ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INVESTIGATION OF ALTERNATIVE STRATEGIES FOR OPTIMUM RELIABILITY IN CONDITION ASSESSMENT OF EXISTING RC BUILDINGS USING NDT METHODS

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MEVCUT BİNALARIN NDT YÖNTEMLERİ KULLANILARAK DURUM TESPİTİNDE OPTİMUM GÜVENİLİRLİK SAĞLANMASI İÇİN ALTERNATİF YÖNTEMLERİN İNCELENMESİ

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Hadi Abbaszadeh, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 501161063, successfully defended the thesis/dissertation entitled “INVESTIGATION OF ALTERNATIVE STRATEGIES FOR OPTIMUM RELIABILITY IN CONDITION ASSESSMENT OF EXISTING RC BUILDINGS USING NDT METHODS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family,

FOREWORD

It is my pleasure to greatly thank my advisor, Asst. Prof. Dr. Oguz Gunes, who made this opportunity for me to participate in this project and emerge my thesis from that and also due to his encouragement and technical supports from the beginning of the project through the last day and final processes. I must honestly indicate that without his help this thesis would not have been developed and completed.

Finally, I offer my best regards and blessings to my family especially my dad due to all of those who supported me in any respect towards the completion of my thesis.

September 2018 Hadi ABBASZADEH

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ABBREVIATIONS

NDT	**:** Non-destructive Test
DT	**:** Destructive Tests
SonReb	**:** Combined Ultrasonic pulse velocity and Rebound hammer
UPV	**:** Ultrasonic Pulse Velociy
Rebound-R	**:** Rebound Hammer type R
Rebound-Q	**:** Rebound Hammer type Q
SD	**:** Standard Deviation

SYMBOLS

$\boldsymbol{F_c}$	**:** Compressive strenght of concrete
$\boldsymbol{r^2}$	**:** Coefficient of determination
R	**:** Normal schmidt (rebound) number
Q	**:** Silver schmidt (rebound) number
V	**:** Velocity
t	**:** Time
CI	**:** Core I
CJ	**:** Core J
CK	**:** Core K
CIJK	**:** Core I, then Core J, then Core K, repectively
L	**:** Length
e	**:** neper number
σi	**:** The stress which was applied by the plunger when the concrete surface is disordered
σr	**:** The reflected compression wave via plunger
$\boldsymbol{f_{c,car}}$	**:** Characteristic strength of concrete (core)
$\boldsymbol{I_{rm}}$	**:** Normal schmidt (rebound) number
$\boldsymbol{V_{L,S}}$	**:** Velocity in specific length and time
$\boldsymbol{f_{c,est}}$	**:** Estimated strength of concrete (core)
$\boldsymbol{f_{c,est,mean}}$	**:** Mean value of estimated strength of concrete elements (cores)
$\boldsymbol{f_{c,car,mean}}$	**:** Mean value of characteristic strength of concrete elements (cores)
k	**:** The ratio of estimated over characteristic mean values of concrete elements (cores) strength

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INVESTIGATION OF ALTERNATIVE STRATEGIES FOR OPTIMUM RELIABILITY IN CONDITION ASSESSMENT OF EXISTING RC BUILDINGS USING NDT METHODS

SUMMARY

The condition assessment of existing RC buildings is an important task in structural engineering. Deterioration of buildings occurs due to several factors such as environmental exposure and chemical attacks, poor concrete quality due to bad mixture design or poor workmanship and loading effects.

There are various methods to evaluate the condition of buildings including destructive testigng (DT) and non-destructive testing (NDT) methods. DT methods are relatively more reliable but are costly, often take more time and have their own limitations. NDT methods, when correlated with limited DT results could reduce the time and cost of condition assessment, the reliability of which can be improved through increased number of testing or through combination with other DT or NDT methods.

Non-destructive test methods are improving continuously and new methods and equipment with better reliability and easier procedures are being developed to be included in standard updates. Most commonly used methods are (a) Rebound (Schmidt) Hammer, (b) Ultrasonic Pulse velocity, and (c) Pull-out tests.

In this study, four incomplete fifteen-story buildings that were built nearly 30 years ago in Zeytinburnu area, Istanbul, Turkey were chosen as case study buildings. Three cores were taken from each story of all four buildings that were designated as Building A, B, C, and D. Since the buildings were tunnel formwork construction, cores taken from shear walls. The total number of cores taken from each building was 45, with a total of 180 cores taken from all four buildings.

Three non-destructive methods were chosen as (a) Rebound (Schmidt) hammer, (b) Silver-Schmidt hammer, and (c) UPV and measurements were performed in all building at the locations of cores.

Uniaxial compressive strength tests were performed on cores at Istanbul Technical University`s Construction Materials Laboratory and UPV was done on cores instead of in-situ in order to obtain the quality of results.

Various assessment scenarios were implemented in this research and results were demonstrated for each different scenario which consisted of variations in core numbers and the number of floors that the cores were taken.

The first scenario included a single core taken from each story, with four different combinations of floor numbers in each building.

The second scenario considers two cores taken from each story and with variations in core locations.

The third scenario includes three cores taken from each story as instructed by code to serve as a basis for comparison with previous scenarios.

The fourth scenario considers cores taken from two, four, and eight stories to determine the optimum correlations in view of cost and accuracy. Reducing the number of cores with minimum trade-off in reliability is main objective of this scenario considering the cost and difficulty of taking cores.

The results indicate that each scenario has its advantages and disadvantages which can be considered based on requirements regarding assessment cost and reliability.

MEVCUT BİNALARIN NDT YÖNTEMLERİ KULLANILARAK DURUM TESPİTİNDE OPTİMUM GÜVENİLİRLİK SAĞLANMASI İÇİN ALTERNATİF YÖNTEMLERİN İNCELENMESİ

ÖZET

Mevcut betonarme binalarının durum değerlendirmesi, yapı mühendisliği alanında önemli bir konudur ve eski,hasarlı binaların ve altyapı sistemlerinin zamanla artması nedeniyle gelecekte daha fazla ihtiyaç duyulacak bir konudur. Binaların çürümesi, kirlenmiş ortamlardaki kimyasal saldırılar ve çevreden gelen diğer etkiler, betonun yüksek gözenekli olması ve nemli alandaki yüksek su emilimi, zayıf karışım tasarımına göre düşük beton kalitesi ile çelik çubuk (donatı) korozyon etkisi gibi çeşitli faktörlere bağlı olarak ortaya çıkar. Düşük işçilik kalitesi, deprem sırasında darbe yüklemesi gibi faktörler de betonun bozulmasına yol açan nedenler arasında sıralanabilir.

Bina hakkında yapı değerlendirmesi yapılırken tahribatlı (DT) ve tahribatsız (NDT) muayene yöntemleri kullanılır. Muayene esnasında yüksek hasar oranı bulunduran ve ekonomik olarak maliyetli sayılabilecek DT yöntemleri yapı üzerinde uygulanabilirlik açısından bazı kısıtlamalar barındırdığından efektif bir değerlendirme yöntemi değildir. Bunun yanında, NDT yöntemleri zaman ve maliyet açısından daha efektif sonuçlar vermesinin yanında, alınan testlerin sayısını da yüksek güvenilirlikle artırabilir.

Tahribatsız deneyler; prekast yapı elemanlarının yerinde kalite kontrollerinde, temin edilen malzemelerin istenilen özelliklerinin uygunluğuna dair belirsizlikleri ortadan kaldırmada, beton işçiliğinin dahil olduğu karıştırma, yerleştirme, sıkıştırma ve kürleme işlemlerine ait şüpheleri gidermede, kalıbın çıkarılması, kürlemenin bitmesi, yük etkimesi ve benzer koşullarda dayanım artışının gözlenmesinde, beton elemanın çatlak boyutlarının, boşluklarının v.b. kusurlarının ve bu kusurların yerlerinin belirlenmesinde, karot alma ve yükleme testleri gibi pahalı ve tahribatlı deneylerden önce betonun uniformluğunun kontrolünde, donatıların yerlerinin, miktarlarının ve mevcut durumlarının belirlenmesinde, düşük sayıda tahribatlı deneyle güvenilir sonuç almada, aşırı yükleme, yorulma, dahili ve harici kimsayal ataklar, patlamalar ve yangınlar gibi çevresel etkiler sonucu betondaki bozulmaların tayininde, betonun durabilitesinin değerlendirilmesinde, betonun özelliklerinde uzun dönem değişmeleri gözlemede ve yapının kullanımında gidilecek değişikliklerde ilgili kişilere bilgi sağlamak amacıyla Tahribatsız Deneyler kullanılmaktadır

Tahribatsız muayene yöntemleri sürekli geliştirilmekte ve daha yüksek doğrulukta, daha kolay uygulanabilir ekipmanlar üretilmektedir. Standartlar daha iyi sonuçlar elde etmek için bilgilerini güncellemektedir. Bununla birlikte, en çok kullanılan ekipmanlar şunlardır: (a) R tipi Schmidt Çekici (ve yeni tip Q), (b) Ultrasonik Geçiş hızı ve (c) Prob testleri.

Schmidt Çekici, 1948 yılında İsviçreli bilim adamı olan Ernst Schmidt tarafından betonun yüzey sertliğini tayin etmek amacıyla "geri tepme" prensibi kullanılarak geliştirilmiştir. Schmidt Çekici, uygulanması kolay ve ucuz olduğundan dolayı betonun tahribatsız muayenesinde yaygın olarak kullanılmaktadır. Fakat bu gibi aletler beton yüzeyinin ilk 30 mm'lik kısmı için yüzey sertliği hakkında bilgi verdiğinden tek başına dayanım belirlenmesinde kullanılması çok sakıncalıdır. Aşağıdaki şekil Schmidt Çekicinin kesitinin şematik olarak gösterimidir.

Ultrases Hızı Testi ile beton dayanımı arasında doğrudan bir ilişki yoktur. Fakat betonun yoğunluğunun, dayanımla olan ilişkisi bilinen bir gerçektir. Büyük çoğunlukla, beton yoğunluğunun artması basınç dayanımının da artmasına sebep olmaktadır. Bunun sebebi ise w/c oranının azalması ile beton içerisindeki kılcal boşlukların azalmasıdır. Betondaki kılcal boşlukların azalması ile Ultrases aletinin ürettiği sesüstü dalgalar bir probdan diğer proba daha hızlı aktarılacaktır.

Ultrases Hızı Testi, probların ürettiği sesüstü dalgalarının betonun içinde ilerleme hızının ölçülmesidir. Probların ürettiği ses dalgaları, gres yağı v.b. viskoz maddeler yardımıyla betona aktarılır. Bu itkinin başladığı esnada elektronik saat çalışmaya başlar. Boyuna ve kesme dalgaları olarak üretilen bu ses dalgalarından boyuna dalgalar ikinci proba ilk olarak ulaşır ve prob tarafından elektronik sinyallere dönüştürülür. Dalga, alıcı prob tarafından algılandığı anda elektronik saat durur ve ulaşma süresi tespit edilir. Dalgaların ilerlediği mesafenin süreye oranı ile dalga hızına ulaşılır.

Ultrases Testi araştırmalarında, küp numunelere uygulanan gerilmelerin kırıldıkları yükleme değerinin %50'sine ulaşmadan ultrases hızında değişikliğin görülmediği belirtilmiştir. Yükleme değerleri arttıkça numune içerisinde oluşan deformasyonların yarattığı boşluklar dalga hızlarını düşürecektir. Bunun sebebi, yayılan ses dalgalarının boşlukta ilerleyememesi ve etrafından dolaşması sebebiyle alıcıya ulaşma sürelerinin uzamasıdır.

Aynı koşullardaki beton numunelerde, doymuş numunelerin ultrases hızları kuru haldeki numunelere göre %5 daha daha fazladır. Bu fark, dayanım artmasıyla gittikçe azalarak kaybolur. Doymuş küp numuneler, yüksek ultrases hızlarına karşı düşük dayanımlar verirken, kuru haldeki küp numuneler düşük ultrases hızlarına karşı daha yüksek dayanım verirler.

Ultrases hızının ölçümünde alıcı ve verici problar arası mesafenin artması, ultrases hızının büyüklüğünü etkilemediği bilinmektedir. Bunun yanında, maksimum agrega çapı 20 mm ve daha az olan numuneler için problar arası mesafe 100 mm, maksimum agrega çapı 20-40 mm arasında olan numuneler için ise, 150 mm olması önerilir (probların karşılıklı yerleştirildiği direkt okumalar için).

10ºC-30ºC arasındaki sıcaklık değişimleri, dayanımlarda ve malzemenin elastik özelliklerinde bir değişiklik olmadığı sürece ultrases hızında önemli bir değişikliğe yol açmamaktadır.

Tahribatsız yöntemler ile dayanımların belirlenmesindeki avantajlar ilerideki gibi sıralanabilir, (i) Diğer test yöntemlerine göre tahribatsız deneyler daha ekonomiktir, (ii) Yapıda tahrip azalır, (iii) Yüzeyleri tahrip etmediğinden onarım ve güçlendirme çalışmaları minimuma düşer, (iv) Test için kullanılacak eleman sayısı azdır, ve (v) Teste tabi tutulacak elemanların ön hazırlık ihtiyaçları azalır.

Bu çalışmada, 30 yılı aşkın bir süre önce kaba inşaatı tamamlanan ve sonrasında kullanılmayan, her biri on beş katlı dört adet bina, İstanbul, Türkiye için örnek çalışma binaları olarak seçilmiştir. Bu araştırmada (A, B, C, ve D) olarak adlandırılan her dört binanın her bir katından üçer adet karot alınmıştır. Bünyesinde hiç kolon bulundurmayan ve taşıyıcı olarak perde duvar sisteminin seçildiği binada karotlar, perde duvarlardan alınmıştır. Her binadan 45 adet olamak üzere toplamda dört binadan elde edilen karot sayısı 180'dir.

Seçilen tahribatsız muayene yöntemleri: (a) R tipi Schmidt Çekici, (b) Q tipi Schmidt Çekici ve (c) Ultrases geçiş hızı yöntemleridir. Sayılan tüm tahribatsız muayene yöntemlerinin tümü, karot alınmış tüm perde duvarlar üzerinde uygulanmıştır.

Basınç dayanımı testleri İstanbul Teknik Üniversitesi İnşaat Fakültesi Yapı Malzemesi Laboratuvarı'nda karotlar üzerinde uygulanmıştır. Daha yi korelasyon eğrileri elde edebilmek adına ultrases geçiş hızı testleri aynı laboratuarda, karotlar üzerinde uygulanmıştır.

Buna ek olarak, bu araştırmada bazı senaryolar geliştirilmiş ve sonuçlar, her bir binadaki optimum karot sayısını elde etmek için kullanılmıştır. Her kat için farklı sayıda karot alınması ve son olarak belli katlarda belli sayıda karot alınması durumlarının farklı kombinasyonlarının betonun basınç dayanım tahmini üzerindeki güvenirliliği analiz edilmiştir. Belirtilen senaryolarda öncelikle her bina kendi içersinde değerlendirilmiş, sonrasında tüm binalardan alınan karotlar için basınç dayanımı ile NDT deneyleri sonucunda elde edilen verilerin korelasyonları incelenmiştir.

İlk senaryo, her kattan tek karot alınması durumunu içindir. Her bir kattaki üç karottan bir karot seçmek için farklı temel seçim yöntemi geliştirilmiştir. Buna göre: Her kattan alınan üç karot numunesi I, J, K harfleri ile kodlanmıştır. İlk durum için her kattan alınmış I kodlu numuneler üzerinde yapılmış NDT ve basınç dayanımları arasındaki korelasyon, ikinci ve üçüncü olarak durum için sırasıyla J ve K numuneleri üzerinde yapılan NDT ve basınç dayanımları arasındaki korelasyon analiz edilmiştir. Karotlar arası seçim yapılırken dördüncü durum olarak her katta I, J, K düzenine göre karot seçimi yapılmış NDT sonuçları ve basınç dayanımları arasındaki korelasyonlar analiz edilmiştir. Buna göre her dört durum için elde edilen korelasyon eğrileri arasında en yüksek R2 değerini sağlayan kombinasyonlara göre optimum karot sayısı belirlenmeye çalışılmıştır.

İkinci senaryoda, her kattan iki karot alınması durumu incelenmiştir ve bu senaryo için iki temel seçim yöntemi belirlenmiştir. Buna göre: Daha önce I, J, K ile kodlanmış numuneler arasında önce her kat için, birinci durumda I, J ikinci durum için J, K üçüncü durum için I, K numuneleri alınarak NDT ve basınç dayanımları arasında korelasyon analiz edilmiştir.

Üçüncü senaryoda, her kattan alınan ve yukarıda belirtildiği şekilde üç gruba ayrılmış her üç karot (tüm verileri) için elde edilmiş olan basınç dayanımı ve NDT sonuçları arasındaki korelasyon incelenmiştir.

Dördüncü senaryo kapsamında özellikle çok katlı binaların durum tespiti çalışmaları sırasında karşılaşılan iş gücü,uygulama zorlukları ve ekonomik nedenler göz önünde bulundurularak her binanın sadece ilk iki, ilk dört, ve ilk sekiz katından alınan numuneler incelenmiştir.İnclenen verilerin, binalarınnın beton basınç dayanımlarının belirlenmesi üzerindeki güvenilirliği, her üç durum için de incelenmiştir.

Çalışmalardan elde edilen sonuçlar her senaryonun kendine özgü avantaj ve dezavantajları olduğunu göstermiş, durum tespit çalışmalarının gerektirdiği bütçe ve güvenilirlik şartlarına göre seçim yapılması gerektiği sonucuna varılmıştır.

1. INTRODUCTION

Non-destructive testing (NDT) is explained as the field of testing, inspecting, or assessing with no destruction or ruin in serviceability of the whole system and/or part (Workman & O. Moore, 2012). The aim of NDT is to demonstrate the quality and integrity of components, assemblies, or, materials with no negative effect on the serviceability and/or ability of them to perform their predestinate functions. Non-destructiveness should not to be considered equal with non-invasiveness. Testing methods whcih do not have negative effect on the future ability or performance of a part or system are classified as non-destructive even if they include some invasive actions in their implemention. For instance, taking cores from concrete elements in buildings or other civil infrastructures is a common NDT method which is used due to obtaining the mechanical properties of intended in-situ concrete. Although, coring change the appearance of the elements apperance and effects its structural ability; If its implementaion was completed correctly with qulified performers, it could has no negative effect on serviceability of the structural element, so it could be considered to be a NDT method (J. Helal et al, 2015).

Destructive tests (DT) seek failure or collapse mechanisms to find out the materials major mechanical properties like compressive strength, yield strength, flexural strength, tensile strength, fracture toughness, ductility and etc. NDT methods seeking determination of properties with causing no failures at element and/or assembly. A wide range of improvments and attempts have been developed in order to give the intended and required capablity to NDT methods for determining the mechanical, chemical, acoustical, electrical, physical, and magnetic properties of materials. The earliest documented research of NDT dates back to the 19th century where acoustic tap testing was provided due to cracks detection in railroad wheels (Stanley, 1995). More extensive, reliable, sensitive, and quantifiable NDT methods have largly developed and created in recent decades.

In order to need for detecting and preventing the structural damage, NDT methods have produced as a response to the intended requirement. The economy plays the major rules in most of engineering project and specially in condition assessment of buildings, NDT methods could response to this issue and additionaly bring more safety in implementation of assessment. In order to eliminate the problems associated with structural failure or deterioration some in-site testing techniques have been developed as a pre-emptive treatment to provide ability to assess concrete during the construction and service life of a structure (J. Helal et al, 2015).

Depth of penetration, physical properties contrast,vertical and lateral resolution, signal-to-noise ratio and available information about the building (structure) are the main factors which effect the successfulness of a non-destructive test (McCann & Forde, 2001). The adequate knowledge about material properties and the major issues associated with those material`s application in structural engineering is mandatory for any NDT method to reach success. The steps to selecting an adequate NDT method are (Shull, 2002):

(i) The adequate knowledge about physical nature of the material property or discontinuity in order to examined;

(ii) The adequate knowledge about the basic physical processes which control the NDT method;

(iii) The adequate knowledge about the physical nature of the interaction of test material with the the researching field;

(iv) The adequate knowledge about the major restrictions of available NDT technology;

(v) Considering environmental, economic, regulatory and other factors that have negative impact.

There methods and equipments of NDT methods which was used in this research was explained below,

1.1 Surface Hardness Methods (Standard and Silver Schmidt)

Non-destructive surface hardness methods are type of method that act non-invasive and evaluate the material`s strength characteristics. Indentation methods and rebound methods are two different categories which perform based on concrete surface hardness techniques. Extraction of experimental correlations between surface hardness either indentation or rebound and strength properties of concrete is the major aims of this methods. indentations methods which was originated in the 1930 (Jones, 1969), are no longer common in the civil engineering industry; however, rebound methods are mostly applied to obtain concrete strength characteristics with reference to standard guidelines on testing and interpretation (J. Helal et al, 2015).

(a) (b)

Figure 1. 1: Schmidt Rebound Hammer (a) Standard (R), and (b) Silver (Q).

The most widely used surface hardness method is the standard rebound hammer (R) measurement. The test and equipment was developed in 1948 by Ernst Schmidt (Swiss engineer) and is commonly called the Schmidt Rebound Hammer (Kolek, 1969). In addition, there is a more developed hammer which called silver rebound hammer (Q). Silver Schmidt hammer determines the results of testing using waves and automatically (digitally) with higher accuracy.

The rebounded hammer determines a rebound number when impact with the concrete surface, which demonstrates an quantity of strength properties by referencing provided experimental correlations between the rebound numbers and trength properties of concrete (compressive and/or flexural).

The theory of wave propagation is the basic understanding of impact and rebound. At the time which surface of the concrete is disordered by the plunger (σi), a compression wave is propagated. The reaction force propagates back a reflected compression wave via plunger (σr). The ratio of the wave amplitudes (σr/ σi) is detected to be proportional with the rebound number that was determined by hammer and could be correlated with compressive and flexural strength (Akashi & Amasaki, 1984).

Implementation of the Rebound Hammer either standard or silver needs less mechanical and emperical skills compared with other NDT methods. Smooth and clear surfaces are required for performing rebound hammer tests, in order to perform a qualified test the intended surfaces should be chosen piror to test. The test could be done with various calibration charts which may reduce the various gravity affects; and in any directional angle. The hammer is pressed to the clean ans smooth concrete surface until a spring loaded mass is released causing the plunger to impact against the surface and rebound a distanced measured by a slide indicator (Fig. 1.2). The rebound number is the distance that was measured (J. Helal et al, 2015).

Several manufacturer attempt to releasing empirical correlations to relate concrete compressive strength to the rebound number; however, the environment and testing conditions of each manufacturer oftenly might not be similar to the case that is going to be studied at present time. Therefore, it is suggested to provide a test-specific correlation procedure where a number of cores adjusting in strength are provided and measurements was performed by both compression testing machine and rebound hammer (both R and Q). Then, the results for two tests are arranged to be paired of test one by one and an empirical correlation with simple regression analysis model was obtained and controled by intended correlation`s R-square value.

There some standard guidlines was demonstarted for further information; however, the standard that was used in this research was EN 13791,

(i) EN 13791: 2007: Assessment of in-situ compressive strength in structures and precast concrete components;

(ii) ASTM C 805: Standard Test Method for Re- bound Number of Hardened Concrete;

(iii) BS EN 12504-2: 2012: Testing Concrete in Structures - Non-destructive Testing - Determination of Rebound Number.

The Rebound Hammer provides an economic, and simple, method to determine concrete compressive strength. However, there are also some effects such as test specimen geometric properties, the surface smoothness, surface and internal moisture conditions of the concrete, test specimen age, type of used coarse aggregate, type of cement that was used in concrete, concrete surface carbonation and type of mold which could alter the results of intended case (Malhotra, 2004).

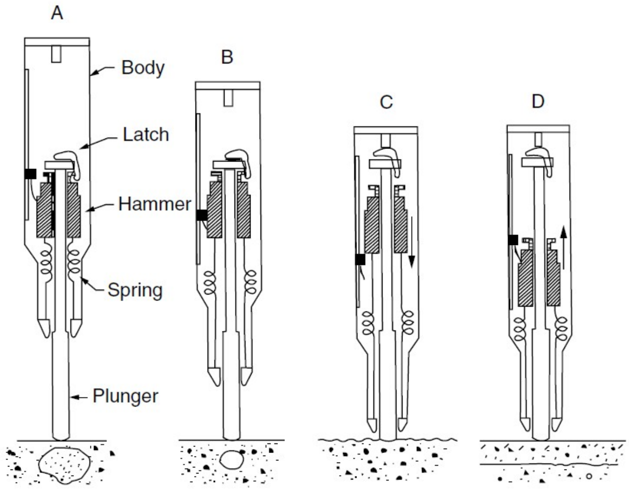


Figure 1. 2: Schematic diagram of Schmidt rebound hammer procedure (Malhotra, 2004).

Strength determination from rebound records of specimens similar to correlation curve specimens were reached 15% to 20% accuracy compared to actual strength (Concrete Institute of Australia, 2008).

1.2 Ultrasonic Pulse Velocity (UPV) Method

Ultrasonic pulse velocity methods procedure is to propagate ultrasonic waves in solids and receiving the wave while measuring the time which needs for this process. The characterization of a material's composition, structure, elastic properties, density and geometry while considering previously provided correlations and mathematical equations are some features of ultrasonic wave propagation. This non-invasive method is also used to determining and detecting flaws in material and their degree of damage by exploring the scattering of ultrasonic waves (J. Helal et al, 2015).

The fundamental technique of ultrasonic pulse velocity methods is to transform a voltage pulse to an ultrasonic pulse and obtain it back by a transmitting and receiving transducer respectively. The transmitting transducer that was soaked with special gel was placed on the surface of concrete and then transmit an ultrasonic pulse through the specimen. The ultrasonic pulse penetrates through the concrete specimen and is determined by a receiving transducer at the other side which transforms the ultrasonic pulse to a voltage pulse (Figure 1.3). The velocity of the wave pulse could be easly obtained by finding out the distance between the two points. Then, an empirical correlation with simple regression analysis model was obtained by velocity and concrete compressive strength and controled by intended correlation`s R-square value. There some standard guidlines was demonstarted for further information; however, the standard that was used in this research was EN 13791,

(i) EN 13791: 2007: Assessment of in-situ compressive strength in structures and precast concrete components;

(ii) ASTM C 597: Standard Test Method for Pulse Velocity Through Concrete;

(iii) BS EN 12504-4:2004 Testing Concrete. Determination of Ultrasonic Pulse Velocity.

The major factors (applying for concrete) which includes in ultrasonic pulse velocity methods are aggregate properties, cement type, water-cement ratio, admixtures and age of concrete (Naik, Malhotra, & Popovics, 2004).

Figure 1. 3: Ultrasonic pulse velocity test apparatus.

Furthermore, remaining reinforcement in the concrete and in the pulse path could significantly affected the measurements of pulse velocity (Concrete Institute of Australia, 2008). By considering these factors during research and analysis, UPV methods are one of best methods for determining the characteristics and durability of concrete with an inexpensive and easy way.

1.3 Purpose of Thesis

The aim of this thesis is to assess the condition of four real case half-finished existing RC building that was created and left away around 30-years ago by NDT methods and find out the related correlation equation and evaluated each equation and method by R-square values, the optimum number of cores based on different scenarios for each building and for whole research cases was find out by considering the number of cores used in each story and these cores combinations; Also, the differences between type R and type Q schmidt hammer was shown in analysis based on single correlation and their effects in SonReb method.

1.4 Literature Review

There are some studies contain experimental an numerical researches both laboratory and the real case. The analysis shows the reliability of results based on R-square and RSME values and is aim to find out the optimum number of cores for obtaining the best correlation equation. However, there is lack of information both at EN 13791 standard and in the literature about type Q hammer (Silver Schmidt) and this is the point that was studied in this thesis to compare and find out the differences between type R and type Q hammers.

Ali-Benyahia et al. (2017) was studied in a real case by 205 number of cores with both single and combined (SonReb) methods to find out the optimum number of cores for a suitable correlation equation based on both R-square and RMSE results.

In this research, the number NC = 9 can be considered as adequate number regarding the precision of the conversion models.

In addition, For NC <9, statistical uncertainties are larger and the evaluation accuracy is decreased and considering at least six cores in each part guarantee that concrete strength evaluation will improve in combining NDT methods.

In the other section, two statistical parameters (RMSE and r-square) were provided using correlation results to predict the errors which was observed during prediction. It was found out that for common single NDT method NC=9 cores could be adequate for assessing the effective ness in condition assessment and increase in NC number dose not develop the obtained results.

