text_levels':2,
'tick_side':'left',
}
block_1_params={
'block_type':'type_8',
```

```
'f_params':T28_params,
}
F28_params={
'tag':'myscale',
'u_min':4.1,
'u_max':5.5,
'function':lambda u:(u+9.47)/3.5,
'align_func':lambda u:(3.5*u-9.47),
'title':r'F28',
'title_x_shift':0.5,
'tick_levels':3,
'tick_text_levels':2,
'tick_side':'right',
}
block_2_params={
'block_type':'type_8',
'f_params':F28_params,
}
main_params={
'filename':'T28-F28.pdf',
'paper_height':20.0,
'paper_width':10,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $T28=-9.47+3.50 \times F28$',
}
Nomographer(main_params)
```

Eq. 48. Program for the variables F28 and C28

```
### Type8-Sample.py ###
from pynomo.nomographer import *
F28_params={
'tag':'myscale',
'u_min':3.9,
'u_max':5.5,
'function':lambda u:u,
'title':r'F28',
'title_x_shift':-0.5,
'tick_levels':3,
'tick_text_levels':2,
```

```
'tick_side':'left',
}
block_1_params={
'block_type':'type_8',
'f_params':F28_params,
}
C28_params={
'tag':'myscale',
'u_min':30,
'u_max':80,
'function':lambda u:(u-3.03)/0.0294,
'align_func':lambda u:(0.0294*u+3.03),
'title':r'C28',
'title_x_shift':0.5,
'tick_levels':4,
'tick_text_levels':2,
'tick_side':'right',
}
block_2_params={
'block_type':'type_8',
'f_params':C28_params,
}
main_params={
'filename':'F28-C28.pdf',
'paper_height':20.0,
'paper_width':10,
'block_params':[block_1_params,block_2_params],
'transformations':[('scale paper',)],
'title_x':11.0,
'title_y':-1.0,
'title_str':r'\small $F28=3.03+0.0294 \times C28$',
}
Nomographer(main_params)
```

Eq. 55. Program for the variables T28, C28 and F28

```
### Type3-DualScale.py ###
from pynomo.nomographer import *
WB_params={
'u_min':0.25,
'u_max':0.6,
'function':lambda u:(14.6*u),
'scale_type':'linear smart',
'title':r'W/B',
```

```
'title_y_shift':0.8,
'text_format':r"$%3.2f$",
'tick_levels':4,
'tick_text_levels':3,
'extra_titles':[
{'dx':-1.25,
'dy':0.25,
'text':r'\small $Ratio$',
'width':5,
}]
}
C360_params={
'u_min':30,
'u_max':120,
'function':lambda u:(-0.0848*u),
'scale_type':'linear smart',
'title':r'C360',
'title_y_shift':0.8,
'tick_side':'left',
'tick_levels':3,
'text_format':r"$%3.0f$",
'tick_text_levels':2,
'extra_titles':[
{'dx':-1.25,
'dy':0.25,
'text':r'\small $MPa$',
'width':5,
}]
}
T360_params={
'u_min':6,
'u_max':14,
'function':lambda u:(u),
'scale_type':'linear smart',
'title':r'T360',
'title_y_shift':0.8,
'tick_side':'left',
'tick_levels':4,
'text_format':r"$%3.1f$",
'tick_text_levels':2,
'extra_titles':[
{'dx':-1.25,
'dy':0.25,
```

```
'text':r'\small $MPa$',
'width':5,
}]
}
F360_params={
'u_min':5,
'u_max':10,
'function':lambda u:(0.826*u-15.3),
'scale_type':'linear smart',
'title':r'F360',
'title_y_shift':0.8,
'text_format':r"$%1.1f$",
'tick_levels':3,
'tick_text_levels':2,
'extra_titles':[
{'dx':-1.25,
'dy':0.25,
'text':r'\small $MPa$',
'width':5,
}]
}
block_1_params={
'block_type':'type_3',
'width':20.0,
'height':30.0,
#  'reference_titles':['',''],
'f_params':[WB_params,C360_params,F360_params,T360_params],
'isopleth_values':[[0.55,63,'x',7.4102]],
}
main_params={
'filename':'WB-T360-C360-F360.pdf',
'paper_height':30.0,
'paper_width':20.0,
'block_params':[block_1_params],
'transformations':[('rotate',0.01),('scale paper',)],
'title_x':10.0,
'title_y':-1.5,
'title_box_width': 20.0,
'title_str':r'\Large $T360=15.3+0.0848 times C360-0.826 \times F360-14.6 \times W/B$',
'isopleth_params':[{'color':'Gray','linewidth':'thin','linestyle':'dashed','circle_size':0.05,
'transparency':0.0,
},
],
```

```
}
Nomographer(main_params)
```

5. Experimental Results: The Created Nomograms

The Nomograms are created in the form of PDF outputs by executing the written software programs mentioned above.