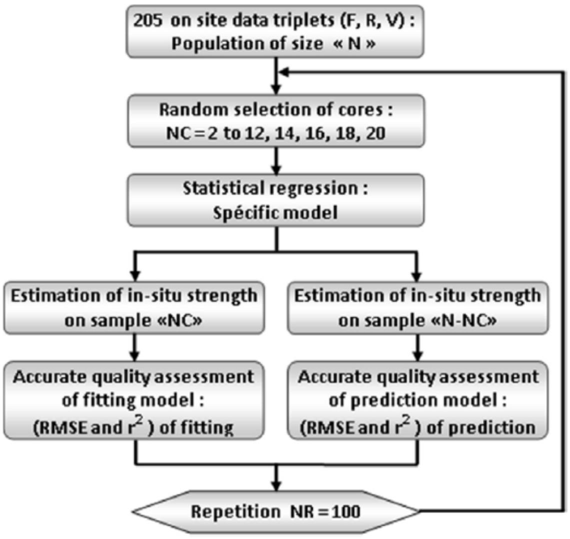


Figure 1. 4: Flow chart of the strength assessment accuracy methodoloy (Ali-Benyahia et al. 2017).

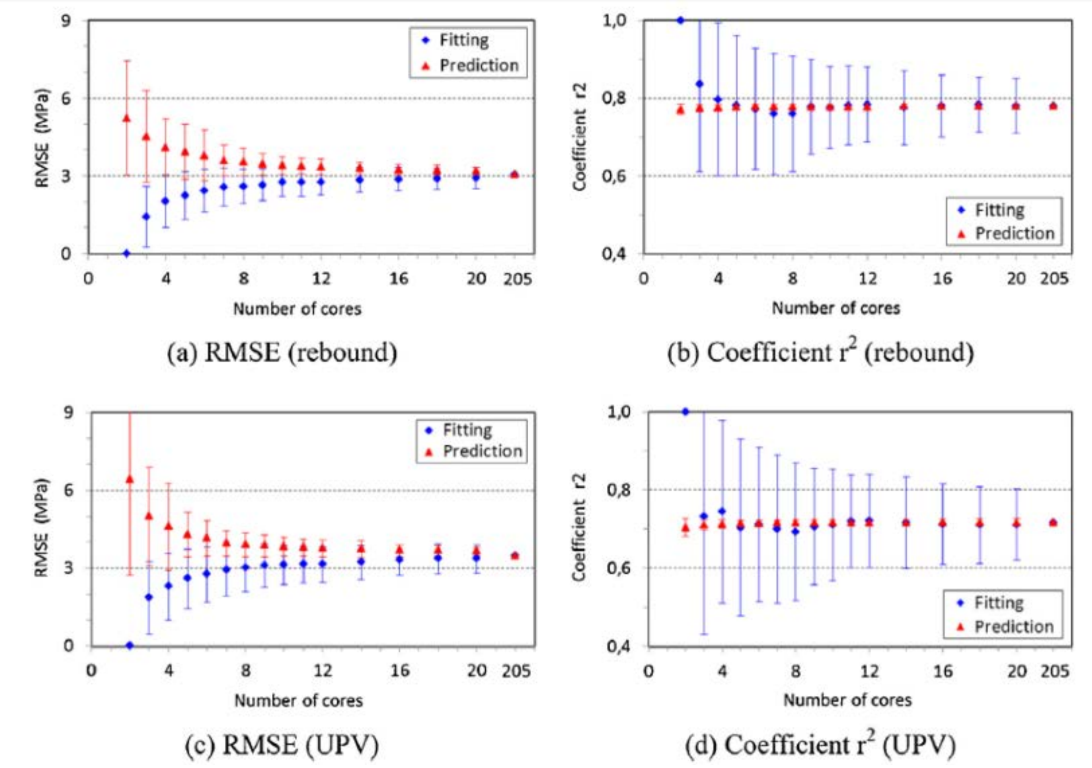


Figure 1. 5: RMSE and r-square for separated NDT (Ali-Benyahia et al. 2017).

Kumvat et al. (2014) was provided a research with various NDT measurements on a eight-year-old structure which was deteriorated by chemical and environmental attacks using maltitude NDT methods such as Ultrasonic pulse velocity, half-cell potential, carbonation depth, rebar locator, cover meter and core sampling.

In this research, half cell potential readings of demonstrates 15 % difference between concrete beam and column and there was 50 to 75% of probability of corrosion in beam member. In this study, direct contact between the concrete surface and the transducers is required for measurements of ultrasonic testing of concrete. It was observed that voids between concrete surface and transducers could cause various errors in results (see Fig. 1.6).

Figure 1. 6: Calibration and UPV test (Kumvat et al. 2014).

Hannachi and Guetteche (2012) represent the effect of using combined (SonReb) method to improve the results of correlation fitting curve.

Table 1. 1: A literature review on regression equations of NDT measurements (Hannachi and Guetteche, 2012).

Eq. No.	Equations	Explanations	Reference	RMSE
Single-variable equations				
1	$fc = 21.575 \times L - 72.276$	fc[MPa], L[cm]	NDT Windsor Sys. Inc.(1994)	3.7813
2	$fc = 1.2 \times 10^{-5} \times V^{1.7447}$	fc[MPa], V[km/s]	Kheder 1 (1998)	6.0974
3	$fc = 0.4030 \times R^{1.2083}$	fc[MPa]	Kheder 2 (1998)	2.1651
4	$fc = 36.72 \times V - 129.077$	fc[MPa], V[km/s]	Quasrawi 1 (2000)	3.6981
5	$fc = 1.353 \times R - 17.393$	fc[MPa]	Quasrawi 1 (2000)	2.8152
6	$fc = -5333 + 5385 \times L$	fc[MPa], L[in]	Malhotra *et al.*	2.2128
Multi-variable equations				
7	$fc = -25.568 + 0.000635 \times R^3 + 8.397V$	fc[MPa], V[km/s]	Bellander (1979)	2.2128
8	$fc = -24.668 + 1.427 \times R + 0.0294V^4$	fc[MPa], V[km/s]	Meynink *et al.* (1979)	7.0654
9	$fc = 0745 \times R + 0.951 \times V - 0.544$	fc[MPa], V[m/s]	Tanigawa *et al.* (1984)	2. 1000
10	$fc = [R/(18.6 + 0.019 \times R + 0.515 \times V)]$	fc[kg/cm²], V[km/s]	Postacioglu (1985)	3.7617
11	11 $fc = 18.6 \times e^{0.019 \times R + 0515V}$	fc[kg/cm²], V[km/s]	Arioglu *et al.* (1991)	2.9205
12	$fc = 10^{3.119} \log R^3 \times {V^4}^{-5.890}$	fc[kg/cm²], V[km/s]	Arioglu *et al.* (1994)	4.2305
13	$fc = -39.570 + 1.532 \times R + 5.0.614 \times V$	fc[kg/cm²], V[km/s]	Raymar *et al.* (1996)	7.5910
14	$fc = 0.00153 \times (R^3 \times V^4)^{0.611}$	fc[kg/cm²], V[km/s]	Arioglu *et al.* (1996)	11.1623
15	$fc = 0.0158 \times V^{0.4254} \times R^{1.1171}$	fc[kg/cm²], V[km/s]	Kheder 3 (1998)	2.1375

Several different linear and nonlinear regression equations have been provided (Table 1.1) and are available in literature such as Tanigawa *et al.* 1984; Malothra and Carino, 1991; Qasrawi, 2000; Arioglu *et al.* 2001.

Using the combined method could decrease the negative effects made by external parameters of each method significantly, these parameters could be certain properties of concrete. For example, an increase in moisture could significantly influence the value of the ultrasonic pulse velocity; however, this change could decrease the value of the rebound hammer simultaneous.

In this research, Rebound hammer and UPV teste was measured simultaneously to obtain concrete properties using correlation analysis between NDT measurements made on existing case study and compressive strength obtained by cores taken from structure.

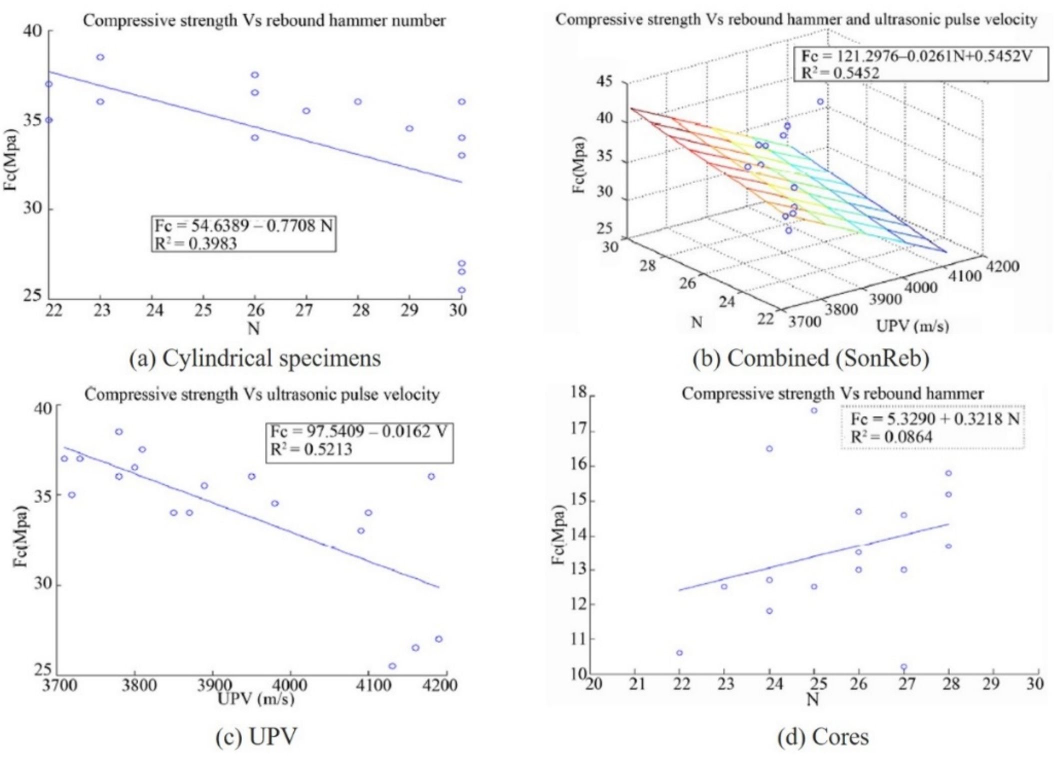


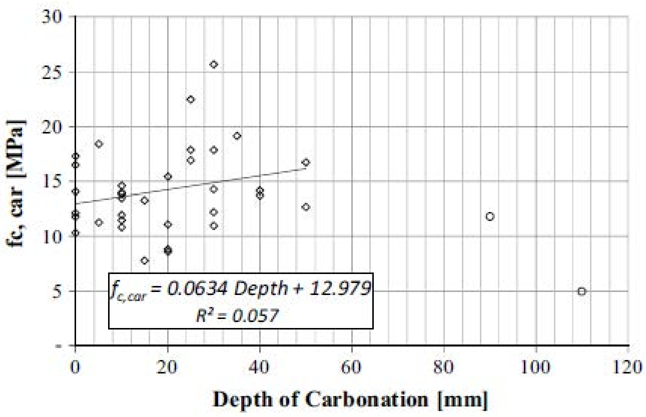
Figure 1. 7: Correlation curves for this study (Hannachi and Guetteche, 2012).

The Equation was developed using both single and combined correlation method to predict the compressive strength of each element in structure; in addition, reliability of predicted results was discussed in this research (see Fig. 1.7).

Pucinotti (2015) provided a research on a series of destructive and non-destructive tests were carried out on an important historic building in Reggio Calabria: the

National Museum of ‘‘Magna Grecia’’. This paper outlines the structure which was tested and the principal results of the testing campaign. The results show the variation of the mechanical properties of the in-situ concrete, the reliability of the combined methods, the need to calibrate the strength obtained by non-destructive methods with the strength of cylindrical specimens (cores) which were extracted from the same structural elements in the proximity of the non-destructive test.

(a)



(b)

Figure 1. 8: Depth of carbonation, (a) test on core C15, (b) test results of all cores (Pucinotti 2015).

The Author shows that the number of calibration cores without decreasing the quality of assessment can be significantly reduced. The Author, in accordance with the EN 13791, considers the two different approaches:

Approach A: consists of looking for a multivariate regression function between the (I and V) values measured on the concrete specimens (either directly on the structure, on cores taken from the structure or on cubes cast with the same concrete) and fc,car values measured on cores:

$$\ln f_{c,car} = \ln a + b \ln V + c \ln I \qquad (1.1)$$

From,

$$f_{c,car} = aV^bI^c \quad (1.2)$$

Approach B: consists in using a prior model, e.g. a ($f_{c,est} = aV^bI^c$) model, where b and c are given, and to calibrate the a value. Calibration can be done by calculating the mean value of estimated strength $f_{c,est,mean}$ and the mean value of experimental strength $f_{c,car,mean}$:

$$k = f_{c,est,mean}/f_{c,car,mean} \quad (1.3)$$

Then can be writinn in this form,

$$f_{c,car} = (a/k)V^bI^c \quad (1.4)$$

Table 1. 2: Regression equation and coefficient of determination.

Method	Correlation curve	Coefficent of determination	Standard deviation
Rebound	$f_{c,car} = 0.00724. I_{rm}^{2.012}$	$R^2 = 0.24$	2.35
UPV	$f_{c,car} = 0.184. e^{0.0011.VLs}$	$R^2 = 0.82$	3.74
SonReb	$f_{c,car} = 9.61. E - 14. I_{rm}^{3.55}. V_{L,s}^{0.90}$	$R^2 = 0.89$	3.53

The Rebound, UPV, and SonReb regressions, R-Square values and standard deviations was derived and illustrated in Table1.2.

The author represent that by simultaneously using of more non-destructive methods under the following conditions, the assessment of concrete properties can be improved (Malhotra and Carette, 1991 and Pucinotti, 2007):

(i) each method provides information about different properties that affect the strength of concrete, (ii) do not require a special sample preparation, (iii) provide a speedy test result, (iv) provide strength estimations through a test method with a similar level of accuracy, (v) do not affect the structural performance of the unit under test. The availability of the two instruments of measure (Rebound Hammer and Ultrasonic Probe) permit the use of the well-known SonReb (Malhotra and Carette, 1991) combined method.

The advantages of implementing the SonReb method is that the variation of some properties of concrete produces opposite effects in the result of each component test. Combined SonReb method could decrease the negative effects of (i) cement type and content, (ii) aggregate size, (iii) moisture content, and (iv) water-to-cement ratio.

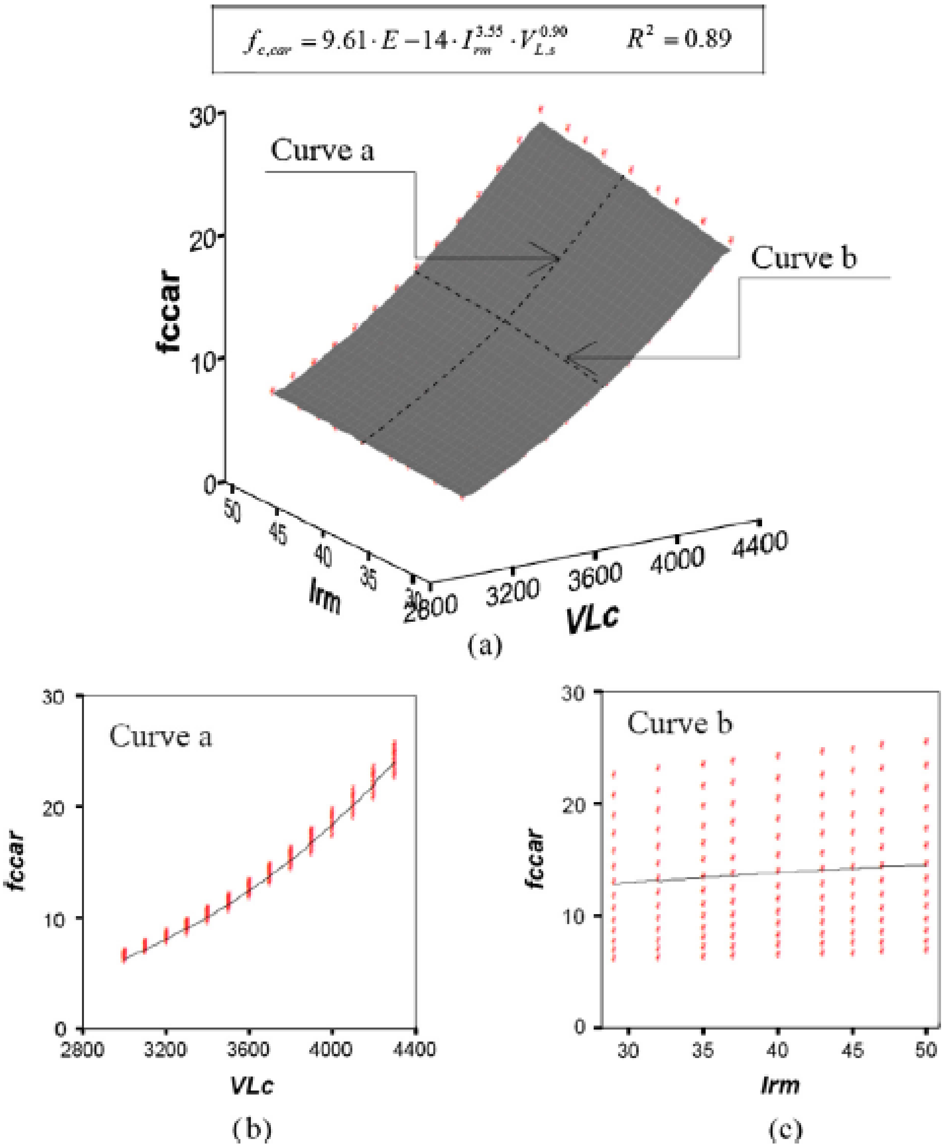


Figure 1. 9: Corellation of combined (SonReb) method (Pucinotti, 2015).

2. DEFINE THE CASE STUDY BUILDINGS

This research was done on four half-finished special fifteen-story buildings that was constructed (the structural part) and was left around 30 years ago at the Zeytinburnu area Istanbul, Turkey (see Fig. 2.1).

Figure 2. 1: Case study buildings (google.com).

The structural design of the building was done based on a unique plan for all stories and buildings and there is no column in the plan as the structural design was done based on lots of shear walls that was shown in Fig. 2.1. The red circles demonstrate the places that cores were taken from which is going to explain in next section.

The heavy black lines show the place of shear walls in building and as it observed plan is symmetric in both directions. In addition, S08 called “CI”, S33 called “CJ”, and S48 called “CK” in data analysis (see Fig. 2.2).

Figure 2. 2: The uniqe plan of buildings.

3. CONDITION ASSESSMENT USING NDT METHODS

The condition assessment of existing buildings was performed using the NDT methods in this section. The Rebound-R, Rebound-Q, and UPV measurements was implemented on the case study buildings associated with coring process.

3.1 Cores and Compressive Strength

In this section, the coring procedure, test, and compressive strength results was measured and intended results was shown for all different cases and sets based on various scenarios.

3.1.1 Coring procedure

In this section, three cores were taken from each story with a total of 45 cores for each building and 180 cores for all four buildings. The process of coring was shown in Figure 3.1.

(a) (b) (c)

Figure 3. 1: Coring process (a) coring machine, (b) taken core and naming, and (c) place of taken core.

3.1.2 Compressive strength of cores

After taking all of the cores from case study buildings they were brought to Istanbul Technical University`s construction materials laboratory and capping was done for all of them by cement paste, then compressive strength was measured by compression machine and stress-strain diagrams was provided by LVDT equipment that was set on machine.

Table 3. 1: Characteristic strength of taken cores from all cases (MPa).

Story	Core	Building			
		A	B	C	D
1	CI	21.224	8.96	25.856	26.032
	CJ	23.024	14.072	19.608	23
	CK	24.416	11.816	21.592	24.416
2	CI	19.024	13.808	28.256	26.952
	CJ	21.648	11.664	23.424	26.12
	CK	21.312	18.584	22.944	32.96
3	CI	17.432	15.184	26.064	23.168
	CJ	13.616	10.376	27.296	24.552
	CK	21.56	14.848	18.64	28.2
4	CI	20.736	10.408	21.968	23.896
	CJ	20.8	12.648	17.488	22.4
	CK	18.928	11.912	23.608	23.784
5	CI	13.512	13.184	29.432	21.6
	CJ	19.608	12.752	23.208	16.016
	CK	22.04	7.216	22.92	21.88
6	CI	23.632	16.304	24.592	17.432
	CJ	16.424	11.192	23.08	24.16
	CK	17.248	12.232	18.504	24.736
7	CI	23.32	13.912	30.768	17.672
	CJ	17.256	16.24	26.952	19.416
	CK	15.504	13.992	23.656	22.056
8	CI	26.12	15.32	33.104	26.536
	CJ	15.296	13.064	29.984	11.704
	CK	24.096	16.968	26.096	22.096
9	CI	16.856	15.584	24.208	24.448
	CJ	19.472	16.496	22.896	20.728
	CK	17.376	15.088	20.784	26.856
10	CI	20.36	18.408	27.944	20.648
	CJ	14.256	18.248	24.576	22.944
	CK	20.912	16.496	22.944	24.24
11	CI	28.592	11.616	29.912	27.504
	CJ	24.24	12.032	27.4	22.96
	CK	27.768	12.136	31.264	22.296
12	CI	28.648	21.488	26.744	22.696
	CJ	20.448	15.088	25.352	22.168
	CK	23.04	14.088	22.72	22.656
13	CI	22.712	11.864	21.888	18.064

	CJ	30	8.16	26.928	24.104
	CK	25.256	13.232	21.888	22.24
14	CI	21.488	14.96	20.544	14.32
	CJ	19.04	16.52	18.872	13.08
	CK	38.528	12.992	23.296	16.032
15	CI	23.4	13.352	19.888	10.88
	CJ	18.984	15.664	20.944	14.328
	CK	21.744	9.808	17.744	18.072

The characteristic strength of all 180 taken cores from four different case study building which were three cores in each story named CI, CJ, and CK was illustrated in Table 3.1.

3.2 NDT Methods (Methodology and Correlations)

Three different methods were used in this section which are as below, Rebound-R, Rebound-R, and UPV measurements.

The process of the experimental and analytical works was explained and shown separately for each building (A, B, C, and D) and for whole data then they were compared and discussed at the end part of each section.

The process of the experimental and Rebound-R type hammer, Rebound-Q type hammer, Ultrasonic Pulse Velocity, SonReb-R, and SonReb-Q was shown and described in introduction part for building A. In this section, the results of measurements for above mentioned test methods was done and analytical study was done on this results.

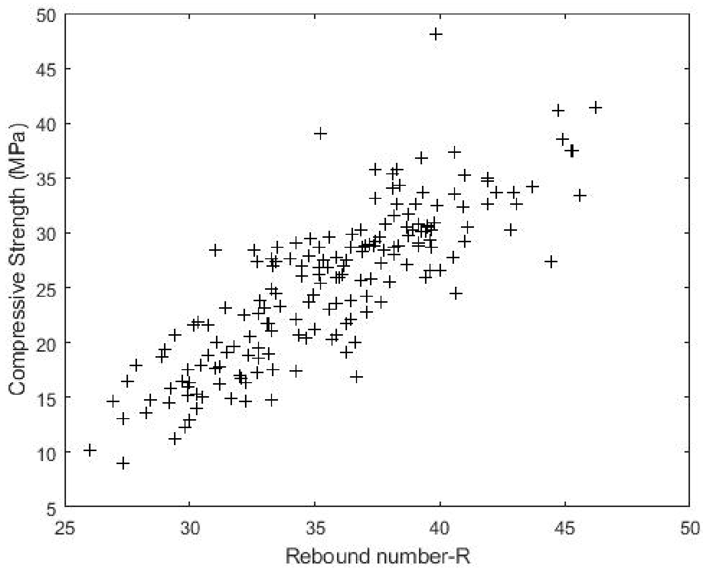


Figure 3. 2: All 180 data for buildings (Rebound-R).

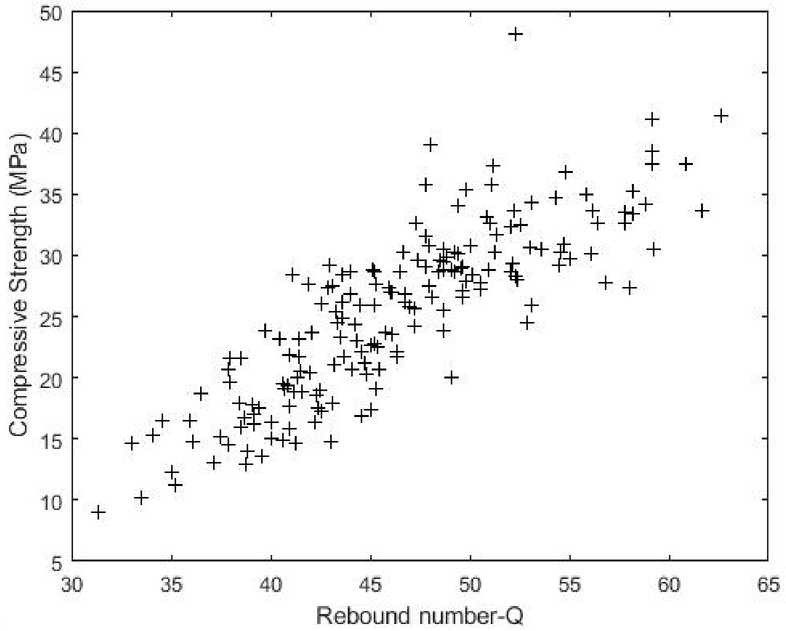


Figure 3. 3: All 180 data for buildings (Rebound-Q).

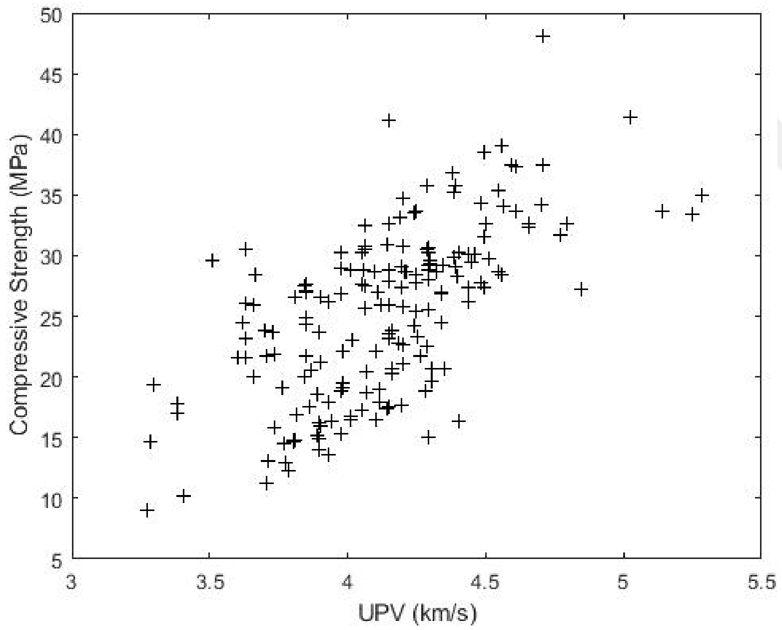


Figure 3. 4: All 180 data for buildings (UPV).

The Rebound R, Rebound Q, UPV vs. Compressive strength (MPa) results for taken cores was shown in Figure 3.2-4 for all 180 paired cores and tests result

The correlations and equation were derived based on different scenarios and R-square values was shown for each equation type and test method also. Considering the R-square values and standard deviations, correlation figures and equations was derived and demonstrated for the optimum selecting set in each scenario for each building and considering all building as one case, also.

3.2.1 First scenario (taking single core in each story)

In this scenario single core was selected in each story and correlations was derived based on the data and measurements for single cores. In order to consider the effect of choosing single cores among three cores in each story four different sets was considered; (1) selecting CI cores in each story, (2) selecting CJ cores in each story, (3) selecting CK cores in each story, and (4) selecting CI in first, CJ in second, CK in third stories and continue this method respectively until 15th story.

3.2.1.1 First scenario-building A

In this part the sets and correlations which was derived based on first scenario was illustrated in various tables and figures fro building A.

Table 3. 2: R-square and standard deviation values of different equations and methods for building (A).

NDT Method	Equation type	CI		CJ		CK		CIJK	
		r^2	SD	r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.254	2.179	0.747	4.207	0.529	3.572	0.536	3.075
	Poly. 2nd	0.272		0.779		0.540		0.536	
	Poly. 3rd	0.363		0.783		0.549		0.537	
	Power	0.251		0.757		0.535		0.536	
	Expo.	0.244		0.771		0.538		0.535	
Rebound-Q	Linear	0.254	3.770	0.730	5.776	0.592	4.591	0.582	4.671
	Poly. 2nd	0.259		0.743		0.618		0.586	
	Poly. 3rd	0.350		0.779		0.621		0.586	
	Power	0.253		0.735		0.603		0.582	
	Expo.	0.248		0.744		0.611		0.586	
UPV	Linear	0.253	0.345	0.600	0.353	0.317	0.446	0.184	0.364
	Poly. 2nd	0.336		0.632		0.317		0.184	
	Poly. 3rd	0.399		0.685		0.320		0.209	
	Power	0.254		0.611		0.317		0.183	
	Expo.	0.265		0.623		0.315		0.183	
SonReb (R)	R 1st , V 1st	0.374	-	0.747	-	0.575	-	0.545	-
	R 2nd , V 2nd	0.448		0.803		0.716		0.599	
SonReb (Q)	Q 1st , V 1st	0.369	-	0.730	-	0.604	-	0.583	-
	Q 2nd , V 2nd	0.451		0.768		0.676		0.607	

Based on the results which are obtained based on Table 3.2 considering R-square and standard deviation values, CIJK set was selected as the same set among the four sets and correlation curves and regression equations was demonstrated for this set for building A.

Table 3. 3: Correlation equations of CIJK set for building (A).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.7465R - 1.694$	0.5363	3.0752
	Poly. 2nd	$F = 0.00266R^2 + 0.5505R + 1.893$	0.5364	
	Poly. 3rd	$F = -0.002698R^3 + 0.3007R^2 - 10.33R + 133.7$	0.5376	
	Power	$F = 0.5501R^{1.067}$	0.5364	
	Expo.	$F = 9.908 \exp(0.02877R)$	0.5353	
Rebound-Q	Linear	$F = 0.5123Q + 1.573$	0.5829	4.6715
	Poly. 2nd	$F = 0.00781Q^2 - 0.2192Q + 18.53$	0.5867	
	Poly. 3rd	$F = -0.00026Q^3 + 0.04417Q^2 - 1.901Q + 44.25$	0.5868	
	Power	$F = 0.6821\ Q^{0.9421}$	0.5826	
	Expo.	$F = 9.918 \exp(0.02013Q)$	0.5862	
UPV	Linear	$F = 3.694\ V + 10.6$	0.1840	0.3640
	Poly. 2nd	$F = 0.03027\ V^2 + 3.443\ V + 11.11$	0.1841	
	Poly. 3rd	$F = -10.79\ V^3 + 136.5\ V^2 - 568.9V + 806.9$	0.2095	
	Power	$F = 11.2\ V^{0.5903}$	0.1839	
	Expo.	$F = 14.35 \exp(0.1422V)$	0.1839	
SonReb (R)	R 1st , V 1st	$F = 0.6948R + 0.926V - 3.595$	0.5453	-
	R 2nd , V 2nd	$F = 0.9056R - 47.3\ V - 0.0456R^2 + 0.7894RV + 2.29V^2 + 90.31$	0.5993	
SonReb (Q)	Q 1st , V 1st	$F = 0.5199Q - 0.1687V + 1.906$	0.5831	-
	Q 2nd , V 2nd	$F = 0.1235Q - 28.19V + 0.01147Q^2 - 0.1574QV + 4.234V^2 + 68.62$	0.6070	

Table 3.3 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The EN 13791 curve in Fig. 3.5 demonstrates the curve which is suggested by the EN 13791 standard considering the data which was obtained from compressive tests and NDT measurements. In addition, the EN 13791 (shifted) curve is the curve with -10 shift from the main curve to consider more accuracy based on EN 13791.

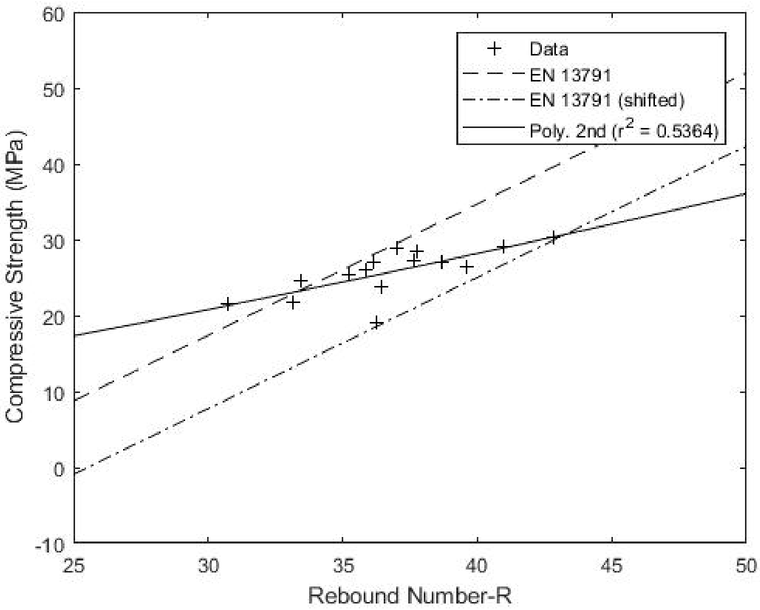


Figure 3. 5: Correlation: Rebound R vs. Compressive Strength of set CIJK (A).

Furthermore, the Poly. 2nd curve in this figure which was drawn using Matlab software demonstrates better proximity to the obtained data with the R-square value of 0.5364; however, because of compaction in data in small length it seems like a linear correlation.

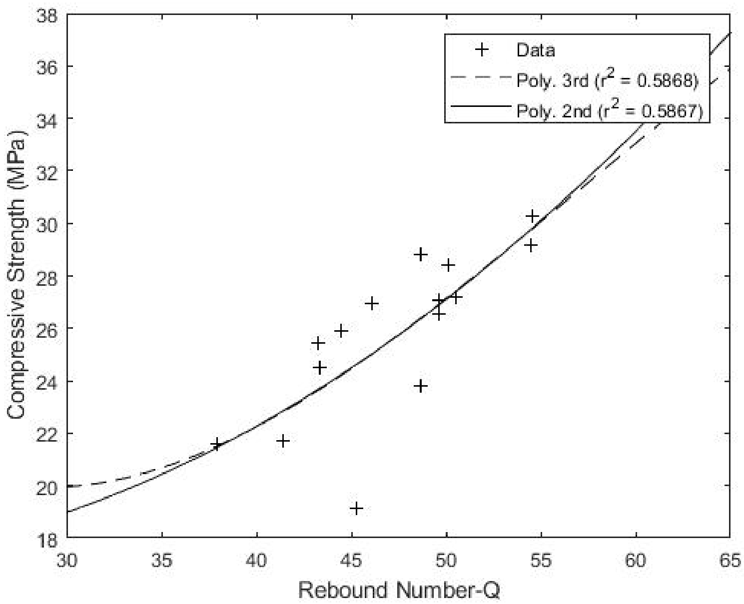


Figure 3. 6: Correlation: Rebound Q vs. Compressive Strength of set CIJK (A).

There is a lack of information for Silver Schmidt hammer (Q type) in the EN 13791 standard thus, there is no suggested equation and curve for data obtained from measurements using this hammer. In order to comparison Poly. 2nd and poly. 3rd degree correlations was shown in Fig. 3.6 and the results demonstrate that due to the dispersion of data there is almost no difference in using poly. 2nd or poly. 3rd degree curves and intended regressions; however, in order to the simplicity of poly. 2nd degree in the equation this curve suggested using for estimate the concrete strength at the studied case (building A).

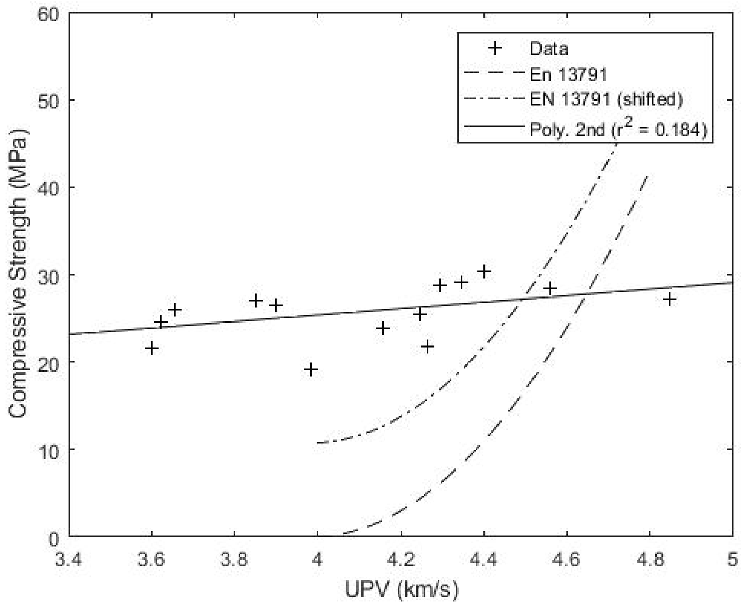


Figure 3. 7: Correlation: UPV vs. Compressive Strength of set CIJK (A).

The data dispersion leads to the approximately linear correlation between UPV measurements and compressive strength and it was observed from the poly. 2nd degree curve which is close to the linear shape than polynomial shape. In addition, in order to standard limits both of standards curves (main curve and the shifted one) was calculated and drawn between 4 and 4.8 using the measurements which was obtained between this range; however, the poly. 2 degree which covers all of the measurements and the related compressive strengths, derived based on all obtained data from 3.6 to 4.85 (km/s) of UPV measurements (see Fig 3.7).

The combined SonReb method significantly increases the accuracy and the R-square value for the correlation using UPV, Rebound Number-R and Compressive Strength measurements due to using 3-D correlation using intended data. As it is illustrated in Fig. 3.8 the correlation which was derived using three different data increase the R-square by 11.7 % compared with Rebound-R to 0.5993 (see Table 3.3).

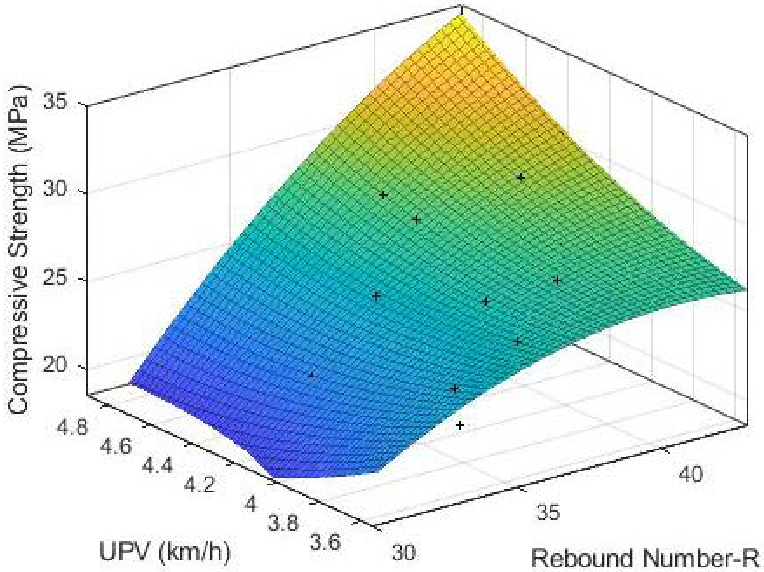


Figure 3. 8: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJK (A).

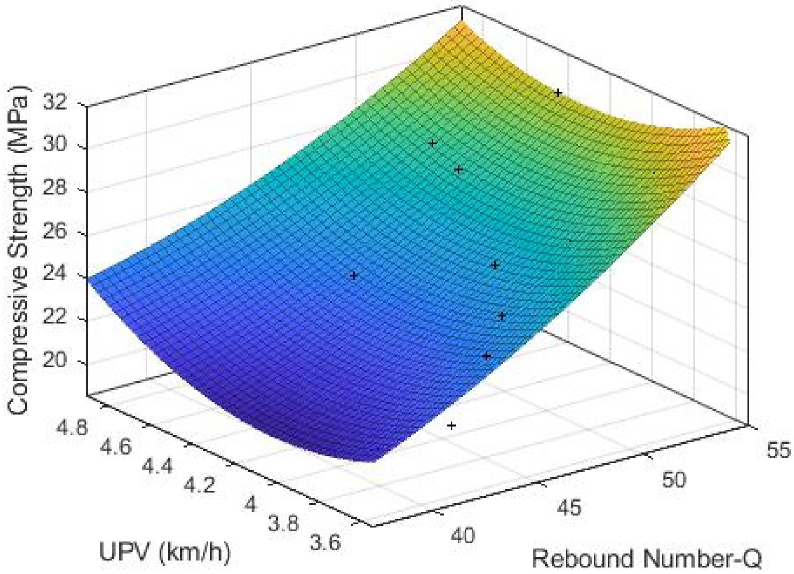


Figure 3. 9: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJK (A).

The combined SonReb method has better results and higher efficiency in Rebound-Q compared Rebound-R and it was observed in Fig. 3.9 and the equations and intended R-square values prove this in Table 3.3. However, it has less increase comparing the Poly. 2nd degree of Rebound-Q correlations (the amount of increase is 3.4 %). This occurs due to the higher R-square value of Rebound-Q than Rebound-R data 2-D correlations with compressive strength.

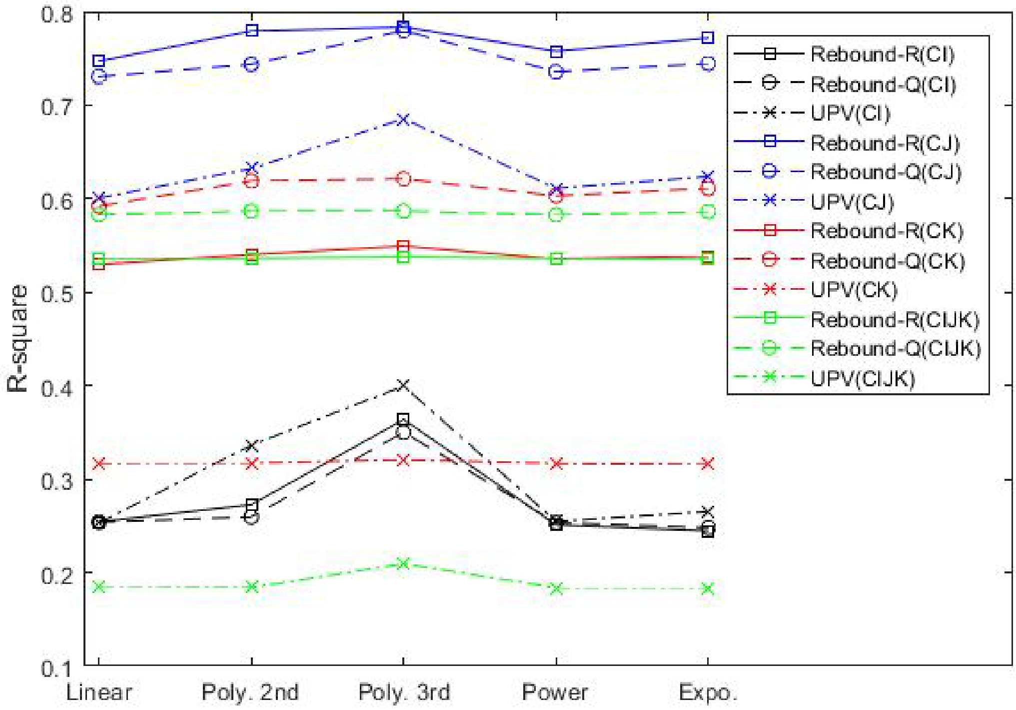


Figure 3. 10: R-square values for different equations, methods, and sets (A).

The R-square values for all single core sets for building A was shown in Fig. 3.10 based on all five different equations which were used for correlations and regressions for all three NDT methods. As it is observed in Fig. 3.10 the R-square values for Poly. 3rd degree correlation reaches the highest amount compare other four correlation equation type and the slop of increase is significant and higher than other sets. However, this change in the slop of curves in Fig. 3.10 for some sets such as CK and CIJK is almost flat with little increase in Poly. 3rd degree correlation. In addition, the increase in R-square value from linear to Poly. 2nd correlation and then decrease from Poly. 3rd to power and expo. correlations was illustrated in this figure.

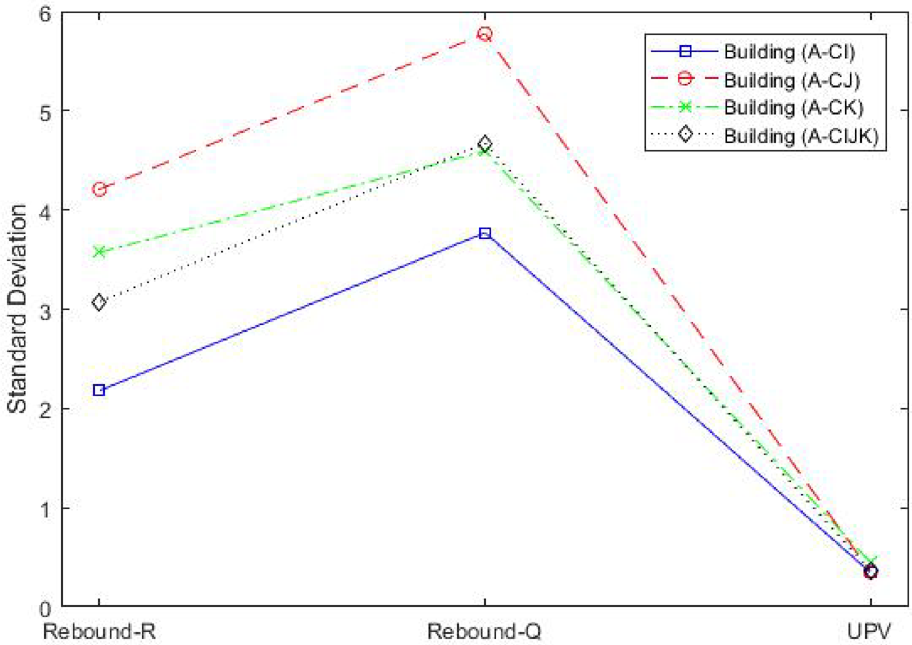


Figure 3. 11: Standard deviation of different sets of single core (A).

The standard deviation for all four sets including CI, CJ, CK, and CIJK and for three various methods was observed in Fig. 3.11. The amount of standard deviation for all sets shows that there is an increase in standard deviation of Rebound-Q compared with Rebound-R and maybe it is the reason that in some sets the amount of R-square value gets higher for Rebound-R type than Rebound-Q. The amount of increase for different sets differs from 30-40 % comparing Rebound-R and Rebound-Q. Furthermore, the standard deviation for UPV measurements demonstrates lower values and in order to differentiate between the amount type the comparison could not make for UPV measurements data and other two rebounds data.

3.2.1.2 First scenario-building B

In this part, the sets and correlations which was derived based on the first scenario was illustrated in various tables and figures fro building B.

Table 3. 4: R-square and standard deviation values of different equations and methods for building (B).

NDT Method	Equation type	CI		CJ		CK		CIJK	
		r^2	SD	r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.637	2.706	0.592	2.784	0.471	2.400	0.377	2.174
	Poly. 2nd	0.677		0.593		0.474		0.396	
	Poly. 3rd	0.711		0.623		0.474		0.442	
	Power	0.648		0.590		0.467		0.381	
	Expo.	0.658		0.585		0.461		0.388	
Rebound-Q	Linear	0.525	3.366	0.461	3.216	0.568	3.988	0.422	3.439
	Poly. 2nd	0.530		0.463		0.578		0.422	
	Poly. 3rd	0.536		0.463		0.607		0.422	
	Power	0.522		0.462		0.564		0.422	
	Expo.	0.517		0.464		0.555		0.421	
UPV	Linear	0.572	0.185	0.578	0.291	0.608	0.215	0.280	0.230
	Poly. 2nd	0.587		0.612		0.609		0.545	
	Poly. 3rd	0.743		0.679		0.637		0.565	
	Power	0.583		0.566		0.605		0.271	
	Expo.	0.587		0.553		0.599		0.259	
SonReb (R)	R 1st , V 1st	0.714	-	0.739	-	0.733	-	0.497	-
	R 2nd , V 2nd	0.820		0.825		0.742		0.823	
SonReb (Q)	Q 1st , V 1st	0.684	-	0.682	-	0.759	-	0.494	-
	Q 2nd , V 2nd	0.793		0.910		0.784		0.749	

Based on the results which are obtained based on Table 3.4 considering R-square and standard deviation values, CIJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set for building B.

Table 3. 5: Correlation equations of CIJK set for building (B).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.8916R - 11.27$	0.3773	2.1749
	Poly. 2nd	$F = 0.07672R^2 - 3.942R + 64.51$	0.3962	
	Poly. 3rd	$F = 0.05187R^3 - 4.807R^2 + 148.7R - 1520$	0.4429	
	Power	$F = 0.04643R^{1.707}$	0.3818	
	Expo.	$F = 3.017\exp(0.05433R)$	0.3881	
Rebound-Q	Linear	$F = 0.5963Q - 7.202$	0.4220	3.4393
	Poly. 2nd	$F = 0.001974Q^2 + 0.4407Q - 4.158$	0.4220	
	Poly. 3rd	$F = -0.00146Q^3 + 0.1758Q^2 - 6.43Q + 85.97$	0.4222	
	Power	$F = 0.08035\ Q^{1.445}$	0.4220	
	Expo.	$F = 3.84\exp(0.0365Q)$	0.4211	
UPV	Linear	$F = 7.242\ V - 12.64$	0.2802	0.2308
	Poly. 2nd	$F = -37.04\ V^2 + 307\ V - 617.1$	0.5450	
	Poly. 3rd	$F = 56.5\ V^3 - 721.6\ V^2 + 3067V - 4320$	0.5653	
	Power	$F = 1.613\ V^{1.669}$	0.2712	
	Expo.	$F = 3.244\exp(0.4031V)$	0.2592	
SonReb (R)	R 1st , V 1st	$F = 0.7161R + 5.015V - 25.89$	0.4971	-
	R 2nd , V 2nd	$F = 0.9056R - 47.3\ V - 0.0456R^2 + 0.7894RV + 2.29V^2 + 90.31$	0.8231	
SonReb (Q)	Q 1st , V 1st	$F = 0.474Q + 4.109V - 18.8$	0.4944	-
	Q 2nd , V 2nd	$F = 6.561Q + 168.2V + 0.06811Q^2 - 2.899QV - 6.123V^2 - 465.5$	0.7495	

Table 3.5 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The obtained data from Rebound-R measurements and compressive strength tests demonstrate that the data is very compacted compared other buildings single sets and the related correlations illustrate low R-square values. Based on Fig. 3.12 the Poly. 2nd degree curve could not cover all data as well as other curves for the same single set core in the other buildings. The En 13791 curves due to data compaction could not cover all data for reaching best results.

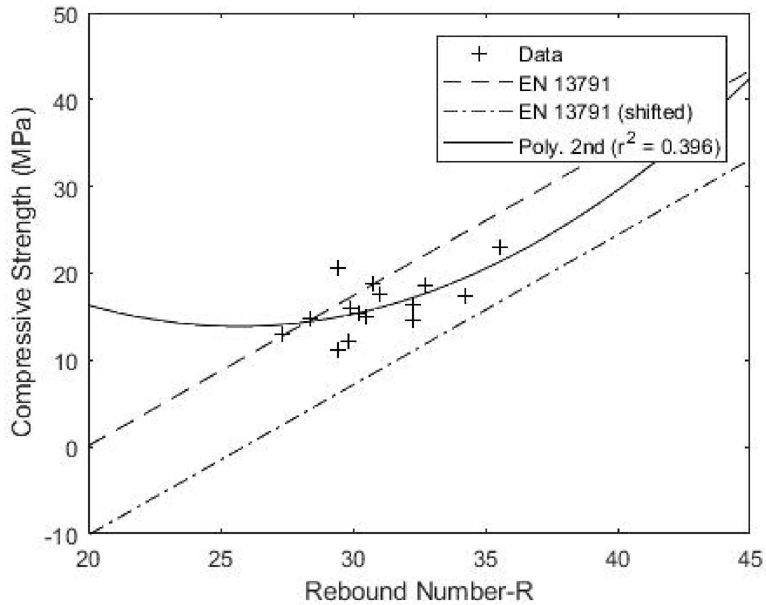


Figure 3. 12: Correlation: Rebound R vs. Compressive Strength of set CIJK (B).

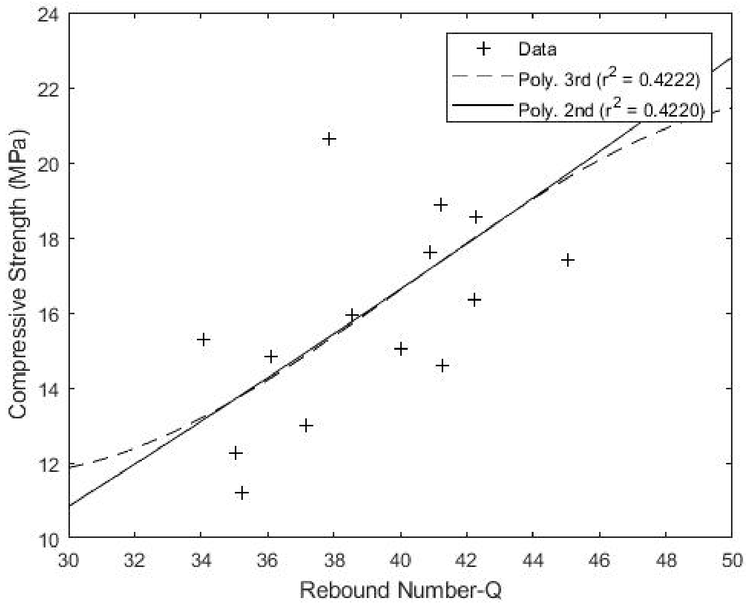


Figure 3. 13: Correlation: Rebound Q vs. Compressive Strength of set CIJK (B).

Despite the Rebound-R data dispersion condition, the data dispersion for the Rebound-Q is in the better condition compared the intended one. According to Fig. 3.13 the correlation curves which was illustrated by Poly. 2nd and Poly. 3rd are approximately the same due to the obtained R-square values (0.4220 and 0.4222 respectively) for each curve.

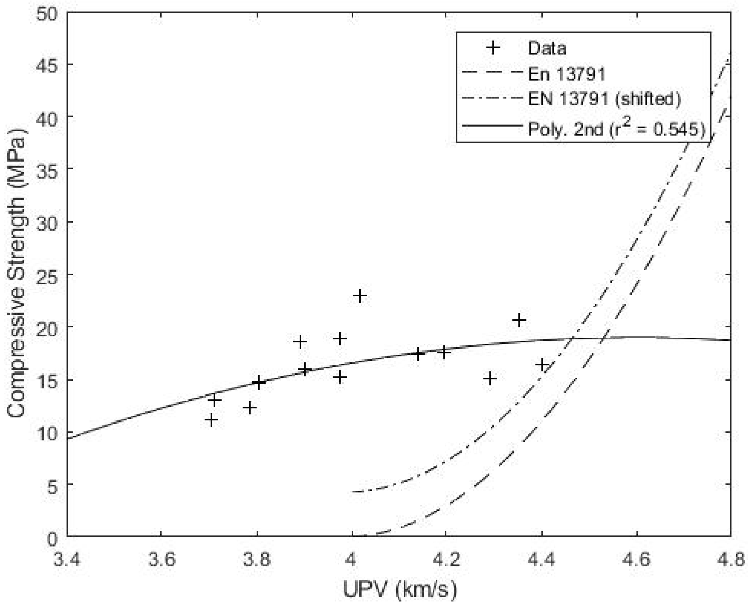


Figure 3. 14: Correlation: UPV vs. Compressive Strength of set CIJK (B).

The UPV measurements for the single core in building B shows better results for UPV-Compressive strength correlations compared other sets and building using inverse Poly. 2nd degree curve with R-square value of 0.5450. However, the number of data which are sited on the range which was determined by the En 13791 standard are lower than other sets and most of the UPV measurements are lower than 4 which is out of the intended range (see Fig. 3.14).

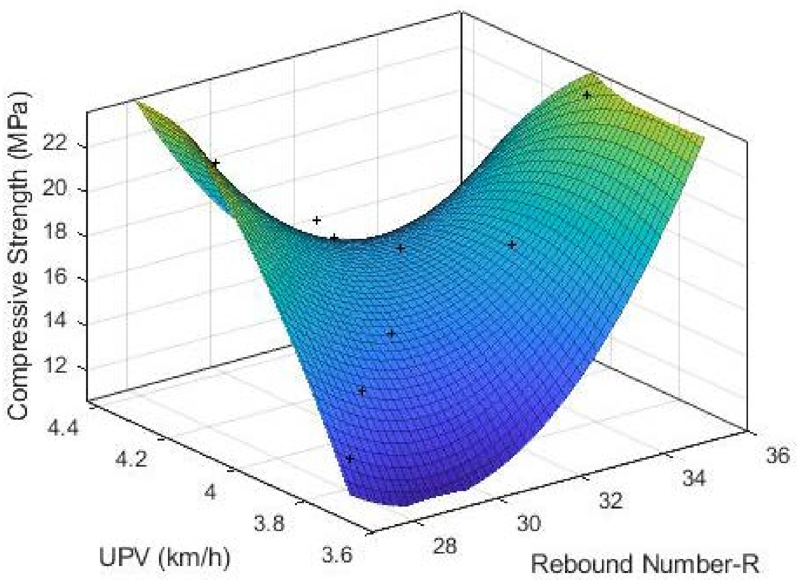


Figure 3. 15: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJK (B).