Nomograms are created for:

1. various compressive strength parameters at different ages and at different W/B ratios.
2. various tensile strength parameters at different ages and at different W/B ratios.
3. various flexural strength parameters at different ages and at different W/B ratios.
4. Compressive strengths, Tensile strengths, & Flexural strengths at different ages and at different W/B ratios.

The resultant nomograms are presented in Appendix-A.

6. Discussion on the Created Nomograms

The created Nomograms are very accurate. Following two proofs supports this statement:

1. It is worth observing that the equation-fit values and the nomogram-values are found to be the same, i.e., no variation between these two values. i.e., the percentage variation between the equation fit value and the Nomogram value is just null.

2. And they match industry norm values as per codal provisions.

Hence, these Nomograms are proven to be very accurate and are reliable for Industry use.

6.1 Applications of the Created Nomograms in Rigid Pavements

- F28 (Flexural strength at 28 days) is one of the important design inputs required for the design of Rigid pavements, as per AASHTO and IRC.
- C28 (Compressive strength at 28 days) is important data to be known before designing the Rigid pavement.
- T28 (Tensile strength at 28 days) is another important factor to be known before designing the rigid pavements. Tensile stresses occur in the rigid pavement due to the bond between the concrete pavement's bottom surface and the top surface of the base.
- C90, T90, F90; C180, T180, F180; C360, T360, F360 - are also formulated, because they are required to assess the serviceability of the rigid pavements at later ages.

6.2 Knowing Unknowns from the Project Outputs

6.2.1 From 2-variable Nomograms: If a variable is known, then an unknown variable can be found.

- For a W/B ratio: C28, C90, C180, C360 can be known. (Eq. 1,2,3,4)
- For a W/B ratio: T28, T90, T180, T360 can be known. (Eq. 13,14,15,16)

- For a W/B ratio: F28, F90, F180, F360 can be known. (Eq. 25,26,27,28)
- If C28 is known, then C90, C180, C360 can be found. (Eq. 5,6,7)
- If C28 is known, then T28, T90, T180, T360 can be found. (Eq. 37,38,39,40)
- If C28 is known, then F28, F90, F180, F360 can be found. (Eq. 48,49,50,51)
- If T28 is known, then T90, T180, T360 can be found. (Eq. 17,18,19)
- If F28 is known, then F90, F180, F360 can be found. (Eq. 29,30,31)

Vice versa is also possible for all the above equations.

6.2.2 From 3-variable Nomograms: An unknown variable can be found, if any 2 variables are known.

6.2.3 From 4-variable Nomograms: An unknown variable can be found, if any 3 variables are known.

6.2.4 From 5-variable Nomograms: An unknown variable can be found, if any 4 variables are known.

7. Conclusion

The created Nomograms are also reliable for use in Concrete Road pavements and the concrete industry using the HVFAC. (as proved in Paragraph 6). The unknown variables from the Nomograms can be known even by unskilled person, by just applying a normal straight edge. Its applications are mainly at the project implementing sites/ offices.