The combined method for the CIJK set of building B was observed in Fig. 3.15 and the related curves demonstrates the double polynomial curve in both directions which helps to reach better correlation in 3-D condition-the double linear correlation has almost no positive effect and shows no improvement due to data special dispersion-with higher R-square value (0.8231) which demonstrates a great improvement considering the weak values which was obtained for Rebound-R (see Table 3.5).

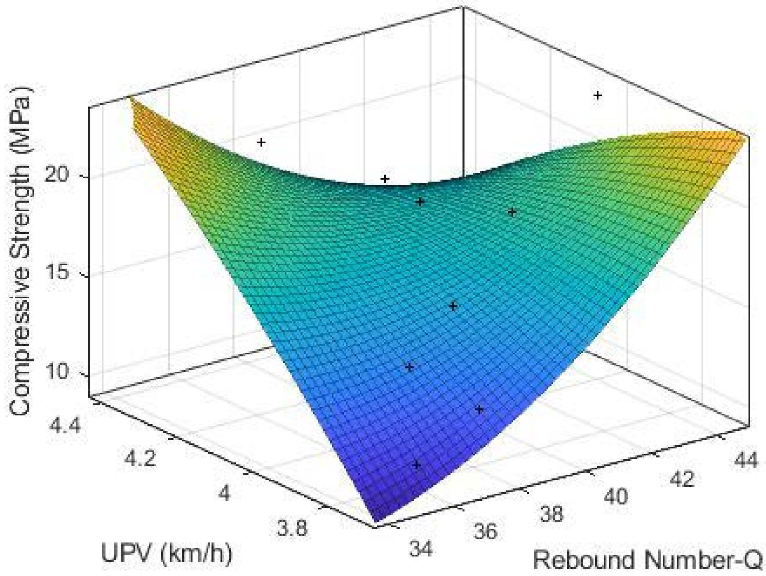


Figure 3. 16: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJK (B).

Figure 3.16 illustrates the 3-D combined SonReb method for Rebound number-Q vs UPV vs Compressive strength and like the Rebound-R the data dispersion requires to have double polynomial correlation curves to reach the higher and improved R-square value. According to Table 3.5, there is a 0.51 % increase in R-square value while using double polynomial correlation compared using linear correlation curves. In addition, the analysis reveals that there is approximately 0.77 % increase in R-square value comparing combined SonReb method and normal Poly. 2nd degree correlation`s R-square values.

The R-square values of four different sets and three various methods was illustrated in Fig. 3.17 for five different correlation equation (regression) types for building B.

The behavior of curves in Fig. 3.17 demonstrates that most of the sets and methods behave like each other; however, there are some differences such as (i) the abnormal increase of R-square value in Poly. 2nd and Poly. 3rd degree equations of UPV-

Compressive strength correlation in set CIJK which occurs due to data dispersion that is not suitable for making the linear correlation and requires polynomial curves, and (ii) the slight increase of R-square value in Poly. 3rd degree equation in some cases like Rebound-R(CI), UPV(CI), UPV(CJ), Rebound-Q(CK), and UPV(CIJK).

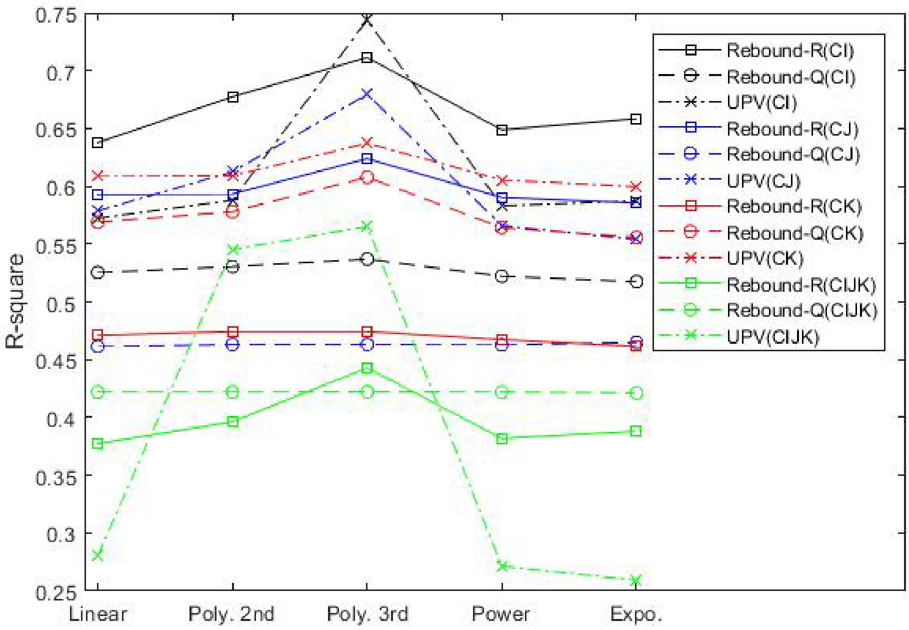


Figure 3. 17: R-square values for different equations, methods, and sets (B).

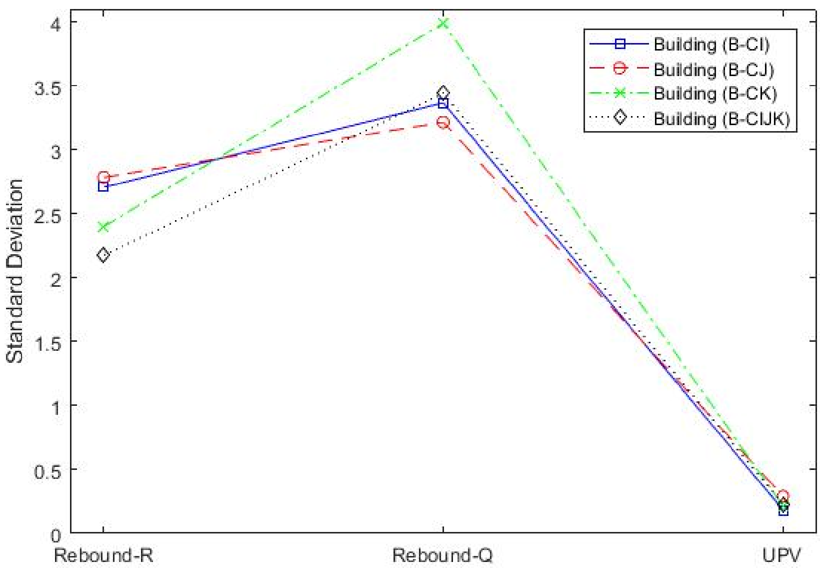


Figure 3. 18: Standard deviation of different sets of single core (B).

There is an increase in the standard deviation magnitude in Rebound-Q compared Rebound-R and it is almost same with the previous buildings sets. In addition, there is almost 35.6 % increase in average for Rebound-Q compared Rebound-R which was observed in Fig. 3.18 and determined in Table 3.4 for different sets.

3.2.1.3 First scenario-building C

In this part the sets and correlations which was derived based on first scenario was demonstrated in various tables and figures fro building C.

Table 3. 6: R-square and standard deviation values of different equations and methods for building (C).

NDT Method	Equation type	CI		CJ		CK		CIJK	
		r^2	SD	r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.402	3.765	0.655	3.732	0.112	3.023	0.612	4.792
	Poly. 2nd	0.445		0.659		0.112		0.679	
	Poly. 3rd	0.458		0.668		0.141		0.724	
	Power	0.402		0.657		0.112		0.616	
	Expo.	0.389		0.659		0.111		0.635	
Rebound-Q	Linear	0.483	5.221	0.612	6.038	0.304	4.112	0.690	6.951
	Poly. 2nd	0.500		0.620		0.317		0.705	
	Poly. 3rd	0.568		0.639		0.331		0.712	
	Power	0.483		0.612		0.305		0.691	
	Expo.	0.473		0.602		0.297		0.699	
UPV	Linear	0.410	0.463	0.602	0.374	0.436	0.236	0.534	0.399
	Poly. 2nd	0.527		0.641		0.521		0.538	
	Poly. 3rd	0.535		0.656		0.562		0.657	
	Power	0.412		0.597		0.449		0.531	
	Expo.	0.389		0.580		0.463		0.518	
SonReb (R)	R 1st , V 1st	0.464	-	0.712	-	0.438	-	0.675	-
	R 2nd , V 2nd	0.559		0.736		0.578		0.747	
SonReb (Q)	Q 1st , V 1st	0.521	-	0.678	-	0.450	-	0.722	-
	Q 2nd , V 2nd	0.597		0.690		0.680		0.760	

Based on the results which are obtained based on Table 3.6 considering R-square and standard deviation values, CIJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set for building C.

Table 3. 7: Correlation equations of CIJK set for building (C).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.8647R - 4.318$	0.6129	4.7921
	Poly. 2nd	$F = 0.06885R^2 - 4.43R + 96.01$	0.6790	
	Poly. 3rd	$F = -0.01607R^3 + 1.905R^2 - 73.69R + 959.1$	0.7243	
	Power	$F = 0.3885R^{1.181}$	0.6166	
	Expo.	$F = 8.701\exp(0.03097R)$	0.6351	
Rebound-Q	Linear	$F = 0.6326Q - 2.636$	0.6903	6.9518
	Poly. 2nd	$F = 0.01838Q^2 - 1.235Q + 43.99$	0.7059	
	Poly. 3rd	$F = -0.002202Q^3 + 0.3504Q^2 - 17.77Q + 315.7$	0.7127	
	Power	$F = 0.3901\,Q^{1.101}$	0.6914	
	Expo.	$F = 9.665\exp(0.02175Q)$	0.6994	
UPV	Linear	$F = 9.696\,V - 12.99$	0.5342	0.3990
	Poly. 2nd	$F = -1.574\,V^2 + 23.68\,V - 43.79$	0.5388	
	Poly. 3rd	$F = -17.45\,V^3 + 231.7\,V^2 - 1007V + 1462$	0.6574	
	Power	$F = 3.622\,V^{1.418}$	0.5313	
	Expo.	$F = 7.504\exp(0.3106V)$	0.5188	
SonReb (R)	R 1st , V 1st	$F = 0.5879R + 4.7V - 14.03$	0.6756	-
	R 2nd , V 2nd	$F = -2.651R - 14.25\,V + 0.09943R^2 - 0.9887RV + 6.322V^2 + 89.79$	0.7476	
SonReb (Q)	Q 1st , V 1st	$F = 0.4859Q + 3.481V - 10.4$	0.7221	-
	Q 2nd , V 2nd	$F = 0.3837Q - 16.82V + 0.0542Q^2 - 1.226QV + 9.242V^2 + 37.87$	0.7603	

Table 3.7 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results was illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data dispersion of CIJK set of building C for Rebound number-R is suitable for a better correlation compared previous sets and buildings and as it is observed in Fig. 3.19 both EN 13791 curves and Poly. 2nd correlation curves could properly cover the data and it was proven by the R-square value of 0.6790 for Poly. 2nd degree correlation. In addition according to Table 3.7 the other correlations demonstrates high magnitude for R-square value, also.

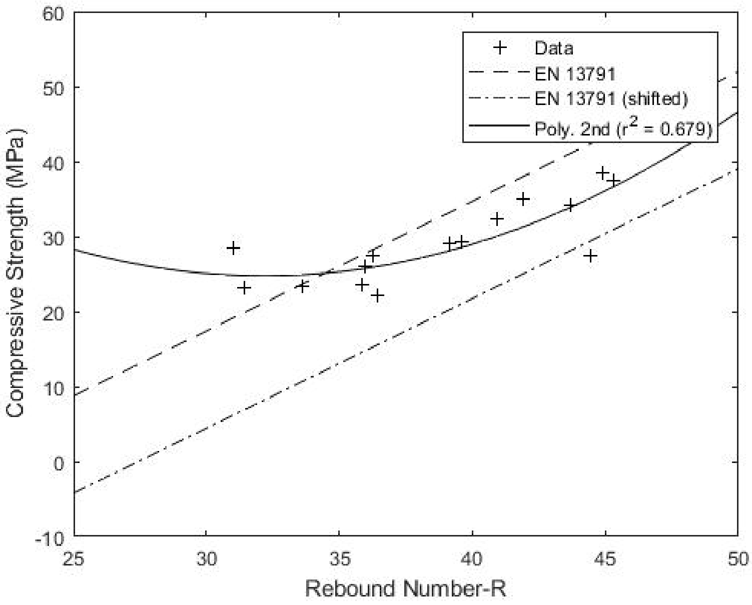


Figure 3. 19: Correlation: Rebound R vs. Compressive Strength of set CIJK (C).

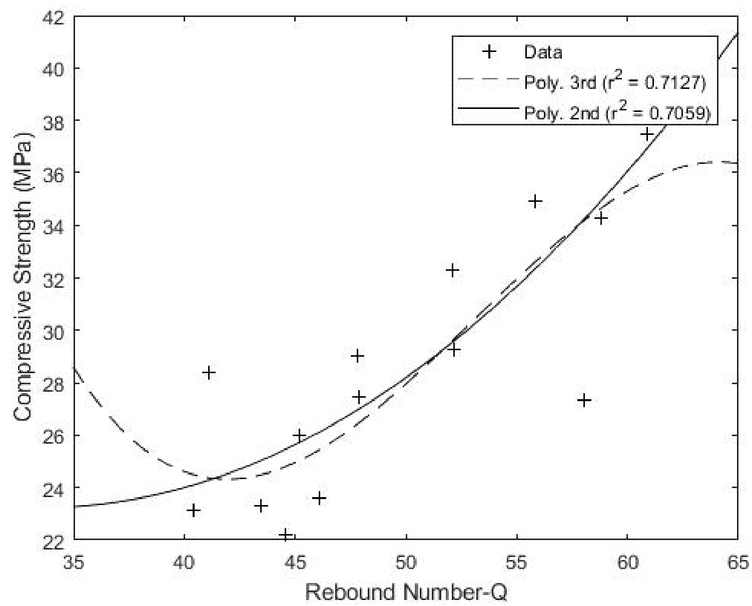


Figure 3. 20: Correlation: Rebound Q vs. Compressive Strength of set CIJK (C).

Figure 3.20 illustrates the Poly. 2nd and Poly. 3rd degree correlations for Rebound-Q vs Compressive strength with R-square values of 0.7059 and 0.7127 respectively. Although the R-square values have a few differences with each other and even with linear and power correlations' R-square values (see Table 3.7), the curve shape in Fig. 3.20 demonstrates that the Poly. 3rd correlation curves have better and proper cover over the intended data thus, it could be more reliable than the other correlation; however, the simplicity factor for the equation was not considered in this decision.

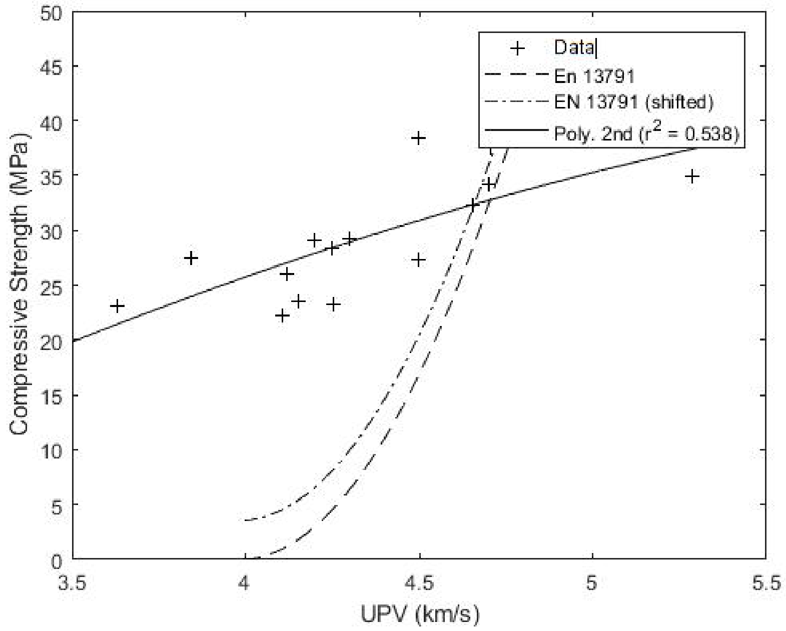


Figure 3. 21: Correlation: UPV vs. Compressive Strength of set CIJK (C).

In some special case when the data dispersion is not in polynomial shape- which is suitable for EN 13791 suggested curve- and the compressive strength values are in high values the EN 13791 curve and it`s shifted curve could not cover the data and the correlation curves by the standards are not reliable anymore as it is observed in Fig 3.21. However, the Poly. 2nd correlation curve by Matlab software could properly cover the data due to using the inverse type of this polynomial which is more suitable for this data dispersion and the R-square value reach to the 0.5380 which is a higher value compared other UPV measurements correlations.

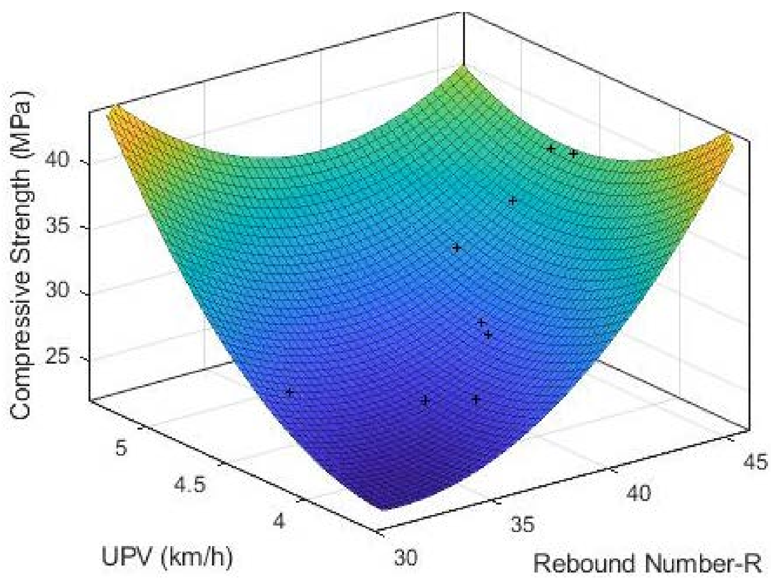


Figure 3. 22: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJK (C).

The plate which was derived using the combined correlation of Rebound-R vs UPV vs Compressive strength in Fig. 3.22. The shape and slope of both curves demonstrate that the polynomial curve is the best option for this data dispersion and the results were observed in Table 3.7 which indicates that there is 10.5 % increase while using polynomial curves instead of using a linear plate for this data correlation. The R-square values for linear and polynomial correlation curves are 0.6756 and 0.7476 respectively.

The shape of the plate is so close to the Rebound-R combined SonReb correlation (Fig. 3.22); however, there is high deflection at final parts of both sides in the plate which shows the difference in data dispersion between the Rebound-Q combined SonReb correlation and the previous one (see Fig. 3.23). In addition, polynomial correlation is also the proper option for the intended data because there is a 5.3 % increase compared linear one; however, if the simplicity of equations and curves was considered, using linear correlation is more reliable because the difference between linear and polynomial correlations`s R-square values is not such a great amount and could be neglected easily considering the simplicity of the linear plate.

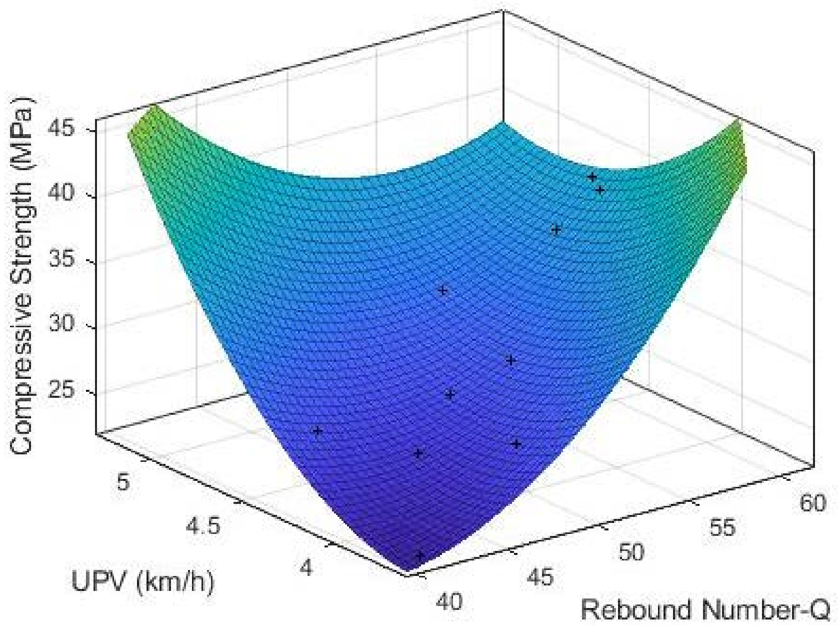


Figure 3. 23: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJK (C).

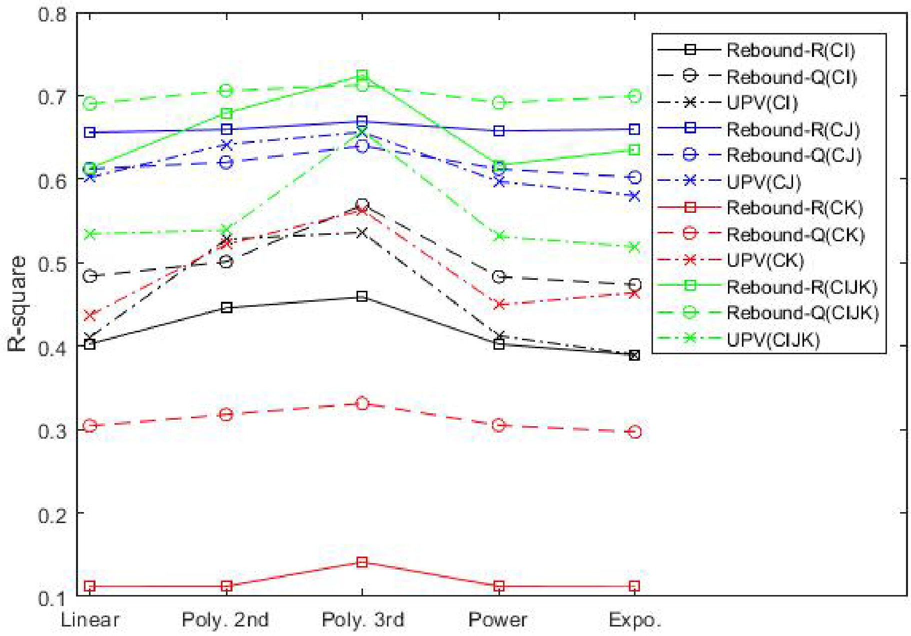


Figure 3. 24: R-square values for different equations, methods, and sets (C).

There is a logical increase from linear to Poly. 2nd degree and then a high slope increase to the Poly. 3rd degree correlation`s R-square values. Then, there is a decrease from Poly. 3rd to Power and then straight continue with an almost equal amount to exponential correlation's R-square value. The R-square values were illustrated in Fig. 3.24 for all four different sets and three NDT methods and the changes of R-square values was observed there.

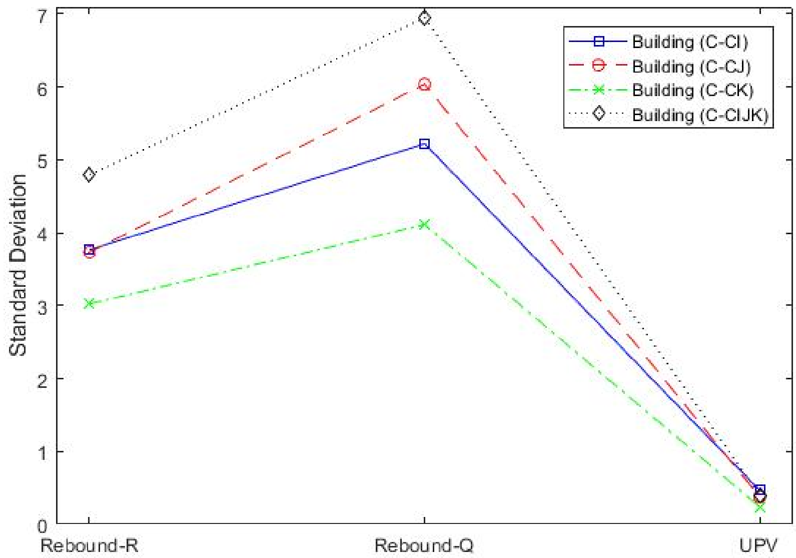


Figure 3. 25: Standard deviation of different sets of single core (C).

The slope of change between Rebound-R to Rebound-Q and Rebound-Q to UPV for all sets are approximately the same and equal to 0.6 and -3 respectively. Furthermore, the standard deviation for Rebound-Q of CIJK set in this building reach the highest amount among the sets and other buildings same set and method (see Fig. 3.25) which indicates the reason that why the R-square values are not much greater than Rebound-R, R-square values.

3.2.1.4 First scenario-building D

In this part the sets and correlations which was derived based on first scenario was demonstrated in various tables and figures fro building D.

Table 3. 8: R-square and standard deviation values of different equations and methods for building (D).

NDT Method	Equation type	CI		CJ		CK		CIJK	
		r^2	SD	r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.815	3.787	0.756	4.405	0.828	3.941	0.798	4.362
	Poly. 2nd	0.816		0.757		0.836		0.798	
	Poly. 3rd	0.816		0.762		0.902		0.801	
	Power	0.810		0.753		0.831		0.797	
	Expo.	0.802		0.745		0.837		0.791	
Rebound-Q	Linear	0.819	4.754	0.695	6.690	0.613	6.513	0.802	6.993
	Poly. 2nd	0.823		0.701		0.631		0.803	
	Poly. 3rd	0.827		0.717		0.670		0.805	
	Power	0.811		0.690		0.613		0.802	
	Expo.	0.799		0.671		0.622		0.794	
UPV	Linear	0.259	0.233	0.511	0.275	0.141	0.227	0.491	0.285
	Poly. 2nd	0.309		0.514		0.291		0.494	
	Poly. 3rd	0.386		0.533		0.294		0.534	
	Power	0.266		0.514		0.139		0.491	
	Expo.	0.272		0.512		0.130		0.494	
SonReb (R)	R 1st , V 1st	0.815	-	0.803	-	0.829	-	0.859	-
	R 2nd , V 2nd	0.860		0.876		0.885		0.930	
SonReb (Q)	Q 1st , V 1st	0.827	-	0.720	-	0.614	-	0.829	-
	Q 2nd , V 2nd	0.857		0.760		0.727		0.878	

Based on the results which is obtained based on Table 3.8 considering R-square and standard deviation values, CIJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set for building D.

Table 3. 9: Correlation equations of CIJK set for building (D).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.314R - 20.91$	0.7985	4.3629
	Poly. 2nd	$F = 0.004021R^2 + 1.032R - 16.06$	0.7986	
	Poly. 3rd	$F = 0.00482R^3 - 0.4942R^2 + 18.01R - 206.6$	0.8019	
	Power	$F = 0.03541R^{1.843}$	0.7973	
	Expo.	$F = 4.026\,\exp(0.05161R)$	0.7916	
Rebound-Q	Linear	$F = 0.8216Q - 13.76$	0.8020	6.9931
	Poly. 2nd	$F = 0.0034Q^2 + 0.501Q - 6.364$	0.8031	
	Poly. 3rd	$F = -0.000991Q^3 + 0.1401Q^2 - 5.66Q + 84.06$	0.8058	
	Power	$F = 0.05983\,Q^{1.564}$	0.8029	
	Expo.	$F = 5.392\,\exp(0.03205Q)$	0.7946	
UPV	Linear	$F = 15.78\,V - 38.65$	0.4917	0.2851
	Poly. 2nd	$F = 2.994\,V^2 - 7.484\,V + 6.136$	0.4944	
	Poly. 3rd	$F = -59.16\,V^3 + 692.6\,V^2 - 2670V + 3410$	0.5341	
	Power	$F = 0.5437\,V^{2.734}$	0.4910	
	Expo.	$F = 1.546\,\exp(0.6845V)$	0.4940	
SonReb (R)	R 1st , V 1st	$F = 1.072R + 6.671V - 39.69$	0.8592	-
	R 2nd , V 2nd	$F = -1.441R - 93.17\,V + 0.07948R^2 - 0.752RV + 16.24V^2 + 192.8$	0.9307	
SonReb (Q)	Q 1st , V 1st	$F = 0.474Q + 4.109V - 18.8$	0.8296	-
	Q 2nd , V 2nd	$F = 1.716Q - 117.2V + 0.02426Q^2 - 0.8115QV + 20.24V^2 + 185.6$	0.8781	

Table 3.9 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

Despite the lowest measurement of Rebound-R which is associated with high compressive strength comparing the nearby points (data), the data dispersion demonstrates the proper fit with both EN 13791 standards suggested curves and with Poly. 2nd degree correlation curves which are mostly close to the linear shape due to the dispersion of data. Figure 3.26 illustrates that the data was dispersed in such case that even with linear shape of correlation curve the R-square value still stays in the high amount of 0.7980 which is the greatest amount comparing the other sets and buildings R-square values for Rebound-R measurements and intended correlations.

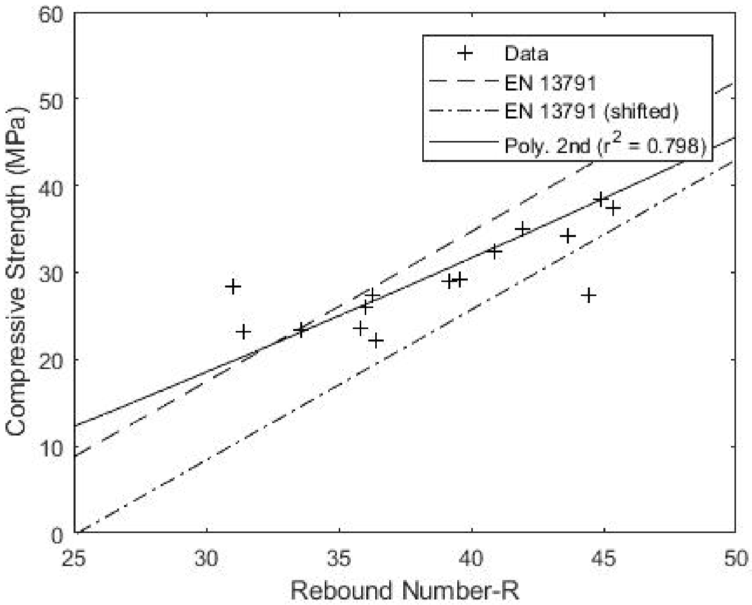


Figure 3. 26: Correlation: Rebound R vs. Compressive Strength of set CIJK (D).

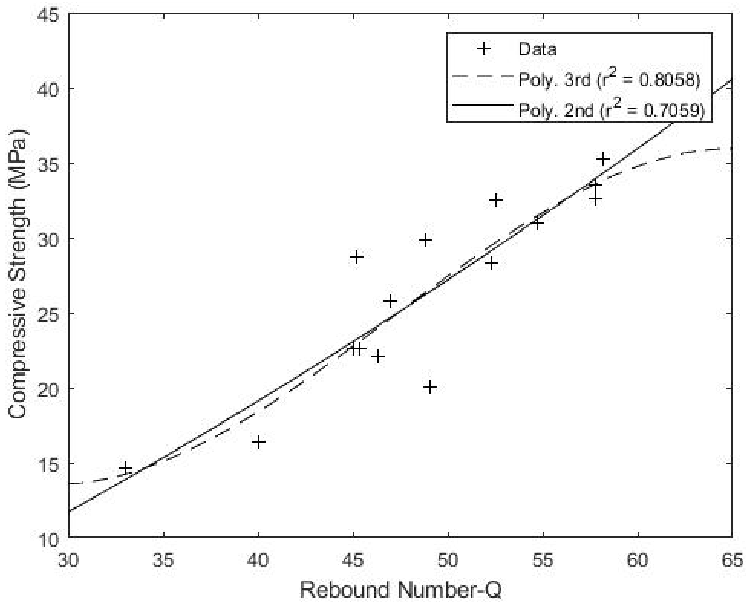


Figure 3. 27: Correlation: Rebound Q vs. Compressive Strength of set CIJK (D).

The high values of R-square for both Poly. 2nd and Poly. 3rd degree correlations (0.7059, and 0.8058 respectively) demonstrates that the data dispersion in this analysis was properly distributed and the intended correlation leads to the high reliable equation for concrete strength estimation in building D (see Fig. 3.27).

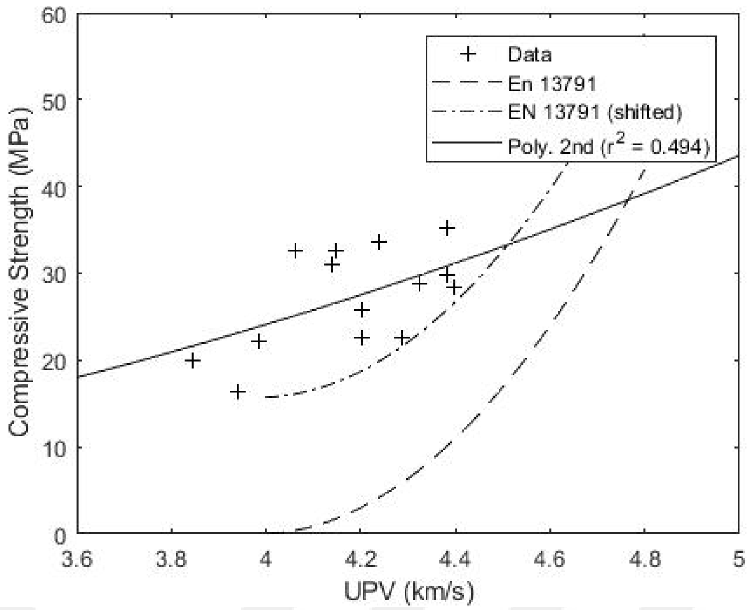


Figure 3. 28: Correlation: UPV vs. Compressive Strength of set CIJK (D).

Despite the EN 13791 standard curve for this set of data the EN 13791 shifted curve could reach the data and cover some part of it with proper proximity. However, the Poly. 2nd degree correlation curve with R-square 0.4940 have better support due to no limits- there is a limit for the standard which requires data between 4-4.8- thus the Poly. 2nd degree reach better results considering that the data is somehow compacted and the dispersion of the data is not that much longitudinal like the previous sets (see Fig. 3.28).

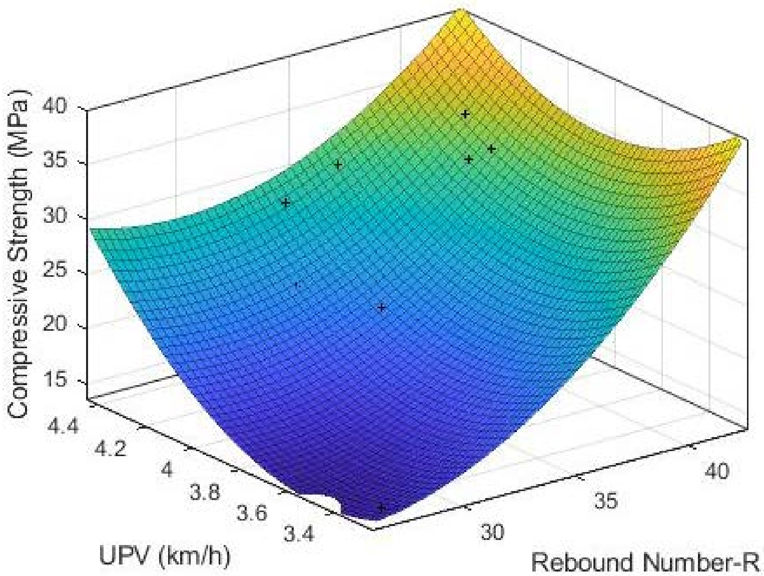


Figure 3. 29: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJK (D).

The combined method could significantly improve the results of correlation and related regressions with higher R-square values in this set of data for Rebound-R, UPV, and Compressive strength. According to the data which was demonstrated in Table 3.9 there is an approximately 16.5 % increase compared with Rebound-R and about 88.2 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value. Fig. 3.29 illustrated that there is much data compaction in the final part of UPV measurements.

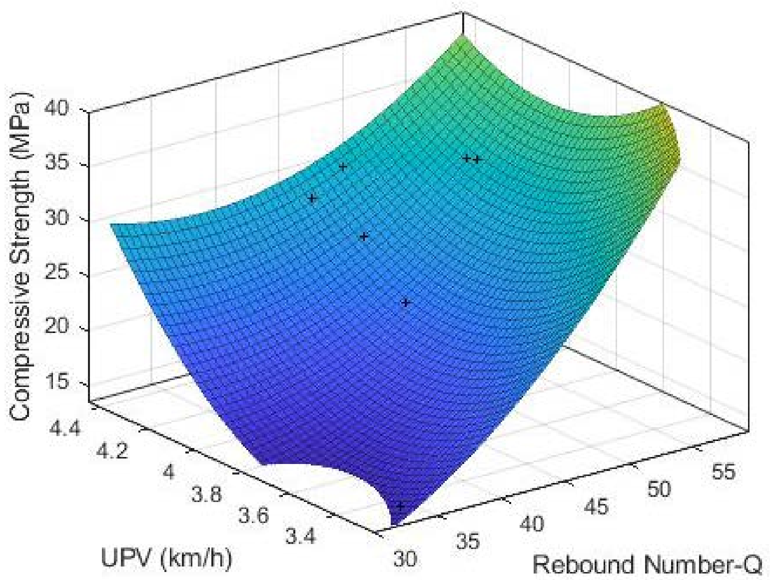


Figure 3. 30: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJK (D).

There is a proper cover of correlation plate in combined SonReb method for Rebound-Q ns UPV vs Compressive strength which was observed in Fig. 3.30. The both Rebound-Q and UPV sides help to cover the data in both sides to increase the R-square value. Moreover, there is an approximately 10 % increase compared with Rebound-Q and about 77.6 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value (see Table 3.9).

Figure 3.31 shows the changes which were occurred for the R-square values in each method type of each different sets for different five equation types. There is an increase almost in every method-set line from linear to Poly. 2nd degree and then increase with higher slope than the previous step toward Poly. 3rd degree equation correlations R-square values. After this there is sharp decline toward power then continue almost slight toward Exponential equation`s R-square value.

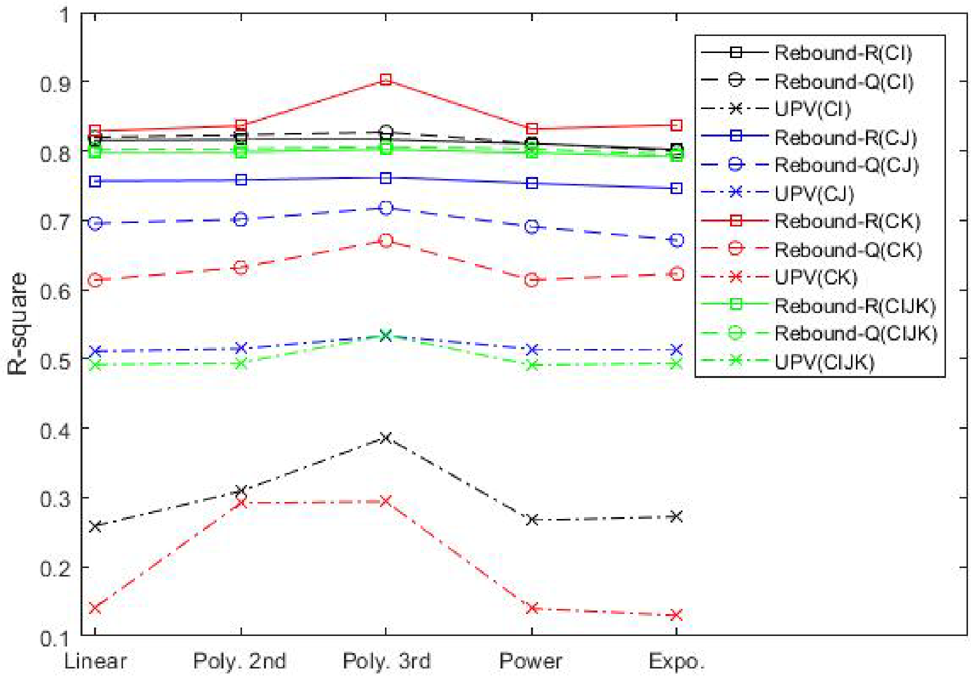


Figure 3. 31: R-square values for different equations, methods, and sets (D).

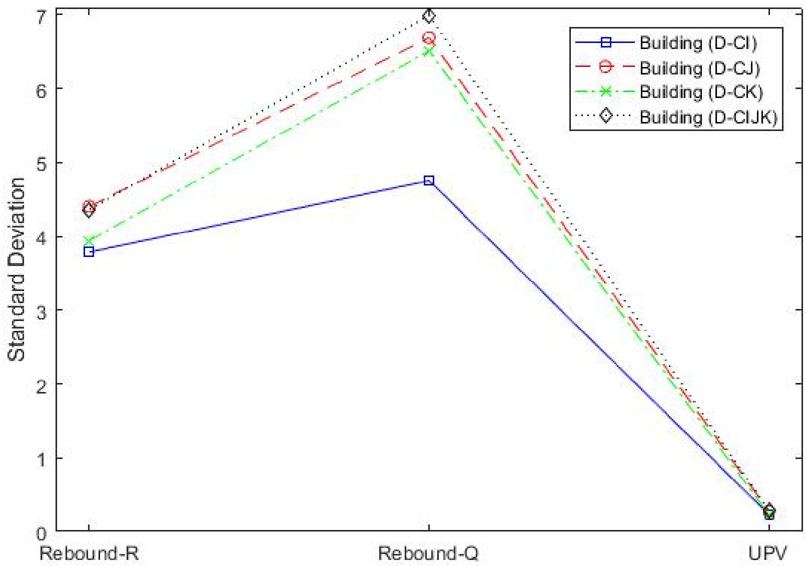


Figure 3. 32: Standard deviation of different sets of single core (D).

Despite the CI set all of the other sets almost has an equal rate in increase of standard deviation from Rebound-R to Rebound-Q and the same rate in deflection from Rebound-Q to UPV. The standard deviation of all sets except CI are so close to each other in each method (see Fig. 3.32).

3.2.1.5 First scenario-building All

In this part the sets and correlations which was derived based on first scenario was demonstrated in various tables and figures for All cases set.

Table 3. 10: R-square and standard deviation values of different equations and methods for All cases.

NDT Method	Equation type	CI		CJ		CK		CIJK	
		r^2	SD	r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.724	4.402	0.804	4.619	0.635	3.921	0.762	4.659
	Poly. 2nd	0.739		0.804		0.644		0.763	
	Poly. 3rd	0.752		0.804		0.647		0.764	
	Power	0.705		0.803		0.623		0.755	
	Expo.	0.676		0.794		0.607		0.742	
Rebound-Q	Linear	0.747	6.231	0.755	6.786	0.667	6.322	0.788	6.992
	Poly. 2nd	0.764		0.760		0.687		0.789	
	Poly. 3rd	0.766		0.761		0.691		0.789	
	Power	0.731		0.747		0.653		0.783	
	Expo.	0.701		0.728		0.624		0.769	
UPV	Linear	0.422	0.374	0.417	0.358	0.394	0.320	0.370	0.342
	Poly. 2nd	0.425		0.419		0.397		0.371	
	Poly. 3rd	0.521		0.420		0.400		0.383	
	Power	0.417		0.419		0.397		0.368	
	Expo.	0.405		0.416		0.396		0.360	
SonReb (R)	R 1st , V 1st	0.731	-	0.808	-	0.697	-	0.772	-
	R 2nd , V 2nd	0.756		0.815		0.714		0.779	
SonReb (Q)	Q 1st , V 1st	0.753	-	0.757	-	0.699	-	0.790	-
	Q 2nd , V 2nd	0.785		0.776		0.721		0.798	

Based on the results which are obtained based on Table 3.10 considering R-square and standard deviation values, CIJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set for All cases.

Table 3. 11: Correlation equations of CIJK set for All cases.

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.256R - 20.33$	0.7623	4.6598
	Poly. 2nd	$F = -0.01128R^2 + 2.07R - 34.76$	0.7638	
	Poly. 3rd	$F = -0.0009546R^3 + 0.09249R^2 - 1.645R + 9.043$	0.7641	
	Power	$F = 0.03843R^{1.803}$	0.7559	
	Expo.	$F = 4.221\exp(0.04859R)$	0.7420	
Rebound-Q	Linear	$F = 0.8515Q - 15.14$	0.7884	6.9926
	Poly. 2nd	$F = -0.003643Q^2 + 1.195Q - 23.05$	0.7892	
	Poly. 3rd	$F = -2.105 \times 10^{-5}Q^3 - 0.0006883Q^2 + 1.059Q - 21.01$	0.7892	
	Power	$F = 0.05185\,Q^{1.601}$	0.7836	
	Expo.	$F = 5.147\exp(0.03297Q)$	0.7690	
UPV	Linear	$F = 11.92\,V - 24.96$	0.3709	0.3427
	Poly. 2nd	$F = -0.3205\,V^2 + 14.62\,V - 30.61$	0.3710	
	Poly. 3rd	$F = -6.244\,V^3 + 80.08\,V^2 - 327.5V + 450.6$	0.3839	
	Power	$F = 1.479\,V^{1.968}$	0.3684	
	Expo.	$F = 3.751\exp(0.4493V)$	0.3607	
SonReb (R)	R 1st , V 1st	$F = 1.147R + 2.453V - 26.6$	0.7722	-
	R 2nd , V 2nd	$F = 3.095R - 19.34\,V + 0.001769R^2 - 0.493RV + 4.678V^2 - 15.61$	0.7792	
SonReb (Q)	Q 1st , V 1st	$F = 0.8109Q + 1.291V - 18.6$	0.7909	-
	Q 2nd , V 2nd	$F = 1.957Q - 27.82V - 0.000657Q^2 - 0.2564QV + 4.861V^2 + 15.96$	0.7983	

Table 3.11 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The assumption of all single cores data which was analyzed in the previous section for four different building was provided and the intended data correlations using both EN 13791 standard and Poly. 2nd degree correlation curves were drawn in Fig. 3.33. The data dispersion was in a proper condition along the both EN 13791 suggested curve for the intended data and for the Poly. 2nd degree correlation curves with the R-square value of 0.7630 which is a reliable value for the Rebound-R considering other buildings. Thus, the more core leads to more reliable results.

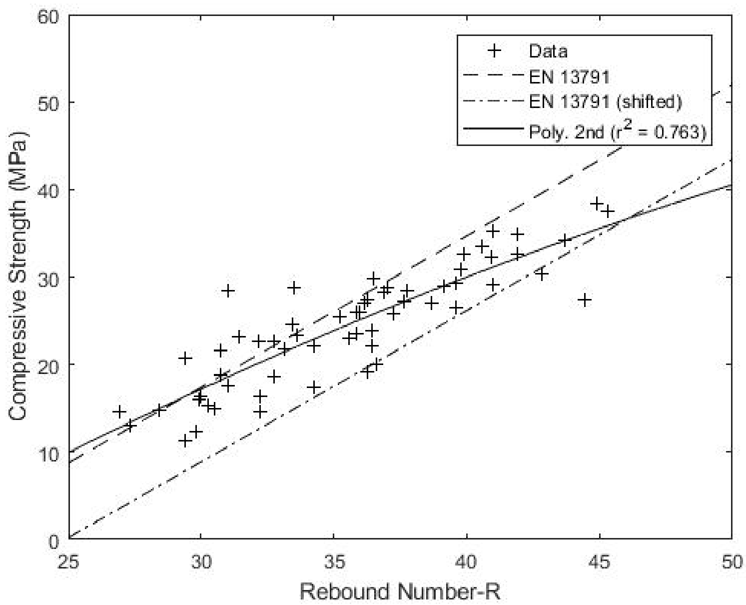


Figure 3. 33: Correlation: Rebound R vs. Compressive Strength of set CIJK (All).

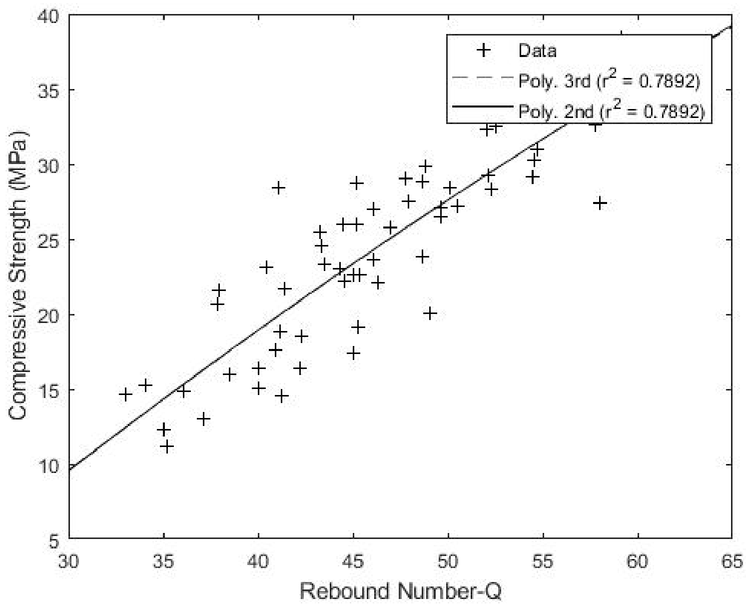


Figure 3. 34: Correlation: Rebound Q vs. Compressive Strength of set CIJK (All).

According to Fig. 3.34 both Poly. 2nd and Poly. 3rd degree correlation curves lay on each other in this section due to the special dispersion of data in the section. The data was suitably distributed around the correlation curves which leads to high R-square values for both Poly. 2nd degree and Poly. 3rd degree (0.7892 for both). In addition in this data correlation, the abnormal dispersion is approximately zero except one point.

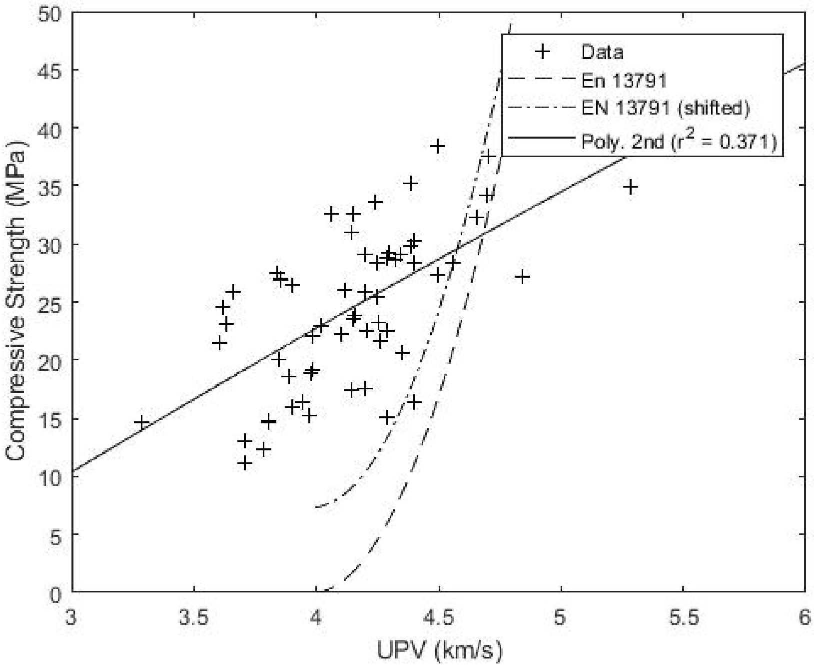


Figure 3. 35: Correlation: UPV vs. Compressive Strength of set CIJK (All).

In order to the special dispersion of UPV measurements data which is more compatible with the equation and the curve suggested by EN 13791 standard, the other correlation curves could not cover the data properly and the obtained R-square value is not such strong value to consider for concrete compressive strength estimation (see Fig 3.35).

The improvement in R-square value indicates the importance and effectiveness of combined SonReb method and using the 3-D correlation with a plate which covers most of the data is the reason for this enhancement in the R-square value. Fig 3. 36 illustrates that approximately the curve for UPV data is in polynomial shape; however, the other curve which is in Rebound-R straight is much linear than polynomial. Table 3.11 demonstrates that there is a 110 % increase compared with UPV-Compressive strength correlation`s R-square value. In addition, there is a slight increase in comparing Rebound-R results with SonReb results and this occurs due to the high R-square value which was obtained for Rebound-R vs. Compressive strength correlation.

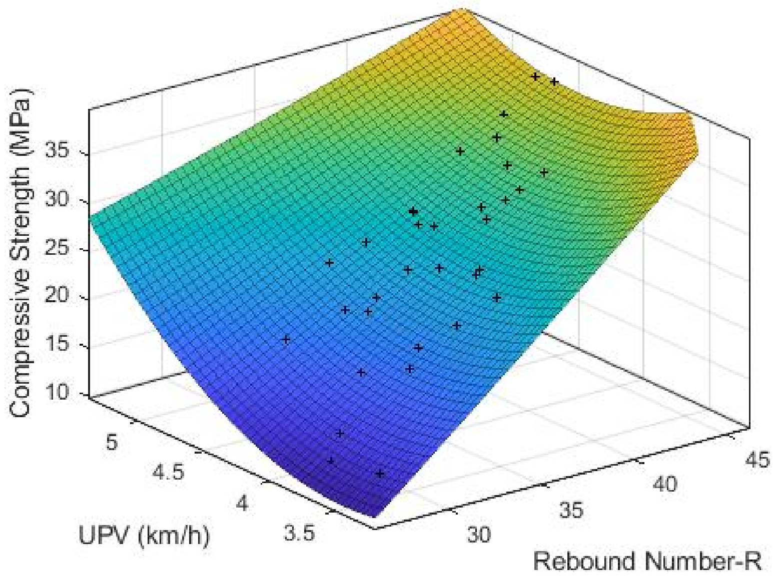


Figure 3. 36: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJK (All).

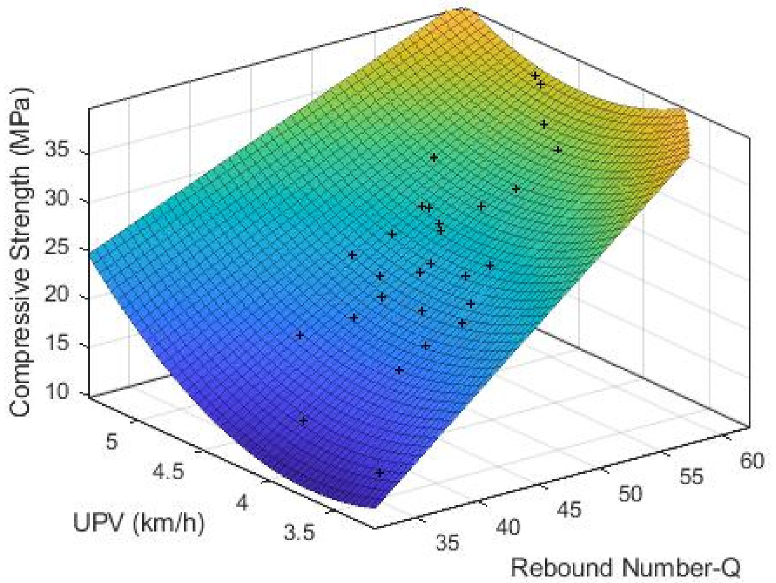


Figure 3. 37: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJK (All).

Despite the Rebound-R combined correlation for this section and set, the combined correlation for Rebound-Q due to the data distribution which was observed in Fig. 3.37 requires double polynomial curves to cover the data and fit the plate to reach the best result for correlation equation and R-square value. Furthermore, there are a few increases in comparing Rebound-Q R-square results with SonReb results and this happens due to the high R-square value which was derived for Rebound-Q vs. Compressive strength correlation. Moreover, there is a 115 % increase in R-square value compared with UPV vs. Compressive strength correlation`s result (see Table 3.11).

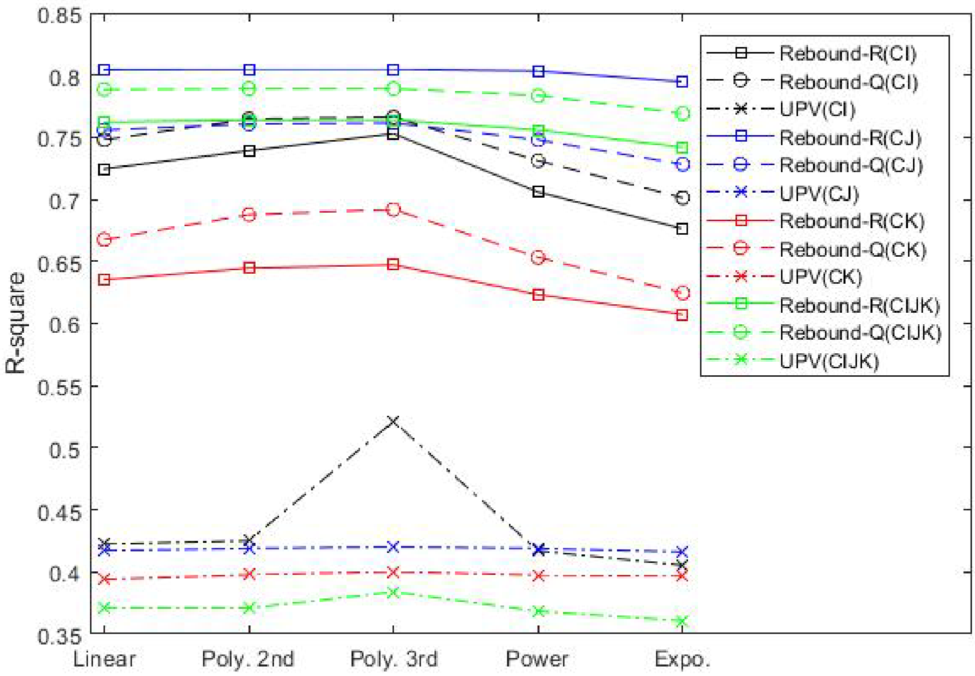


Figure 3. 38: R-square values for different equations, methods, and sets of single core (All).