The Nomograms of a simplified list of 31 equations (given below), out of the 62 nomograms created, are useful in the HVFA mixed concrete rigid pavements:

Table 6: Most Useful Equations

S. No.	Parameters	Equation	Eq. ref. from Chapter 3.3
1	C28 vs. W/B	C28 = 110 - 139 W/B	1
2	C90 vs. W/B	C90 = 154 - 201 W/B	2
3	C180 vs. W/B	C180 = 158 - 199 W/B	3
4	C360 vs. W/B	C360 = 159 - 174 W/B	4
5	C90 vs. C28	C90 = -4.89 + 1.44 C28	5
6	C180 vs. C28	C180 = 1.78 + 1.41 C28	6
7	C360 vs. C28	C360 = 22.1 + 1.23 C28	7
8	T28 vs. W/B	T28 = 13.8 - 17.6 W/B	13
9	T90 vs. W/B	T90 = 19.8 - 26.7 W/B	14
10	T180 vs. W/B	T180 = 18.6 - 22.6 W/B	15
11	T360 vs. W/B	T360 = 19.5 - 22.6 W/B	16
12	T90 vs. T28	T90 = -0.78 + 1.47 T28	17
13	T180 vs. T28	T180 = 0.806 + 1.29 T28	18
14	T360 vs. T28	T360 = 1.96 + 1.26 T28	19
15	F28 vs. W/B	F28 = 6.32 - 4.22 W/B	25
16	F90 vs. W/B	F90 = 7.44 - 4.70 W/B	26