The curves in Fig. 3.38 shows that the behavior of change in R-square values among five different equation and three different NDT methods are close to each other; however, in some cases that data distribution is special and require polynomial curve to reach the proper fit and high R-square value, the R-square value increase with high rate toward Poly. 3rd degree correlation and this occurs mostly in UPV vs. Compressive strength correlation due to the special data dispersion which was observed in previous figures and even EN 13791 suggest the special polynomial curve for UPV correlation (e.g. UPV(CI)).

The assumption of data forces the standard deviation of sets to be more close to each other. Considering the slope of difference from method to the other method, Fig. 39 shows that there is almost no difference among sets change rate and the change in standard deviation occurs normally with no special differences.

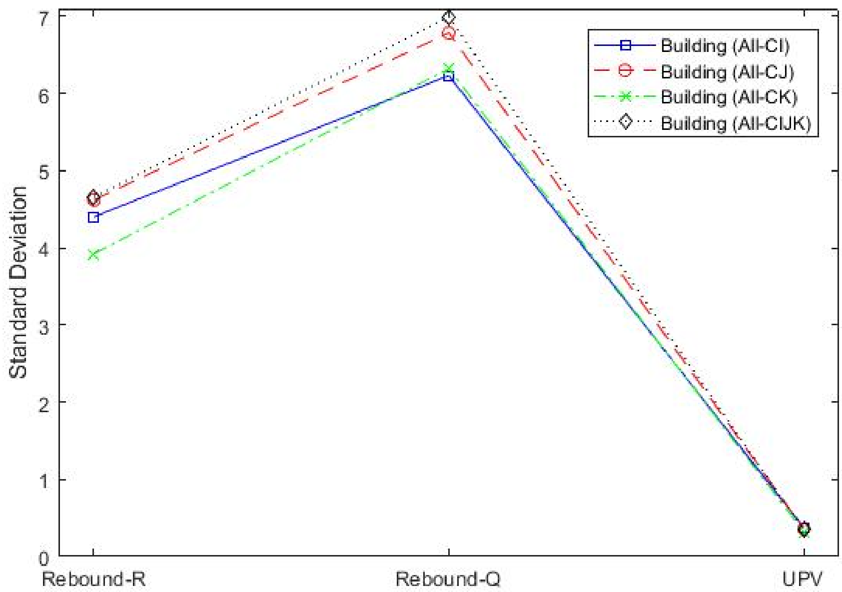


Figure 3. 39: Standard deviation of different sets of single core (All).

3.2.1.6 Data Analysis

The analysis of all evaluation and comparison of obtained values based on each set of five different data was assessed and discussed in this section based on eaution and method which was used for each set.

The correlation results (R-square values) was observed in Fig 3.36 for all different single core sets in all four buildings and considering all together as one case called All for the four different sets in each case. The R-square values illustrate that the behavior of results changes from set to set and building to building; however, considering the overall view in Fig. 3.40 it could be concluded that there are a few increases from Rebound-R to Rebound-Q and a great decrease from Rebound-Q to UPV R-square values. In addition, considering the simplicity factor in implementing the NDT methods, using either Rebound-R or Rebound-Q seems more logical due to the results which was obtain during this section analysis and based on the R-square results which was illustrated in Fig. 3.40.

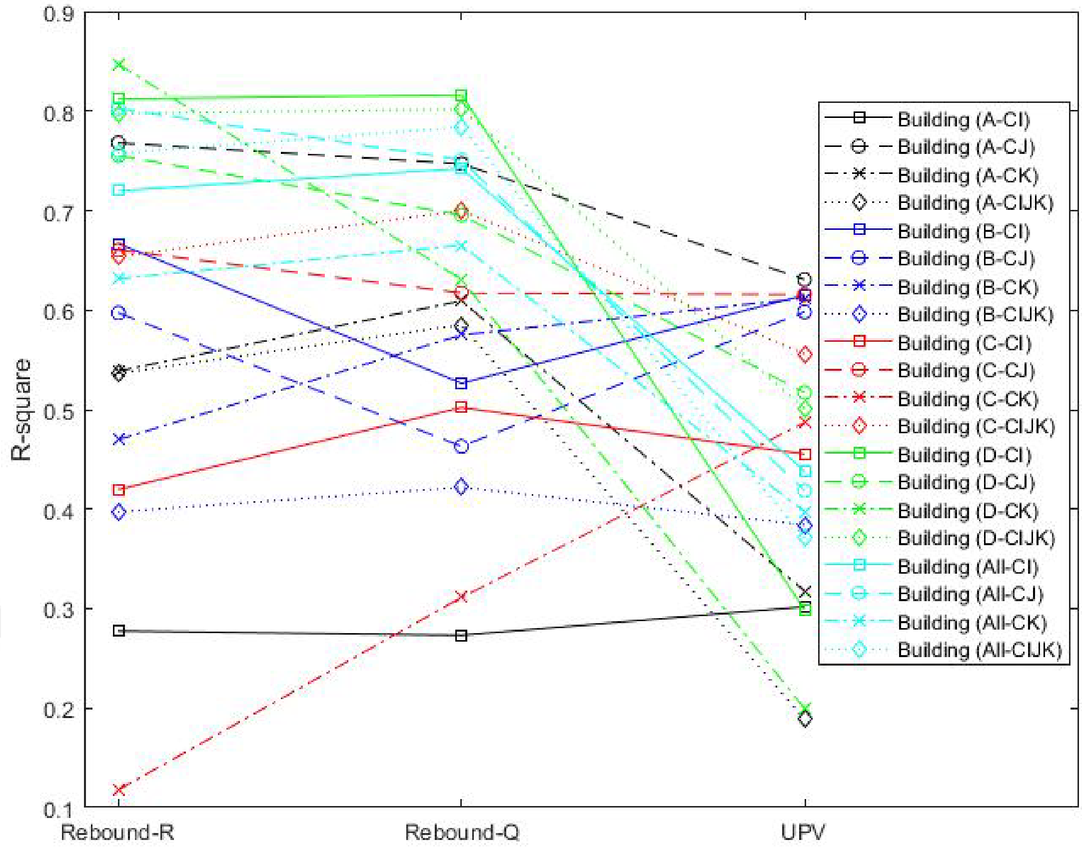


Figure 3. 40: R-square values for different sets based on methods of single core.

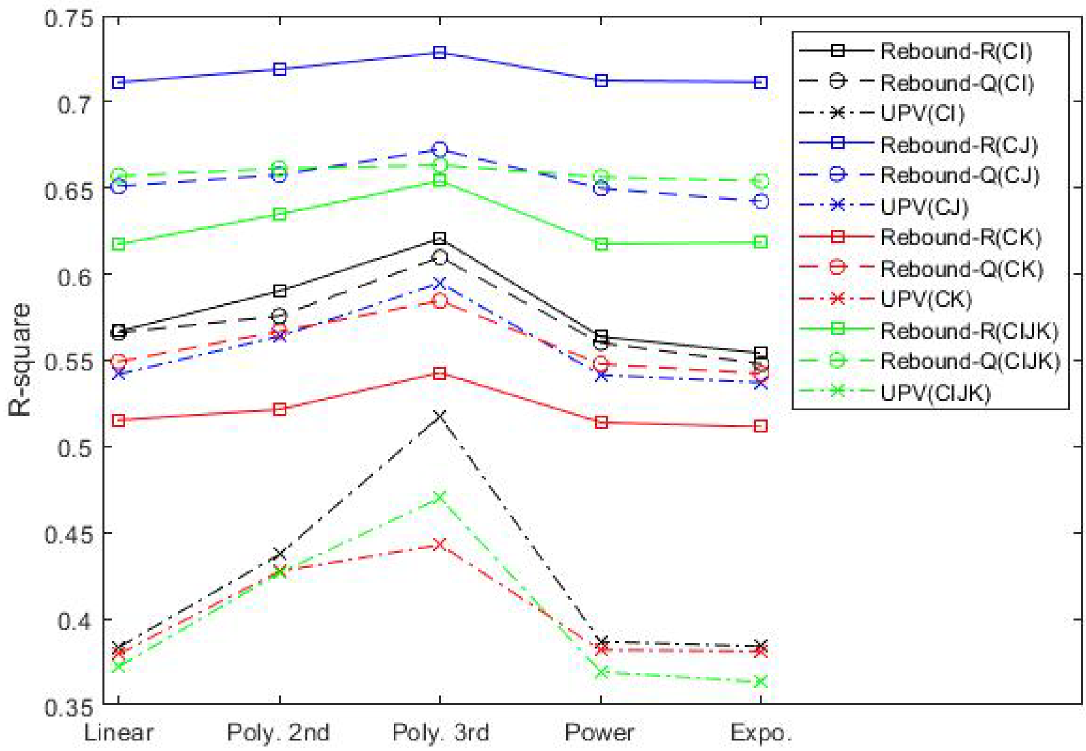


Figure 3. 41: R-square values for different sets based on equations of single core.

The R-square values changes were illustrated in Fig. 3.41 for all four various sets in three NDT methods based on five different equation types. It could be strongly concluded that considering only R-square values, there are a few increases from linear correlation to the Poly. 2nd degree correlation than a great increase with high rate toward Poly. 3rd degree correlation; after this point, it was observed that there is a sudden reduction to the power correlation and then a few decreases to the Exponential correlation R-square value. Thus, if the simplicity of equation was neglected during a process it is strongly suggested to use Poly. 3rd degree correlation, but if the simplicity is an important factor in one project Poly. 2nd degree is a suitable correlation (based on the results observed in Fig. 3.41).

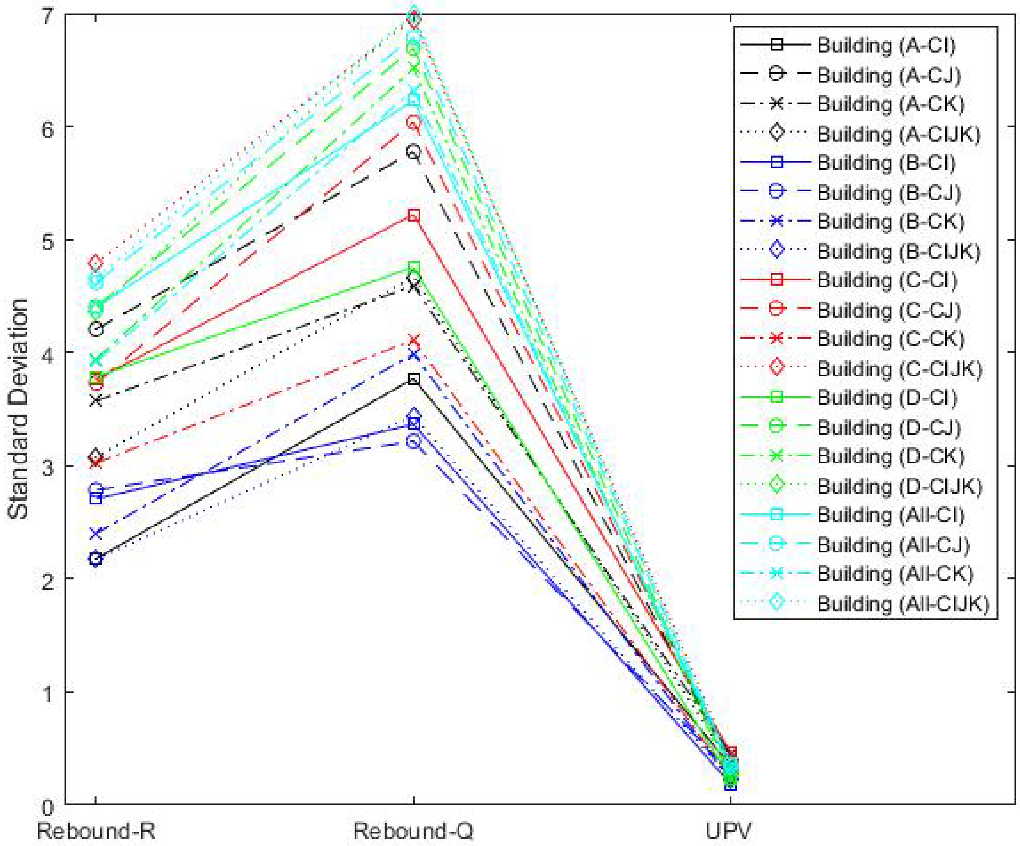


Figure 3. 42: Standard deviation of different sets of single core based on method.

Figure 3.42 illustrates the changes in standard deviation magnitude for all four sets, four buildings and, one All case based on three NDT methods which were used in this project. The behavior and rate of changes observed in previous standard deviation figures and in Fig. 3.42 for all shows that there is a slight increase from Rebound-R to Rebound-Q and then a reduction with the high rate from Rebound-Q to UPV standard deviation magnitude.

3.2.2 Second scenario (taking couple cores in each story)

In this scenario, a couple of cores was selected in each story and correlations were derived based on the data and measurements for the intended two cores. In order to consider the effect of selection criteria, for choosing two cores among three cores in each story three different sets was considered; (1) selecting CI & CJ cores in each story (called CIJ), (2) selecting CI & CJ cores in each story (called CIK), (3) selecting CJ & CK cores in each story (called CJK).

3.2.2.1 Second scenario-building A

In this part the sets and correlations which was derived based on second scenario was demonstrated in various tables and figures for building A.

Table 3. 12: R-square and standard deviation values of different equations and methods of couple cores for building (A).

NDT Method	Equation type	CI & CJ		CI & CK		CJ & CK	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.5001	3.3118	0.4171	2.9109	0.5684	3.8419
	Poly. 2nd	0.5001		0.4213		0.5707	
	Poly. 3rd	0.5001		0.4355		0.5855	
	Power	0.4996		0.4201		0.5706	
	Expo.	0.4951		0.4203		0.5678	
Rebound-Q	Linear	0.4894	4.8161	0.4400	4.1283	0.5966	5.1457
	Poly. 2nd	0.4896		0.4430		0.5969	
	Poly. 3rd	0.4931		0.4644		0.6045	
	Power	0.4886		0.4420		0.5967	
	Expo.	0.4838		0.4420		0.5910	
UPV	Linear	0.4435	0.3561	0.2926	0.3925	0.4493	0.4095
	Poly. 2nd	0.4684		0.3019		0.4517	
	Poly. 3rd	0.4785		0.3024		0.4562	
	Power	0.4485		0.2938		0.4508	
	Expo.	0.4565		0.2978		0.4520	
SonReb (R)	R 1st , V 1st	0.5652	-	0.4910	-	0.6161	-
	R 2nd , V 2nd	0.5937		0.5766		0.6530	
SonReb (Q)	Q 1st , V 1st	0.5557	-	0.4923	-	0.6196	-
	Q 2nd , V 2nd	0.6160		0.5060		0.6268	

Based on the results which is obtained based on Table 3.12 considering R-square and standard deviation values, CJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for building A.

Table 3. 13: Correlation equations of CJK set for building (A).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.236R - 18.51$	0.5684	3.8419
	Poly. 2nd	$F = 0.01602R^2 + 0.06472R + 2.658$	0.5707	
	Poly. 3rd	$F = -0.00925R^3 + 1.045R^2 - 37.75R + 461.2$	0.5855	
	Power	$F = 0.05601R^{1.711}$	0.5706	
	Expo.	$F = 4.937\exp(0.04573R)$	0.5678	
Rebound-Q	Linear	$F = 0.9452Q - 17.17$	0.5966	5.1457
	Poly. 2nd	$F = 0.003262Q^2 + 0.6372Q - 9.99$	0.5969	
	Poly. 3rd	$F = -0.002878Q^3 + 0.419Q^2 - 19.18Q + 301.5$	0.6045	
	Power	$F = 0.05048\,Q^{1.632}$	0.5967	
	Expo.	$F = 5.488\exp(0.03376Q)$	0.5910	
UPV	Linear	$F = 10.31\,V - 14.92$	0.4493	0.4095
	Poly. 2nd	$F = 1.776\,V^2 - 4.066V + 13.86$	0.4517	
	Poly. 3rd	$F = 5.31\,V^3 - 62.76\,V^2 + 255.6V - 331.8$	0.4562	
	Power	$F = 2.957\,V^{1.573}$	0.4508	
	Expo.	$F = 5.547\exp(0.3862V)$	0.4520	
SonReb (R)	R 1st , V 1st	$F = 0.9078R + 4.554V - 24.85$	0.6161	-
	R 2nd , V 2nd	$F = 0.9733R - 53.56V - 0.05055R^2 + 0.9401RV + 2.848V^2 + 89.06$	0.6530	
SonReb (Q)	Q 1st , V 1st	$F = 0.7444Q + 3.433V - 21.68$	0.6196	-
	Q 2nd , V 2nd	$F = 0.2585Q - 16.42V - 0.007834Q^2 + 0.3021QV + 0.7229V^2 + 29.13$	0.6268	

Table 3.13 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data was compacted in the range between 30-40 Rebound number so both EN 13791 suggested curves and Polynomial 2nd degree correlation by Matlab software could not highly cover the data and release high reliable results for R-square value (R-square = 0.570).

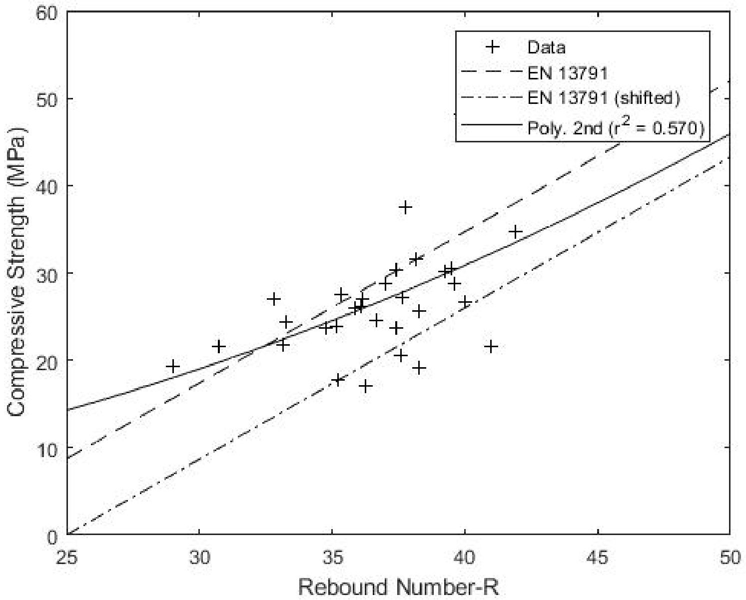


Figure 3. 43: Correlation: Rebound R vs. Compressive Strength of set CJK (A).

In addition, dispersion of data in a great range of compressive strength results requires high degree correlations to reach acceptable and reliable results, in this case for CJK set the data was dispersed in a way that even by Poly. 2nd degree curves expected results were not obtained and this set needs higher degree correlation (see Fig. 3.43).

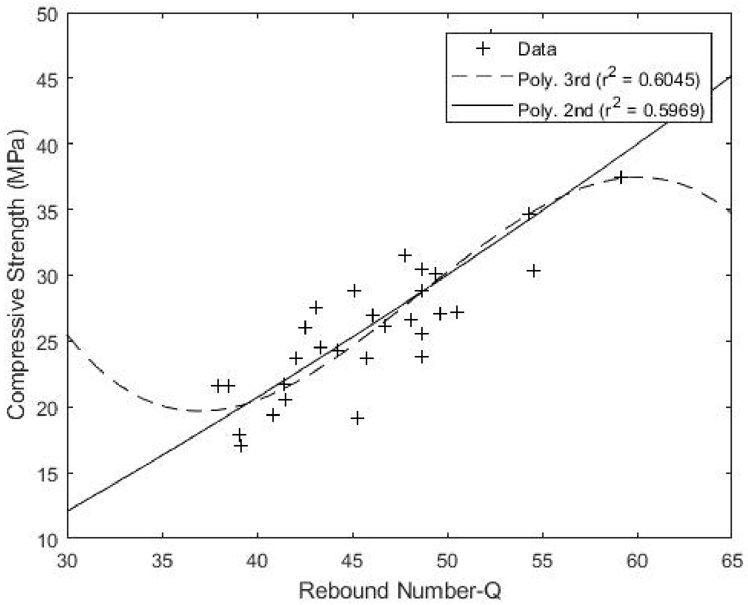


Figure 3. 44: Correlation: Rebound Q vs. Compressive Strength of set CJK (A).

In the range between 40-60 both Poly. 2nd and Poly. 3rd degree correlation curves lay on each other approximately for this set of data in Fig. 3.44; however, some small changes in Poly. 3rd degree correlation causes a bit higher R-square value for this correlation (0.6045). In addition, the acceptable value for R-square demonstrates that the data in this analysis was properly distributed and the intended correlation leads to the high reliable equation for concrete strength estimation in building A.

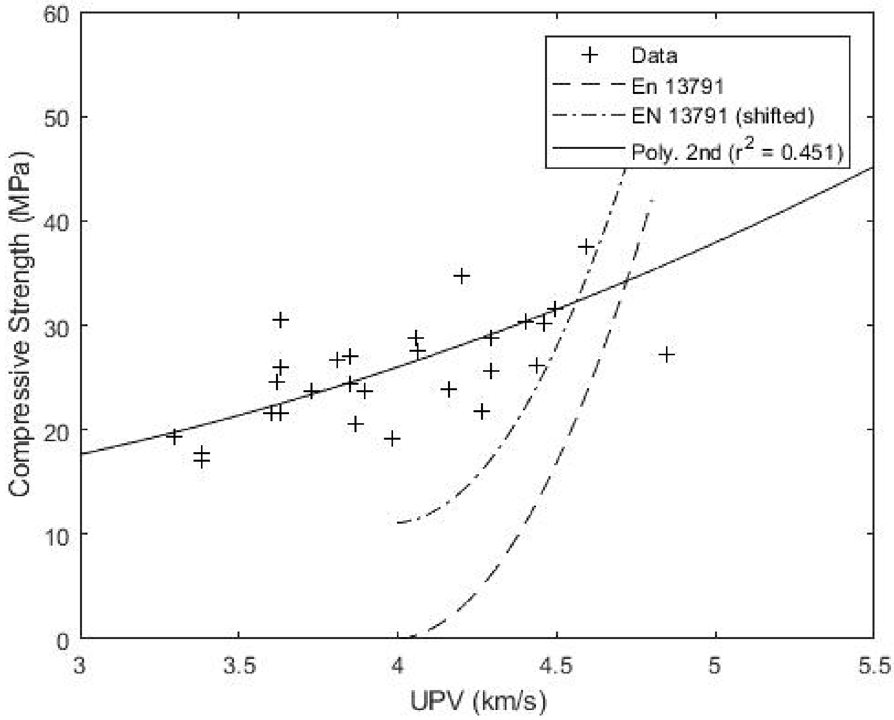


Figure 3. 45: Correlation: UPV vs. Compressive Strength of set CJK (A).

Despite the EN 13791 standard curve for this set of data the EN 13791 shifted curve could reach the data and cover some part of it with proper proximity. However, the Poly. 2nd degree correlation curve with R-square 0.451 have better support due to no limits- there is a limit for a standard which requires data between 4-4.8- thus the Poly. 2nd degree reaches better results considering that the data is somehow compacted and the dispersion of the data is not that much longitudinal like the previous sets. It was illustrated in Fig. 3.45 that the Poly. 2nd degree correlation suggested by Matlab software has provided a better correlation with higher reliability.

The combined method could significantly improve the results of correlation and related regressions with higher R-square values in this set of data for Rebound-R, UPV, and Compressive strength. According to the data which was demonstrated in Table 3.13 there is an approximately 14.5 % increase compared with Rebound-R and about 44.5 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value. Fig. 3.46 illustrates that there is more data compaction in the final part of UPV measurements than other parts.

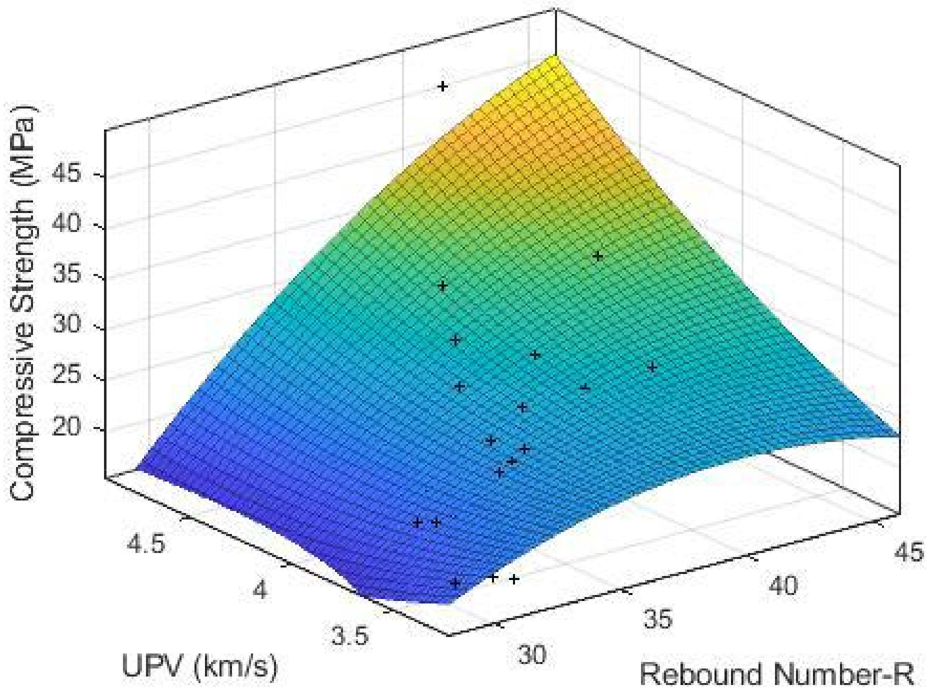


Figure 3. 46: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CJK (A).

There is a proper cover of correlation plate in combined SonReb method for Rebound-Q vs. UPV vs. Compressive strength which was observed in Fig. 3.47. The both Rebound-Q and UPV sides help to cover the data in both sides to increase the R-square value. Moreover, according to Table 3.13, there is an approximately 5 % increase compared with Rebound-Q and about a 38 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value. In addition, except one paired of data most of the paired data was compacted to lower compressive strength associated with higher Rebound Number-Q and lower UPV measurements.

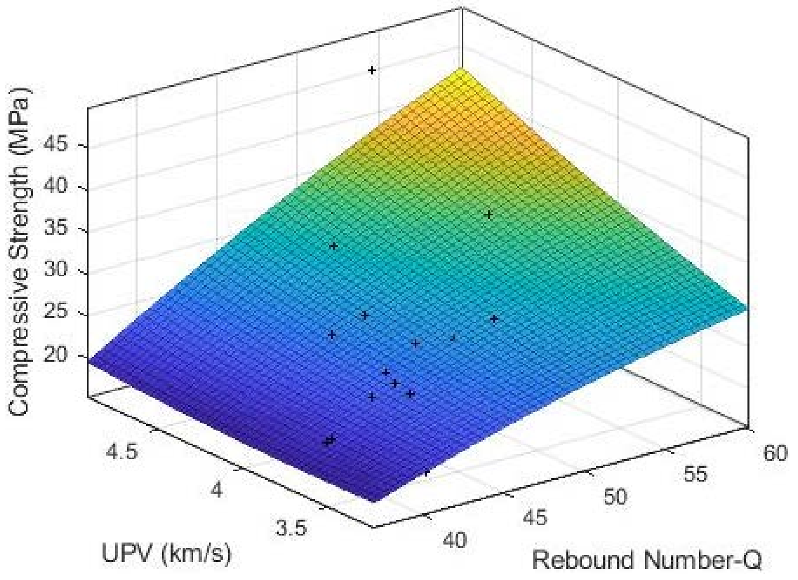


Figure 3. 47: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CJK (A).

Figure 3.48 shows the changes which were occurred for the R-square values in each method type of each different sets for different five equation types.