17	F180 vs. W/B	F180 = 9.10 - 6.10 W/B	27
18	F360 vs. W/B	F360 = 11.3 - 8.49 W/B	28
19	F90 vs. F28	F90 = 1.20 + 0.941 F28	29
20	F180 vs. F28	F180 = 1.23 + 1.17 F28	30
21	F360 vs. F28	F360 = 0.37 + 1.62 F28	31
22	T28 vs. C28	T28 = -0.064 + 0.126 C28	37
23	T90 vs. C28	T90 = -1.18 + 0.190 C28	38
24	T180 vs. C28	T180 = 0.641 + 0.163 C28	39
25	T360 vs. C28	T360 = 1.80 + 0.159 C28	40
26	T28 vs. F28	T28 = -9.47 + 3.50 F28	44
27	F28 vs. C28	F28 = 3.03 + 0.0294 C28	48
28	F90 vs. C28	F90 = 3.77 + 0.0329 C28	49
29	F180 vs. C28	F180 = 4.39 + 0.0419 C28	50
30	F360 vs. C28	F360 = 4.63 + 0.0600 C28	51
31	T28 vs. C28, F28	T28 = -1.25 + 0.112 C28 + 0.413 F28	55

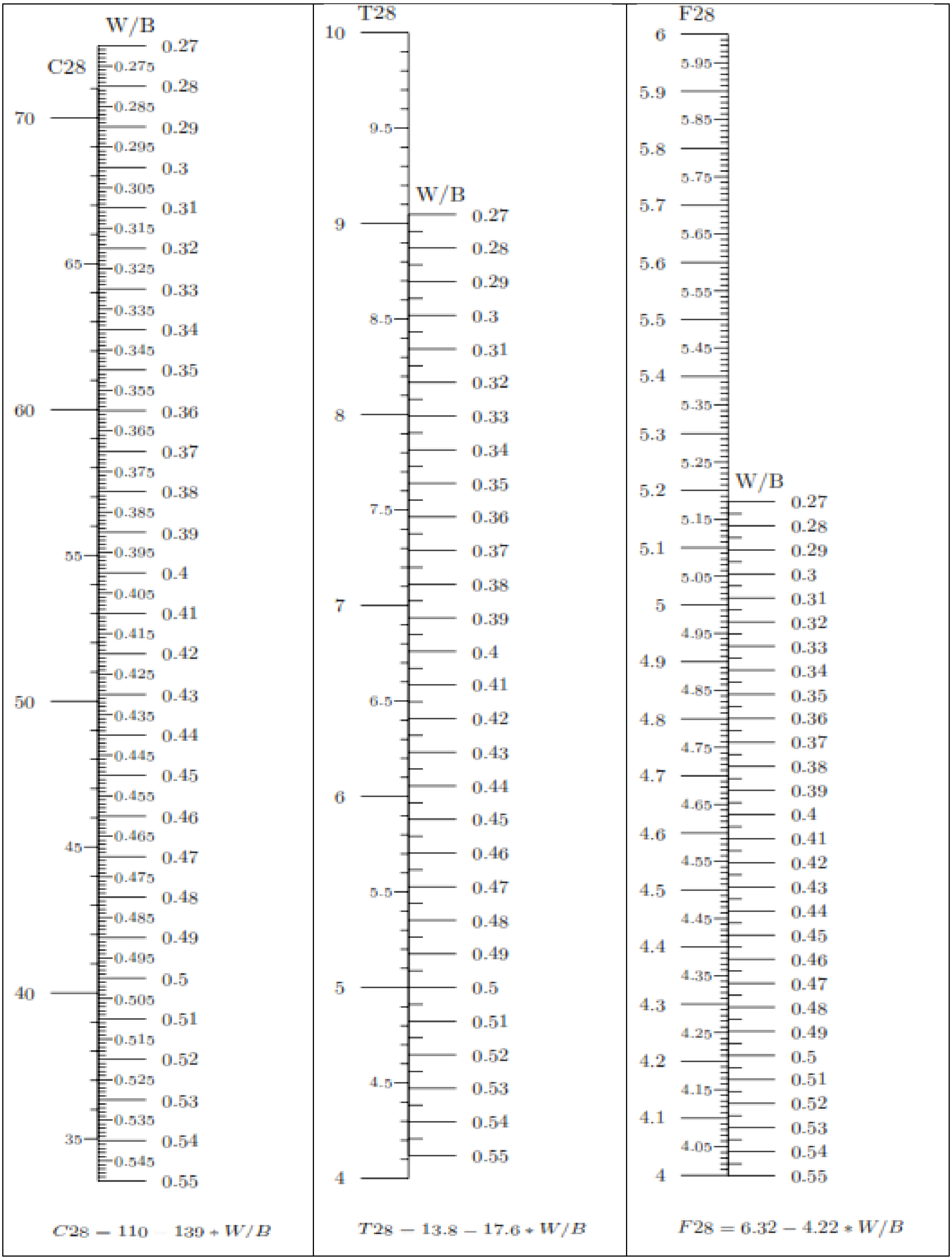
8. Scope for Further Work

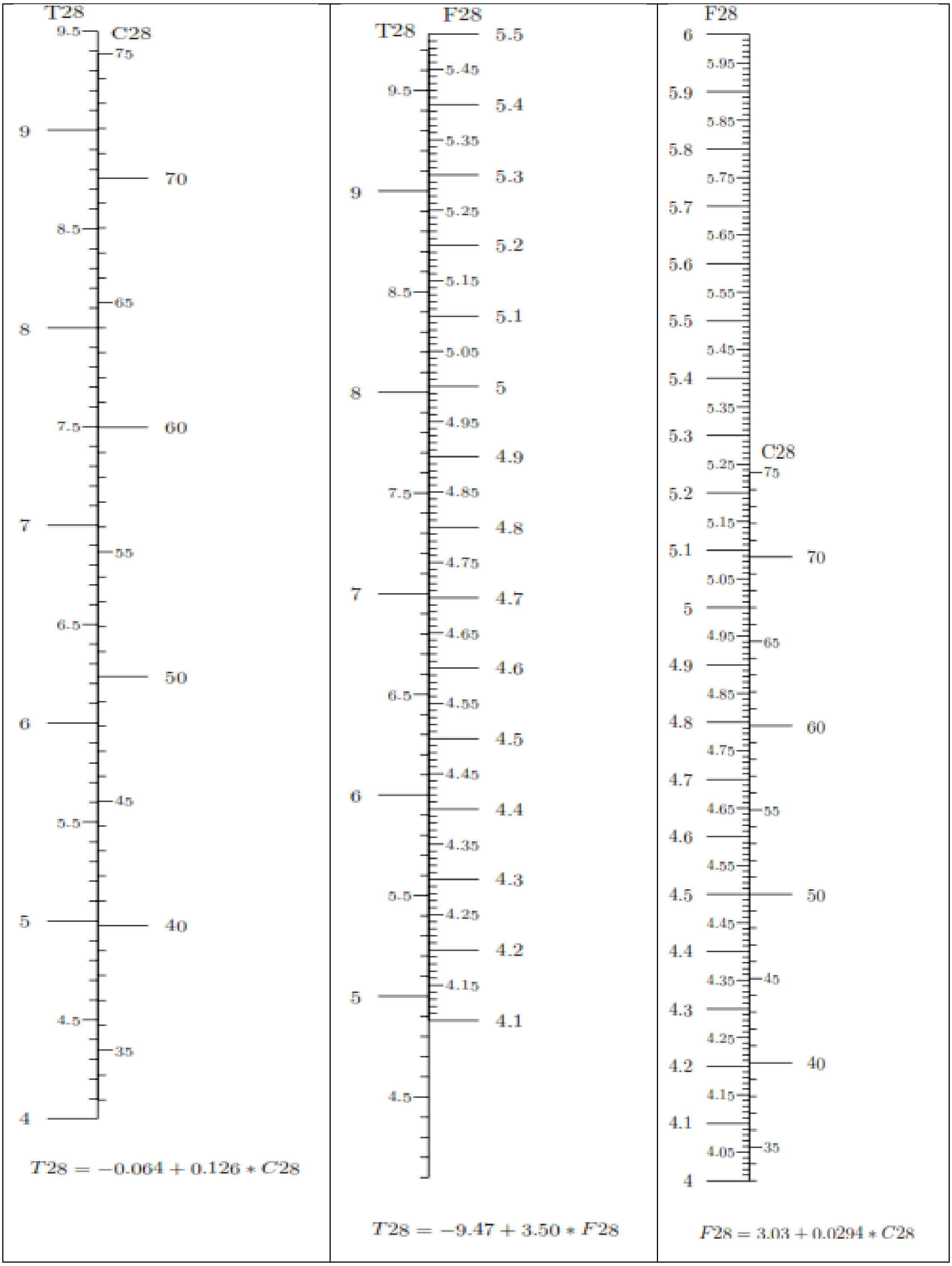
In further work, the Nomograms can be created for different combinations of the parameters mentioned below:

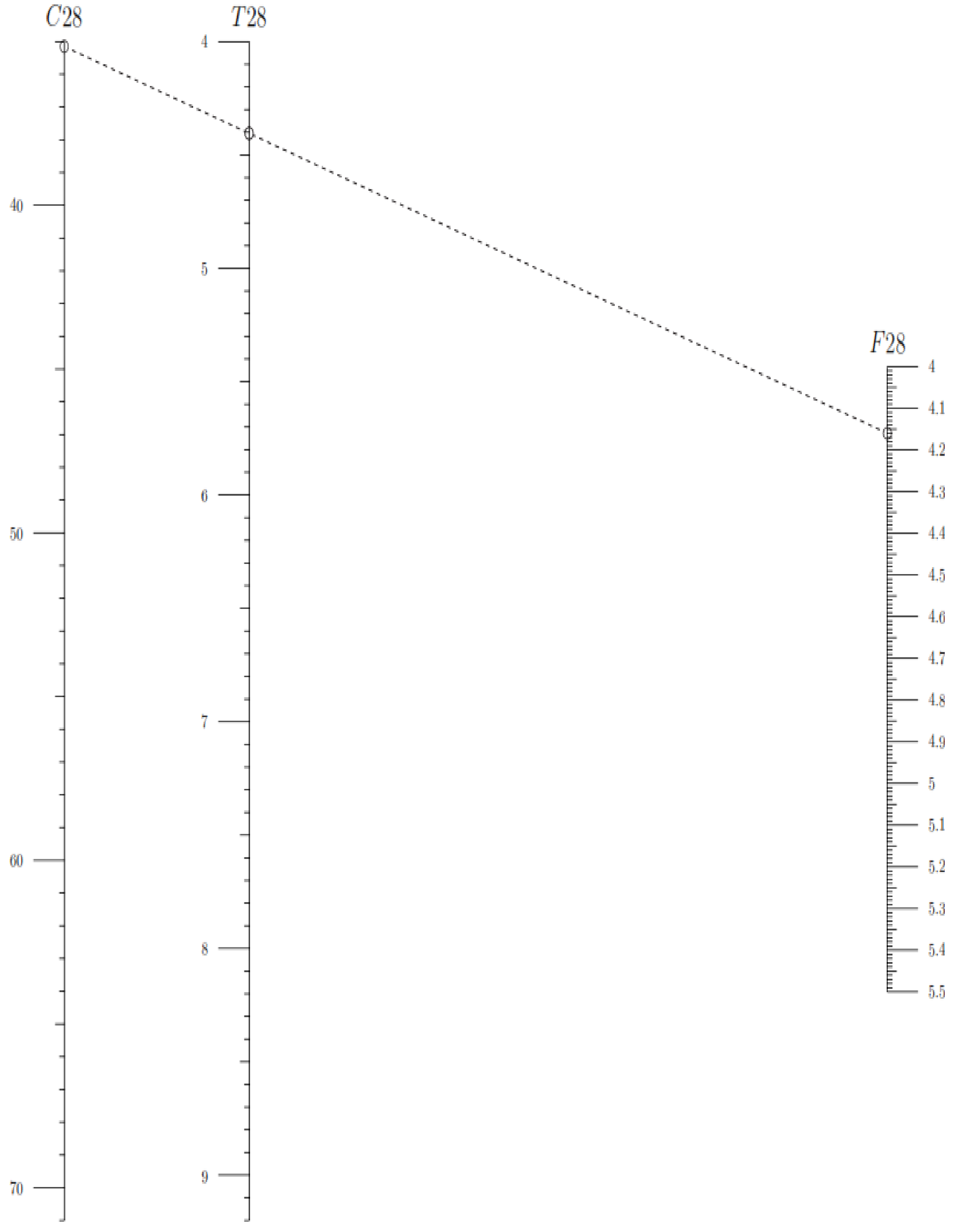
- **Various Grades of Cement:** 33G, 43G, 53G, and others.
- **Concrete Grades:** M15, M20, M25, M30, M35, M40, M45, M50, M60 etc.
- **Properties of Concrete:** Modulus of Elasticity, Slump value, Compressive Strength, Tensile Strength, Flexural Strength.
- **Different Quantities of Concrete constituents:** Cement, Coarse aggregate, Fine aggregate, Water, Superplasticizer, Fly ash, GGBFS, Copper slag.
- **Various Properties of Fly Ash:** Loss on Ignition, Grade of Fly Ash
- **Different Curing Temperatures of Concrete**
- **Various Properties of Aggregates:** Specific Gravity, Impact Value, Aggregate Crushing Value, Flakiness, 10% Fines Value, Fineness Modulus.

9. Appendix-A (The Created Nomograms)

Due to space constraints in the journal, only a few of the Nomograms are made available in this paper / journal.


W/B
C28
T28
F28
C28 = 110 − 139 * W/B
T28 = 13.8 − 17.6 * W/B
F28 = 6.32 − 4.22 * W/B


T28
C28
T28 = −0.064 + 0.126 ∗ C28
T28
F28
T28 = −9.47 + 3.50 ∗ F28
F28
C28
F28 = 3.03 + 0.0294 ∗ C28



$$T28 = -1.25 + 0.112 * C28 + 0.413 * F28$$

10. Acknowledgement
The author is thankful to his guide, Prof. Mrs. P. Sravana, JNTU, Hyderabad, for her valuable guidance and support in completing the project successfully.

11. Author's Biography

Raja Gopala Raju Veepuri is a Research scholar from Jawaharlal Nehru Technological University, Kakinada. He is a Postgraduate in Transportation Engineering and has over 30 years of experience in the execution of Highways and Railways. He is a certified Project Management professional. He is well conversant with Project execution, Design coordination, Project Management, and Contract management.

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