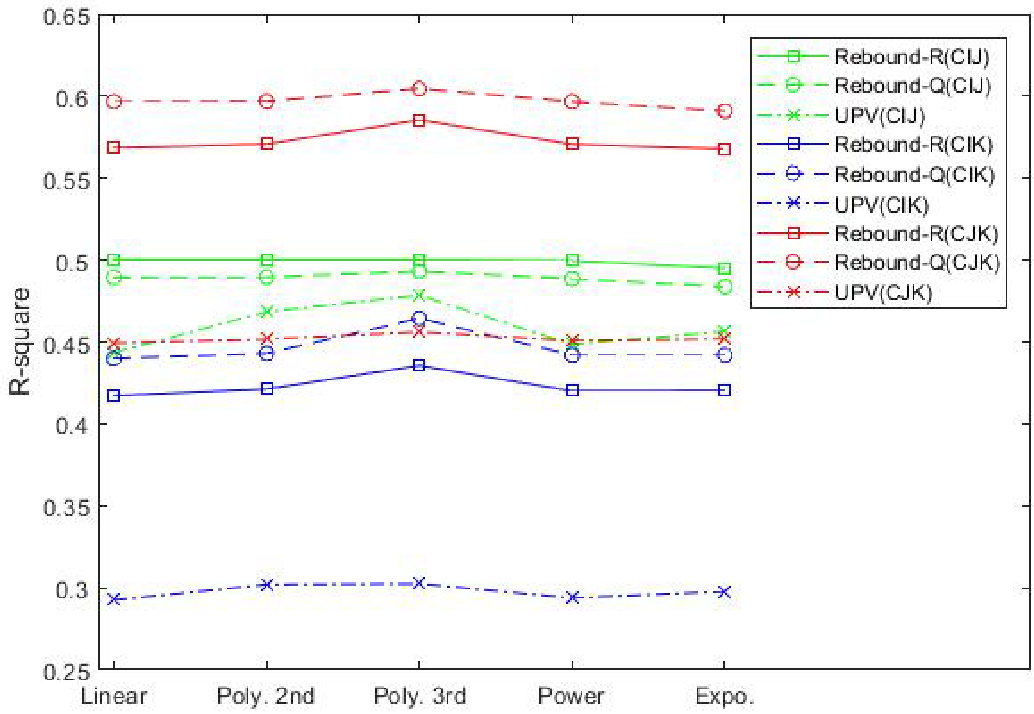


Figure 3. 48: R-square values for different equations, methods, and sets of couple cores (A).

There is an increase almost in every method-set line from linear to Poly. 2nd degree and then increase with higher slope than the previous step toward Poly. 3rd degree equation correlations R-square values. After this there is sharp decline toward power then continue almost slight toward Exponential equation`s R-square value. However, there are some exception such as Rebound-R(CIJ), Rebound-Q(CIJ), and UPV (CIK) which continues almost with no changes among equations and stays approximately constant.

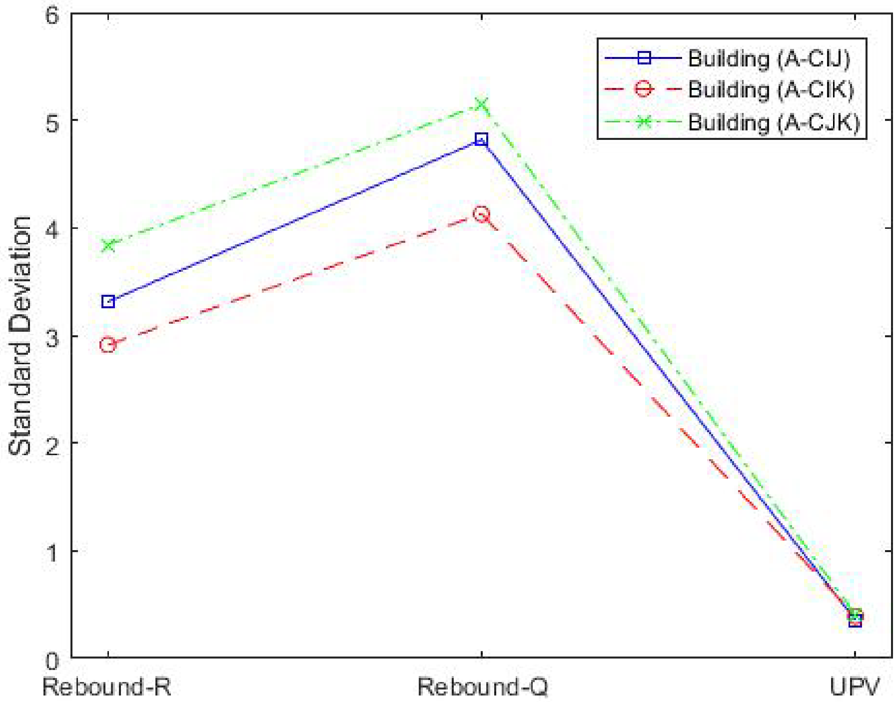


Figure 3. 49: Standard deviation of different sets of couple cores (A).

All of the sets almost has the equal rate in increase of standard deviation from Rebound-R to Rebound-Q and the same rate in deflection from Rebound-Q to UPV which could be observed in Fig. 3.49. The standard deviation of CJK has the highest value for both Rebound-R and Rebound-Q and the CIK has the lowest amount for the intended NDT methods.

3.2.2.2 Second scenario-building B

In this part the sets and correlations which was derived based on second scenario was demonstrated in various tables and figures for building B.

Table 3. 14: R-square and standard deviation values of different equations and methods of couple cores for building (B).

NDT Method	Equation type	CI & CJ		CI & CK		CJ & CK	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.6058	2.6486	0.5616	2.4877	0.5295	2.5132
	Poly. 2nd	0.6088		0.5676		0.5310	
	Poly. 3rd	0.6207		0.5776		0.5395	
	Power	0.6083		0.5654		0.5261	
	Expo.	0.6095		0.5678		0.5204	
Rebound-Q	Linear	0.4650	3.1420	0.5424	3.4161	0.5067	3.3798
	Poly. 2nd	0.4650		0.5444		0.5067	
	Poly. 3rd	0.4869		0.5473		0.5645	
	Power	0.4644		0.5395		0.5055	
	Expo.	0.4632		0.5342		0.5033	
UPV	Linear	0.4774	0.2258	0.5912	0.1814	0.5398	0.2358
	Poly. 2nd	0.5028		0.5995		0.5780	
	Poly. 3rd	0.5204		0.6050		0.6451	
	Power	0.4657		0.5999		0.5209	
	Expo.	0.4562		0.6003		0.5043	
SonReb (R)	R 1st , V 1st	0.6825	-	0.7265	-	0.6948	-
	R 2nd , V 2nd	0.7295		0.7490		0.7410	
SonReb (Q)	Q 1st , V 1st	0.6065	-	0.7187	-	0.6525	-
	Q 2nd , V 2nd	0.6476		0.7498		0.7329	

Based on the results which is obtained based on Table 3.14 considering R-square and standard deviation values, CIJK set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for building B.

Table 3. 15: Correlation equations of CIJK set for building (B).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.102R - 17.37$	0.5616	2.4877
	Poly. 2nd	$F = 0.04519R^2 - 1.753R + 27.45$	0.5676	
	Poly. 3rd	$F = 0.02577R^3 - 2.391R^2 + 74.68R - 768.6$	0.5776	
	Power	$F = 0.01602R^{2.024}$	0.5654	
	Expo.	$F = 2.301\exp(0.06374R)$	0.5678	
Rebound-Q	Linear	$F = 0.7501Q - 12.39$	0.5424	3.4161
	Poly. 2nd	$F = -0.01206Q^2 + 1.69Q - 30.53$	0.5444	
	Poly. 3rd	$F = 0.003548Q^3 - 0.4216Q^2 + 17.35Q - 228.9$	0.5473	
	Power	$F = 0.03013\,Q^{1.726}$	0.5395	
	Expo.	$F = 3.026\exp(0.04375Q)$	0.5342	
UPV	Linear	$F = 14.24\,V - 38.83$	0.5912	0.1814
	Poly. 2nd	$F = 4.613\,V^2 - 21.24\,V + 29.18$	0.5995	
	Poly. 3rd	$F = 13.61\,V^3 - 150.6\,V^2 + 566.1V - 708.2$	0.6050	
	Power	$F = 0.1467\,V^{3.47}$	0.5999	
	Expo.	$F = 0.5259\exp(0.8825V)$	0.6003	
SonReb (R)	R 1st , V 1st	$F = 0.6687R + 9.292V - 40.37$	0.7265	-
	R 2nd , V 2nd	$F = -2.387R - 2.877\,V + 0.1046R^2 - 0.8977RV + 5.16V^2 + 30.77$	0.7490	
SonReb (Q)	Q 1st , V 1st	$F = 0.4462Q + 9.538V - 37.96$	0.7187	-
	Q 2nd , V 2nd	$F = 5.952Q - 122V + 0.001838Q^2 - 1.42QV + 23.88V^2 + 110$	0.7498	

Table 3.15 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results was illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The EN-13791 curve in Fig. 3.50 demonstrates the curve which is suggested by the EN 13791 standard considering the data which was obtained from compressive tests and NDT measurements. In addition, the EN-13791 (shifted) curve is the curve with -7 shift from the main curve to consider more accuracy based on EN 13791. Furthermore, the Poly. 2nd curve in this figure which was drawn using Matlab software demonstrates better proximity to the obtained data with R-square value of 0.567; however, the standard shift which are linear have acceptable cover on data.

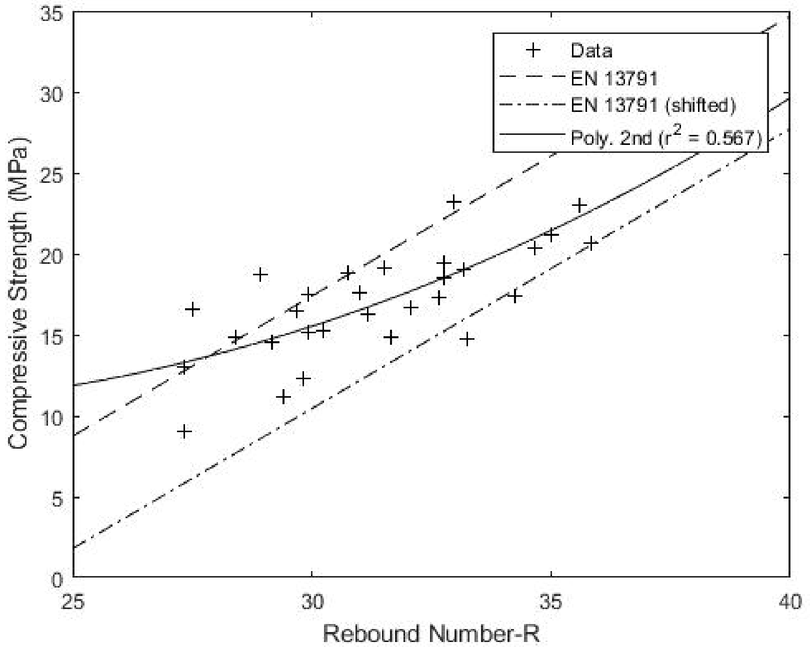


Figure 3. 50: Correlation: Rebound R vs. Compressive Strength of set CIK (B).

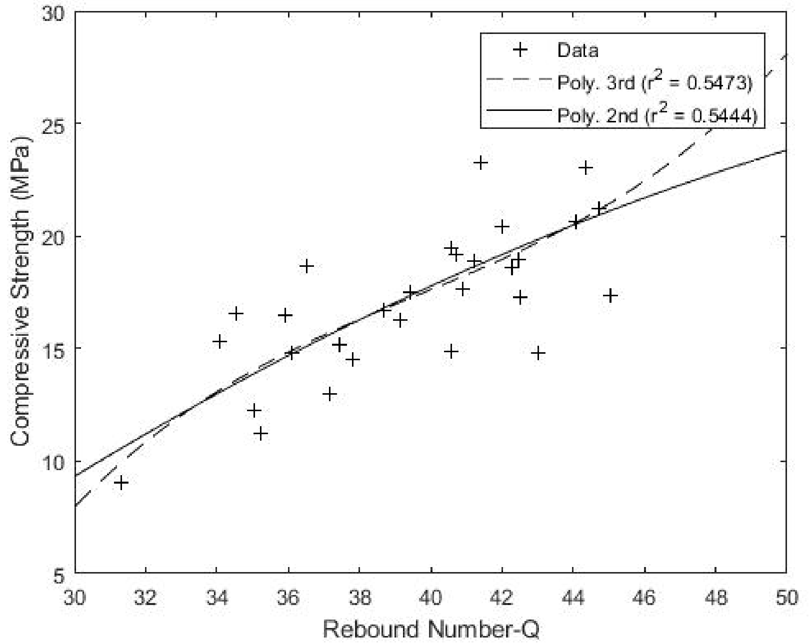


Figure 3. 51: Correlation: Rebound Q vs. Compressive Strength of set CIK (B).

In order to comparison Poly. 2nd and poly. 3rd degree correlations were shown in Fig. 3.51 and the results demonstrate that due to the dispersion of data there are few differences in using poly. 2nd or poly. 3rd degree curves and intended regressions; however, in order to the simplicity of poly. 2nd degree in the equation this curve suggested using for estimate the concrete strength at the studied case (building B). In addition, both Poly. 2nd and Poly. 3rd degree correlations demonstrate acceptable reliability with R-square values of 0.5444, and 0.5473 respectively.

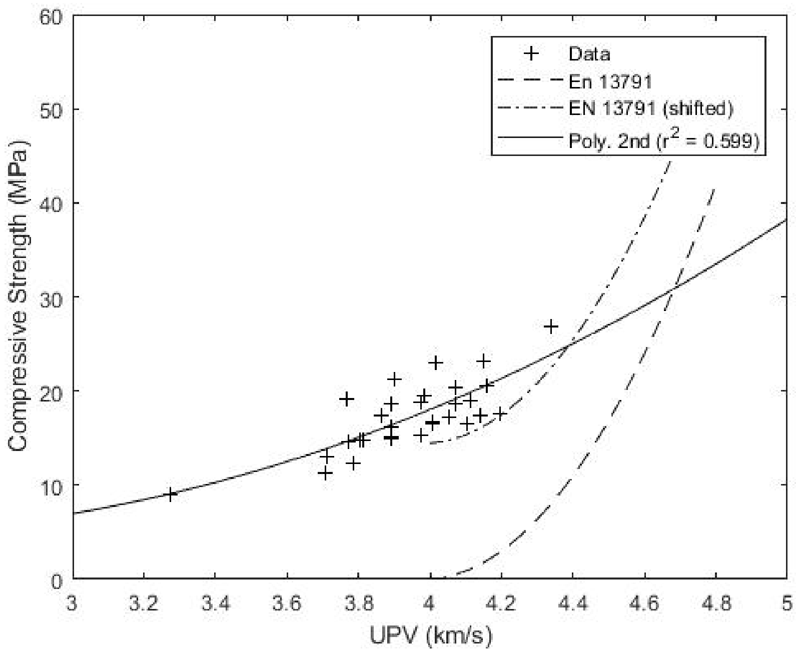


Figure 3. 52: Correlation: UPV vs. Compressive Strength of set CIK (B).

The data dispersion leads to the approximately linear correlation between UPV measurements and compressive strength and it was observed from the poly. 2nd degree curve which is close to the linear shape than polynomial shape if the first point (data) was neglected (see Fig 3.52). In addition, in order to standard limits both of standards curves (main curve and the shifted one) was calculated and drawn between 4 and 4.8 using the measurements which was obtained between this range; however, the poly. 2 degree which covers all of measurements and the related compressive strengths, derived based on all obtained data from 3.2 to 4.8 (km/s) of UPV measurements.

The combined SonReb method significantly increases the accuracy and the R-square value for the correlation using UPV, Rebound Number-R and Compressive Strength measurements due to using 3-D correlation using intended data. As it is illustrated in Fig. 3.53 the correlation which was derived using three different data increase the R-square by approximately 32 % compared with Rebound-R to 0.7490 (see Table 3.15).

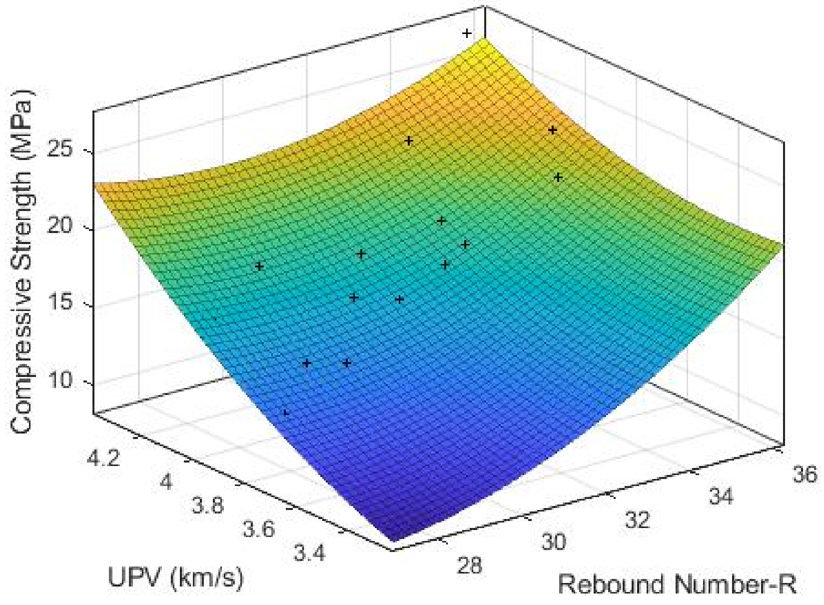


Figure 3. 53: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIK (B).

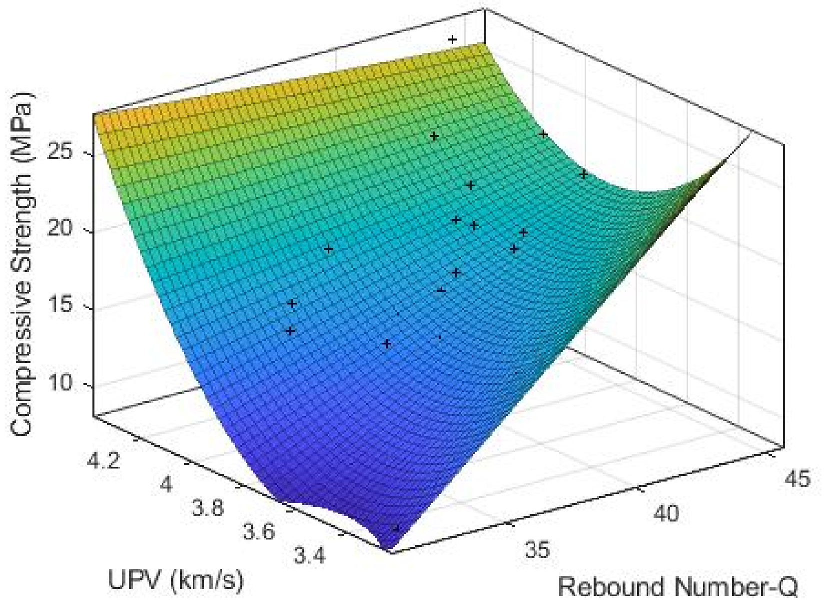


Figure 3. 54: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIK (B).

The combined SonReb method has better results and a higher effect in Rebound-Q compared Rebound-R and it was observed in Fig. 3.54 and the equations and intended R-square values prove this in Table 3.15. However, it has good increase comparing the Poly. 2nd degree of Rebound-Q correlations (the amount of increase is about 38

%). There is a rise in the final parts of the plate for both UPV and Rebound-Q measurements which was observed in the figure which help to cover the data better than a linear plate to reach high reliability.

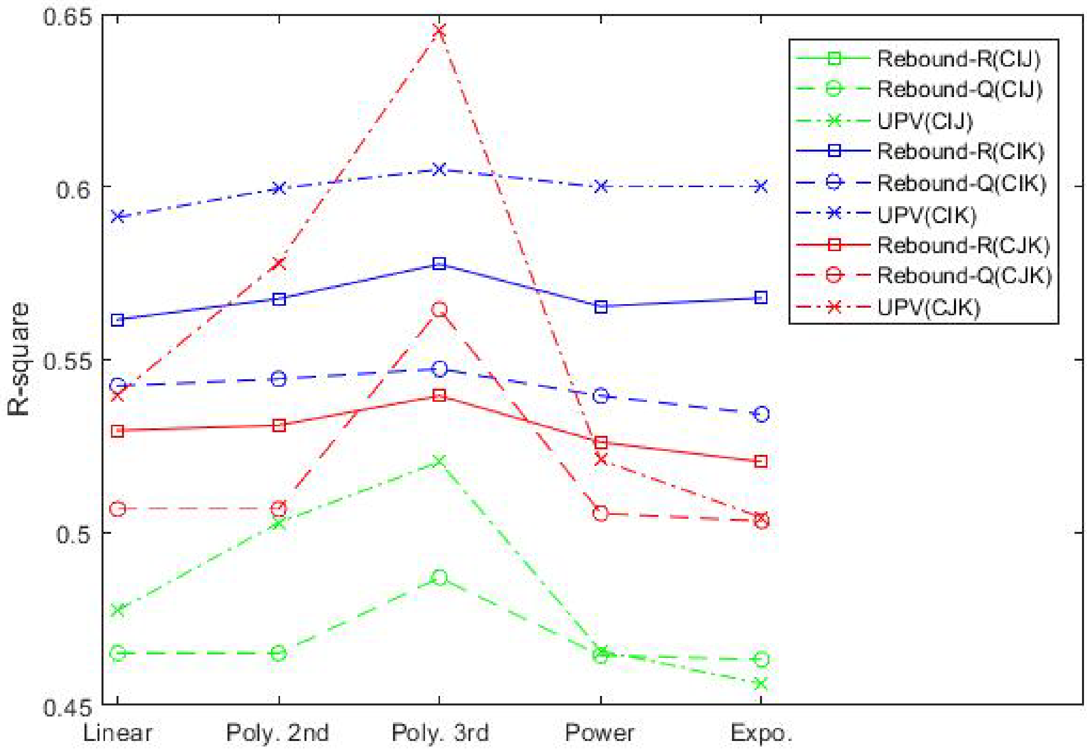


Figure 3. 55: R-square values for different equations, methods, and sets of couple cores (B).

The R-square values for all couple cores sets for building B was shown in Fig. 3.55 based on all five different equations which was used for correlations and regressions for all three NDT methods. As it is observed in Fig. 3.55 the R-square values for Poly. 3rd degree correlation reaches the highest amount compare other four correlation equation type and the slop of increase is significant and higher than other sets. However, this change in slop of curves in Fig. 3.55 for some sets such as CK and CIJK is almost flat with little increase in Poly. 3rd degree correlation. In addition, the increase in R-square value from linear to Poly. 2nd correlation and then decrease from Poly. 3rd to power and Expo. correlations was illustrated in the intended figure. Furthermore, except UPV(CJK) set which illustrates an abnormal increase in Poly. 3rd degree correlation the other sets demonstrate normal behavior as explained above.

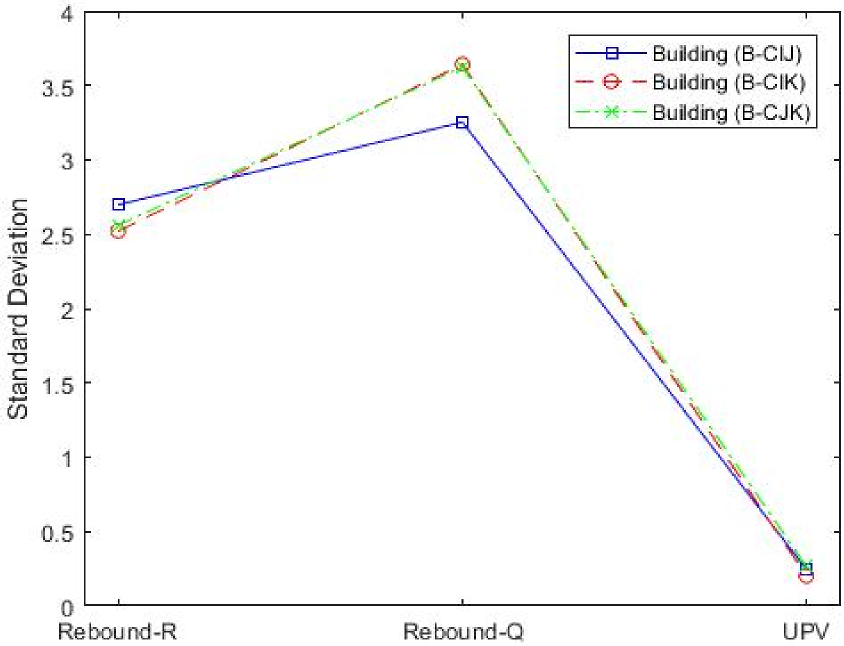


Figure 3. 56: Standard deviation of different sets of couple cores (B).

The standard deviation for all three sets including CIJ, CJK, and CIK and for three various methods was observed in Fig. 3.56. The amount of standard deviation for all sets shows that there is an increase in standard deviation of Rebound-Q compared with Rebound-R and maybe it is the reason that in some sets the amount of R-square value gets higher for Rebound-R type than Rebound-Q. The amount of increase for different sets differs from 30-40 % comparing Rebound-R and Rebound-Q. Furthermore, the standard deviation for UPV measurements demonstrates lower values and in order to difference between the amount type the comparison could not made for UPV measurements data and other two rebounds data.

3.2.2.3 Second scenario-building C

In this part the sets and correlations which was derived based on second scenario was demonstrated in various tables and figures for building C.

Table 3. 16: R-square and standard deviation values of different equations and methods of couple cores for building (C).

NDT Method	Equation type	CI & CJ		CI & CK		CJ & CK	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.5235	3.5803	0.4052	4.2003	0.3725	3.8461
	Poly. 2nd	0.5286		0.4055		0.3785	
	Poly. 3rd	0.5296		0.4055		0.4213	
	Power	0.5221		0.4052		0.3719	
	Expo.	0.5133		0.4028		0.3768	
Rebound-Q	Linear	0.5402	5.4690	0.5227	5.5329	0.4789	5.6028
	Poly. 2nd	0.5543		0.5259		0.4847	
	Poly. 3rd	0.5747		0.5306		0.4919	
	Power	0.5397		0.5224		0.4796	
	Expo.	0.5284		0.5156		0.4716	
UPV	Linear	0.4972	0.4088	0.4497	0.3743	0.5297	0.3054
	Poly. 2nd	0.5659		0.4672		0.5320	
	Poly. 3rd	0.5774		0.5216		0.5688	
	Power	0.4948		0.447		0.5276	
	Expo.	0.4748		0.4333		0.5194	
SonReb (R)	R 1st , V 1st	0.5797	-	0.5127	-	0.5672	-
	R 2nd , V 2nd	0.6062		0.5375		0.6107	
SonReb (Q)	Q 1st , V 1st	0.5939	-	0.5669	-	0.5797	-
	Q 2nd , V 2nd	0.6191		0.5839		0.5937	

Based on the results which are obtained based on Table 3.16 considering R-square and standard deviation values, CIJ set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for building C.

Table 3. 17: Correlation equations of CIJ set for building (C).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.9328R - 5.797$	0.5235	3.5803
	Poly. 2nd	$F = -0.0182R^2 + 2.364R - 33.7$	0.5286	
	Poly. 3rd	$F = 0.002005R^3 - 0.2495R^2 + 11.18R - 144.5$	0.5296	
	Power	$F = 0.4094R^{1.177}$	0.5221	
	Expo.	$F = 9.642\exp(0.02946R)$	0.5133	
Rebound-Q	Linear	$F = 0.6319Q - 1.635$	0.5402	5.4690
	Poly. 2nd	$F = -0.0165Q^2 + 2.364Q - 46.61$	0.5543	
	Poly. 3rd	$F = 0.00343Q^3 - 0.5486Q^2 + 29.64Q - 508.6$	0.5747	
	Power	$F = 0.5115\,Q^{1.041}$	0.5397	
	Expo.	$F = 11.22\exp(0.01957Q)$	0.5284	
UPV	Linear	$F = 8.084\,V - 4.602$	0.4972	0.4088
	Poly. 2nd	$F = -6.556\,V^2 + 67.13\,V - 136.4$	0.5659	
	Poly. 3rd	$F = -6.797\,V^3 + 85.71\,V^2 - 347.7V + 481.4$	0.5774	
	Power	$F = 5.898\,V^{1.119}$	0.4948	
	Expo.	$F = 10.61\exp(0.2425V)$	0.4748	
SonReb (R)	R 1st , V 1st	$F = 0.5723R + 4.203V - 10.12$	0.5797	-
	R 2nd , V 2nd	$F = -0.2179R + 48.16\,V - 0.003049R^2 + 0.1988RV - 5.643V^2 - 92.11$	0.6062	
SonReb (Q)	Q 1st , V 1st	$F = 0.4051Q + 4.026V - 7.679$	0.5939	-
	Q 2nd , V 2nd	$F = -0.3846Q + 48.48V - 0.006618Q^2 + 0.3114QV - 6.624V^2 - 86.58$	0.6191	

Table 3.17 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data for Rebound-R and Compressive strength obtained from NDT measurements and experimental compression tests respectively was provided and the data correlations using both EN 13791 standard and Poly. 2nd degree correlation curves were drawn in Fig. 3.57. The data dispersion was in a proper condition along the both EN 13791 suggested curve for the intended data and for the Poly. 2nd degree correlation curves with R-square value of 0.528 which is a reliable value for the Rebound-R considering other buildings. However, if the core dispersion was a bit more longitudinal the R-square values rise and the results become more reliable.

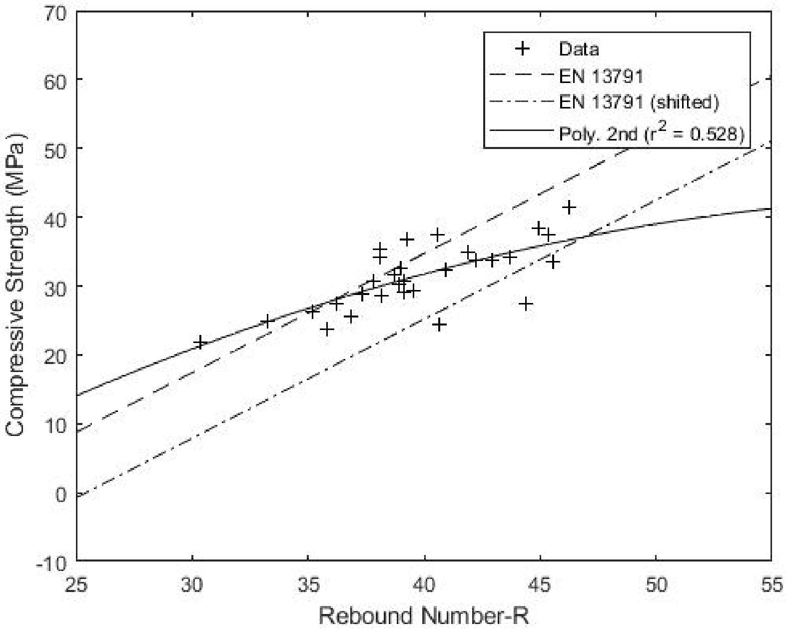


Figure 3. 57: Correlation: Rebound R vs. Compressive Strength of set CIJ (C).

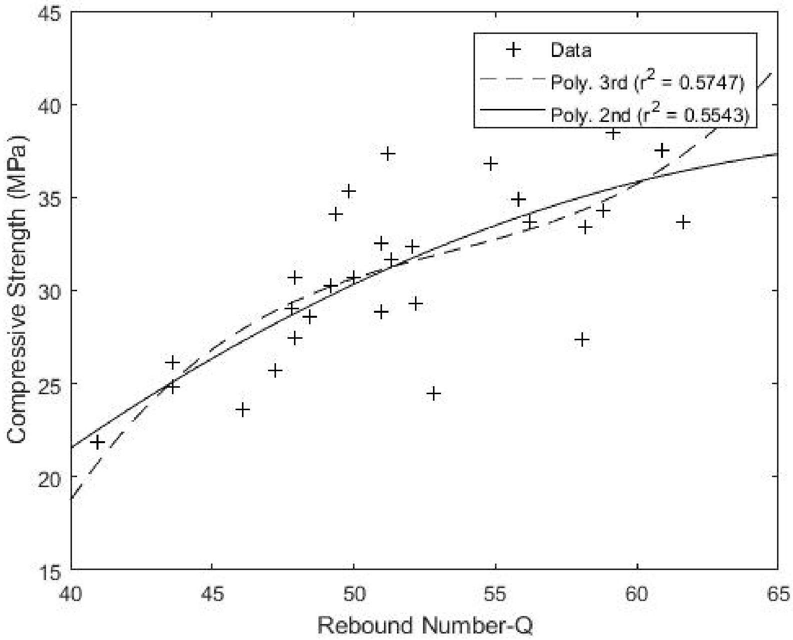


Figure 3. 58: Correlation: Rebound Q vs. Compressive Strength of set CIJ (C).

Based on observations in Fig. 3.58 both Poly. 2nd and Poly. 3rd degree correlation curves are so close to each other and could be considered same in this section due to the special dispersion of data. In addition, the data was suitably distributed around the correlation curves which leads to high R-square values for both Poly. 2nd degree and Poly. 3rd degree (0.5543, 0.5747 respectively). Furthermore, in this data correlation the data dispersion is somehow far from correlation curves which cause reduction in R-square values compared previous Rebound-Q results.

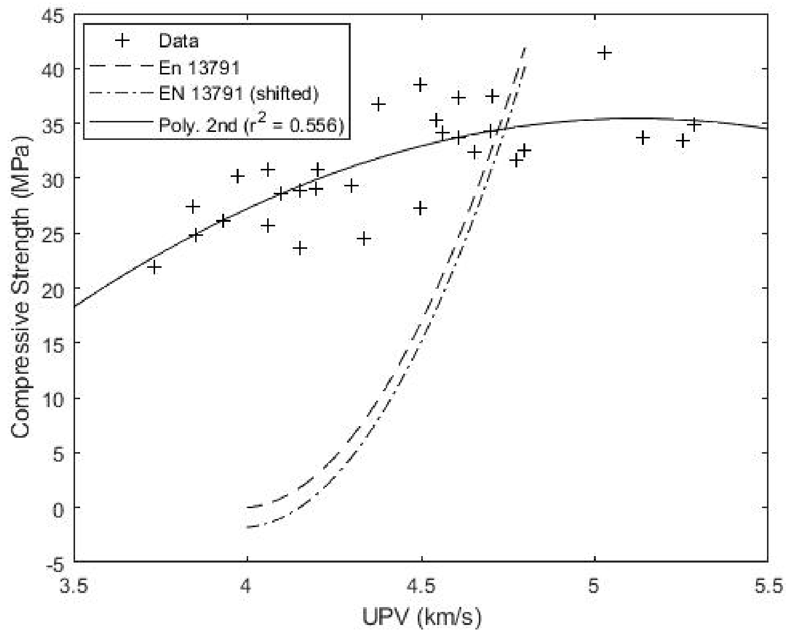


Figure 3. 59: Correlation: UPV vs. Compressive Strength of set CIJ (C).

In order to the special dispersion of UPV measurements data which is more compatible with the equation and the curve suggested by EN 13791 standard, the other correlation curves could not cover the data properly and the obtained R-square value is not such strong value to consider for concrete compressive strength estimation (see Fig 3.59). However, the Poly. 2nd degree correlation which was suggested by Matlab software could cover the data more properly by 0.556 R-square values.

The improvement in R-square value indicates the importance and effectiveness of combined SonReb method and using the 3-D correlation with a plate which covers most of the data is the reason for this enhancement in the R-square value. Fig 3. 60 illustrates that approximately the curve for UPV data is in polynomial shape; however, the other curve which is in Rebound-R straight is much linear than polynomial.

Table 3.17 demonstrates that there is a 7 % increase compared with UPV-Compressive strength correlation`s R-square value. In addition, there is a slight increase in comparing Rebound-R results with SonReb results and this occurs due to the high R-square value which was obtained for Rebound-R vs. Compressive strength correlation.

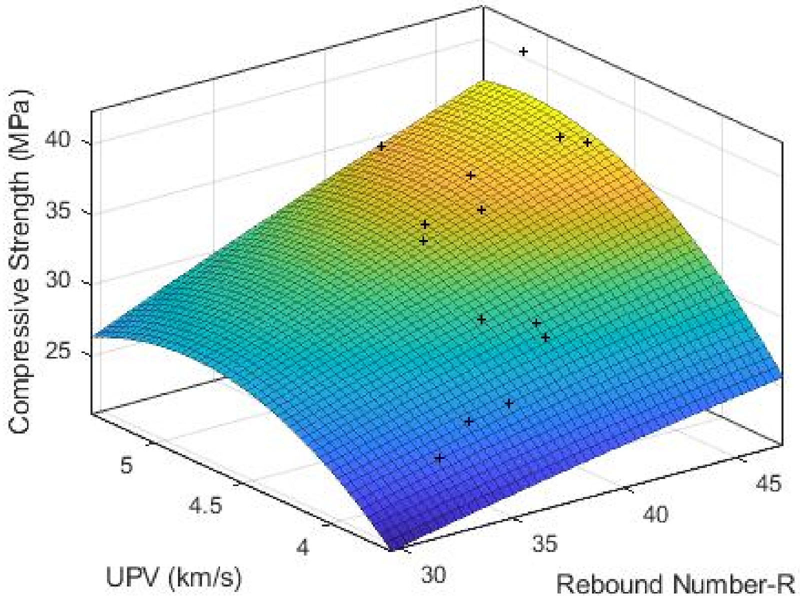


Figure 3. 60: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJ (C).

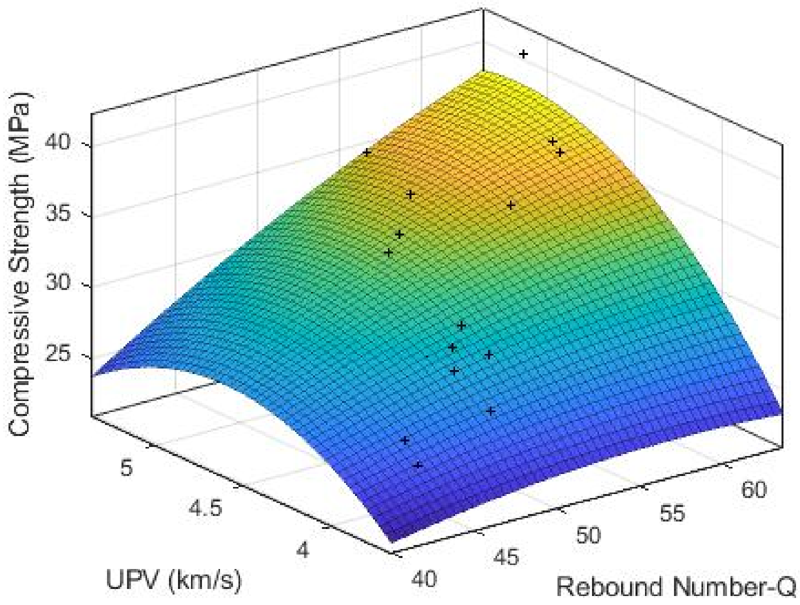


Figure 3. 61: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJ (C).

Despite the Rebound-R combined correlation for this section and set, the combined correlation for Rebound-Q due to the data distribution which was observed in Fig. 3.61 requires double polynomial curves to cover the data and fit the plate to reach the best result for correlation equation and R-square value. Furthermore, there are a few increases in comparing Rebound-Q R-square results with SonReb results and this happens due to the high R-square value which was derived for Rebound-Q vs. Compressive strength correlation. Moreover, there is a 10 % increase in R-square value compared with UPV vs. Compressive strength correlation`s result (see Table 3.17).

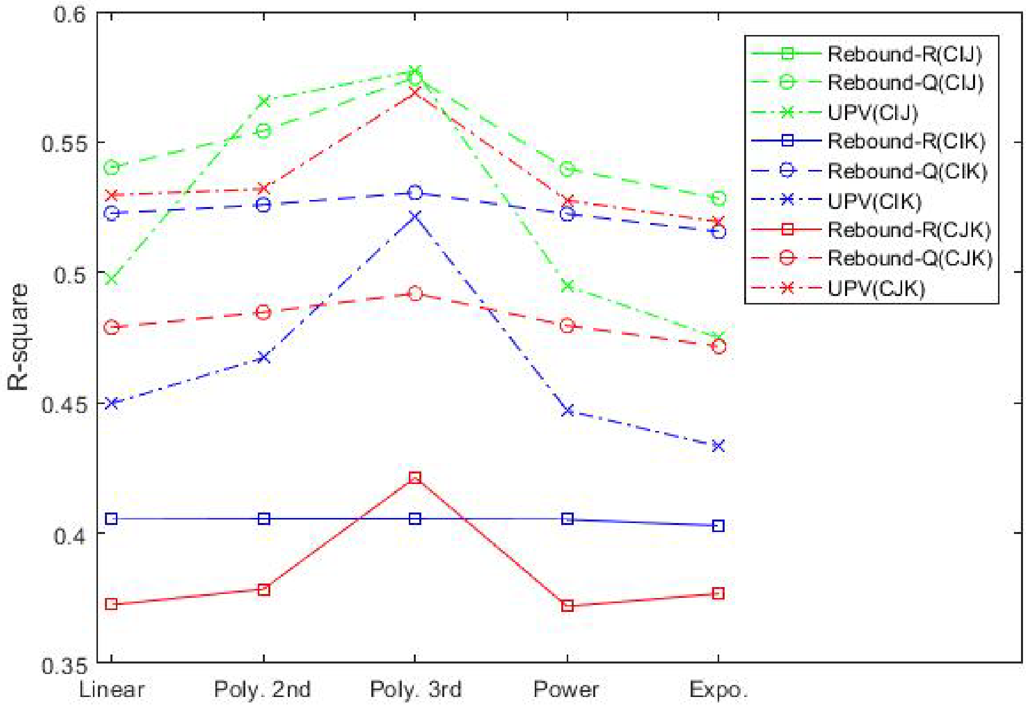


Figure 3. 62: R-square values for different equations, methods, and sets of couple cores (C).

The curves in Fig. 3.62 shows that the behavior of change in R-square values among five different equation and three different NDT methods are close to each other; however, in some cases that data distribution is special and require polynomial curve to reach the proper fit and high R-square value, the R-square value increase with high rate toward Poly. 3rd degree correlation and this occurs mostly in UPV vs. Compressive strength correlation due to the special data dispersion which was observed in previous figures and even EN 13791 suggest the special polynomial curve for UPV correlation. Furthermore, the Rebound-R(CJK), UPV(CIJ), UPV(CIK), and UPV(CJK) demonstrate high rate change toward Poly. 3rd degree correlation result; however, the other sets illustrate normal increase with moderate rate toward Poly. 3rd degree correlation result.

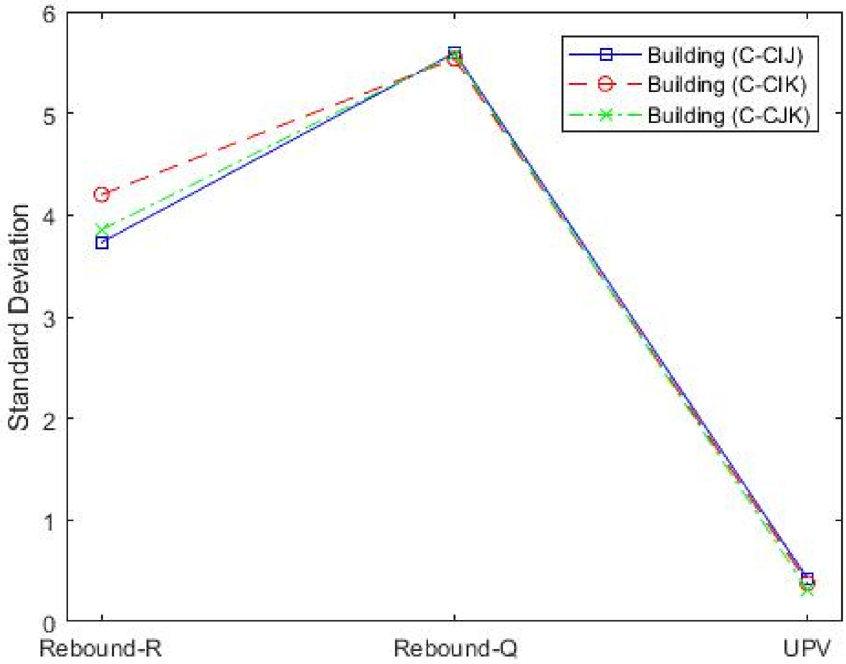


Figure 3. 63: Standard deviation of different sets of couple cores (C).

Considering the slope of difference from method to the other method, Fig. 3.63 illustrates that there is almost no difference among sets change rate and the change in standard deviation occurs normally with no special differences. However, the standard deviation of CIK set is higher than two other sets and standard deviation of CIJ set is lower than other sets.

3.2.2.4 Second scenario-building D

In this part the sets and correlations which was derived based on second scenario was demonstrated in various tables and figures for building D.

Table 3. 18: R-square and standard deviation values of different equations and methods of couple cores for building (D).

NDT Method	Equation type	CI & CJ		CI & CK		CJ & CK	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.7101	3.6133	0.8184	3.7108	0.7183	3.8175
	Poly. 2nd	0.7250		0.8213		0.7183	
	Poly. 3rd	0.7250		0.8369		0.7751	
	Power	0.7012		0.8117		0.7166	
	Expo.	0.6853		0.7985		0.7132	
Rebound-Q	Linear	0.6682	5.1405	0.6788	5.6354	0.6349	6.0648
	Poly. 2nd	0.6841		0.6978		0.6359	
	Poly. 3rd	0.7258		0.7086		0.6532	
	Power	0.6584		0.6732		0.6334	
	Expo.	0.6333		0.6568		0.6255	
UPV	Linear	0.3680	0.2264	0.2237	0.2193	0.3431	0.2163
	Poly. 2nd	0.3728		0.2295		0.3661	
	Poly. 3rd	0.3744		0.2750		0.3833	
	Power	0.3720		0.2220		0.3329	
	Expo.	0.3730		0.2187		0.3216	
SonReb (R)	R 1st , V 1st	0.7294	-	0.8196	-	0.7458	-
	R 2nd , V 2nd	0.7668		0.8229		0.7604	
SonReb (Q)	Q 1st , V 1st	0.6721	-	0.6795	-	0.6507	-
	Q 2nd , V 2nd	0.7505		0.7005		0.6661	

Based on the results which is obtained based on Table 3.18 considering R-square and standard deviation values, CIJ set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for building D.

Table 3. 19: Correlation equations of CIJ set for building (D).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.202R - 16.9$	0.7101	3.6133
	Poly. 2nd	$F = -0.04509R^2 + 4.302R - 69.34$	0.7250	
	Poly. 3rd	$F = -0.0003064R^3 - 0.01348R^2 + 3.225R - 57.24$	0.7250	
	Power	$F = 0.06817R^{1.661}$	0.7012	
	Expo.	$F = 4.738\exp(0.04723R)$	0.6853	
Rebound-Q	Linear	$F = 0.8295Q - 13.78$	0.6682	5.1405
	Poly. 2nd	$F = -0.01723Q^2 + 2.432Q - 50.43$	0.6841	
	Poly. 3rd	$F = -0.003865Q^3 + 0.5136Q^2 - 21.51Q + 303.7$	0.7258	
	Power	$F = 0.07433\ Q^{1.512}$	0.6584	
	Expo.	$F = 5.753\exp(0.03116Q)$	0.6333	
UPV	Linear	$F = 14.16\ V - 31.83$	0.3680	0.2264
	Poly. 2nd	$F = 4.13\ V^2 - 18.47\ V + 32.25$	0.3728	
	Poly. 3rd	$F = 7.533\ V^3 - 84.02\ V^2 + 323.6V - 407.6$	0.3744	
	Power	$F = 0.9291\ V^{2.363}$	0.3720	
	Expo.	$F = 2.318\exp(0.5891V)$	0.3730	
SonReb (R)	R 1st , V 1st	$F = 1.058R + 4.004V - 28.17$	0.7294	-
	R 2nd , V 2nd	$F = 6.764R - 112.1\ V - 0.0251R^2 - 0.9634RV + 18.56V^2 + 104.8$	0.7668	
SonReb (Q)	Q 1st , V 1st	$F = 0.7691Q + 2.026V - 19.18$	0.6721	-
	Q 2nd , V 2nd	$F = 5.273Q - 160.3V - 0.04407Q^2 - 0.05886QV + 20.29V^2 + 202.5$	0.7505	

Table 3.19 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The obtained data from Rebound-R measurements and compressive strength tests in Fig. 3.64 demonstrates that there is a compaction between 35-40 Rebound number for the data compared other parts; however, the related correlations illustrates high R-square values due to data tendency to polynomial shape and leads to highly reliable correlation from Poly. 2nd degree curve which reaches up to 0.725. In addition, the EN 13791 suggested curve also have good cover on data and could provide an acceptable and reliable correlation for the intended data. However, the main curves shows better correlation than the shifted curve which was shifted by 7 toward downside of figure.

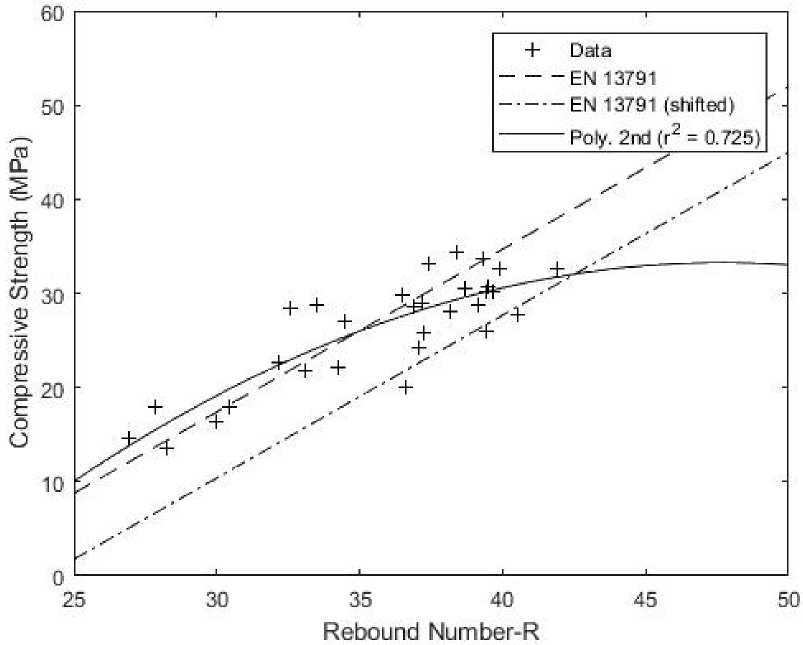


Figure 3. 64: Correlation: Rebound R vs. Compressive Strength of set CIJ (D).

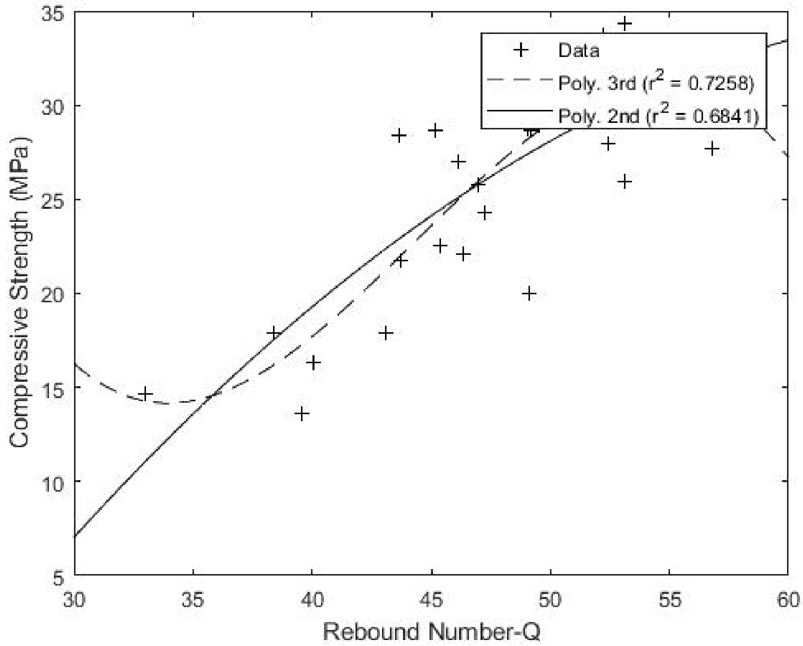


Figure 3. 65: Correlation: Rebound Q vs. Compressive Strength of set CIJ (D).

Figure 3.65 illustrates that in the range between 35-55 of Rebound number both Poly. 2nd and Poly. 3rd degree correlation curves approximately lay on each other for this set of data ; however, some small changes in Poly. 3rd degree correlation causes reaching higher R-square value for this correlation (0.7258). In addition, the acceptable value for R-square demonstrates that the data in this analysis was properly distributed and the intended correlation leads to the high reliable equation for concrete strength estimation in building D. Furthermore, Poly, 2nd degree considering the simplicity compared with Poly. 3rd degree correlation could be used for estimations due to its high reliability.

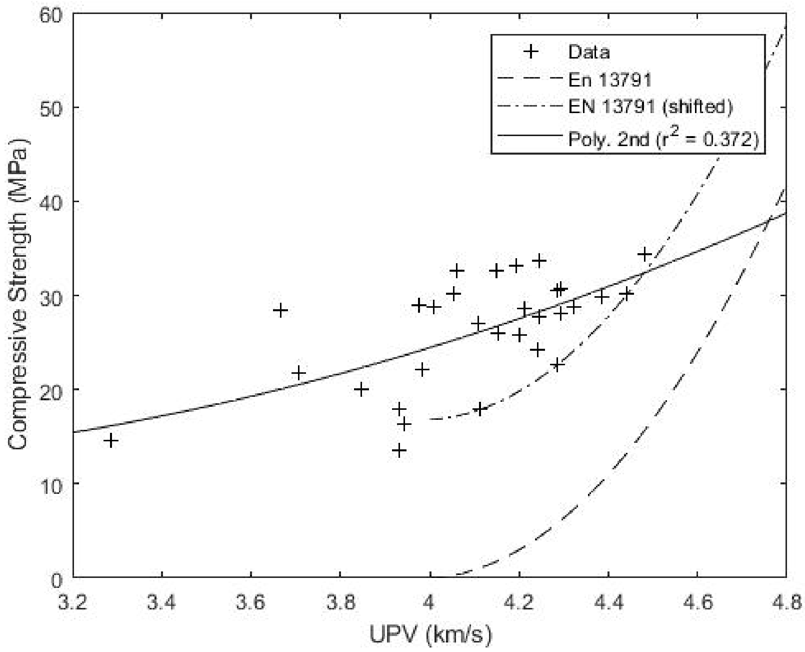


Figure 3. 66: Correlation: UPV vs. Compressive Strength of set CIJ (D).

The UPV measurements for the couple cores in building D shows weak results for UPV-Compressive strength correlations compared other sets and building using Poly. 2nd degree curve with R-square value of 0.372 which was illustrated in Fig 3.66 and is not acceptable and reliable. In addition, the number of data which are sited on the range which was determined by the EN 13791 standard is high enough to have a correlation; however, the standard shifted curve which is more close to data could not cover the data properly but could provide acceptable correlation.

The combined method for the CIJ set of building D was observed in Fig. 3. 67 and the related curves demonstrate the double polynomial curve in both directions which helps to reach better correlation in 3-D condition by R-square value (0.7668) which demonstrates a great improvement considering the weak values which were obtained for UPV vs. Compressive strength measurements correlations (see Table 3.19).

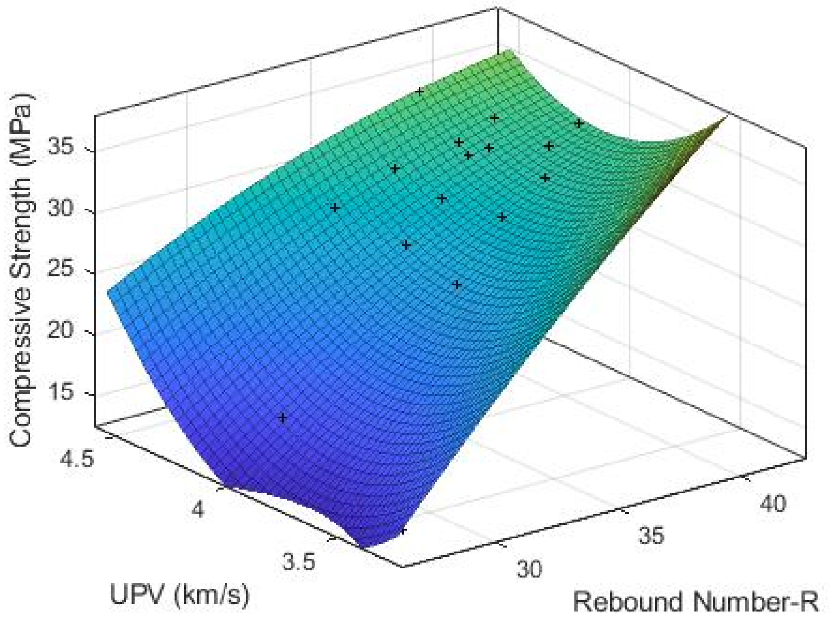


Figure 3. 67: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJ (D).

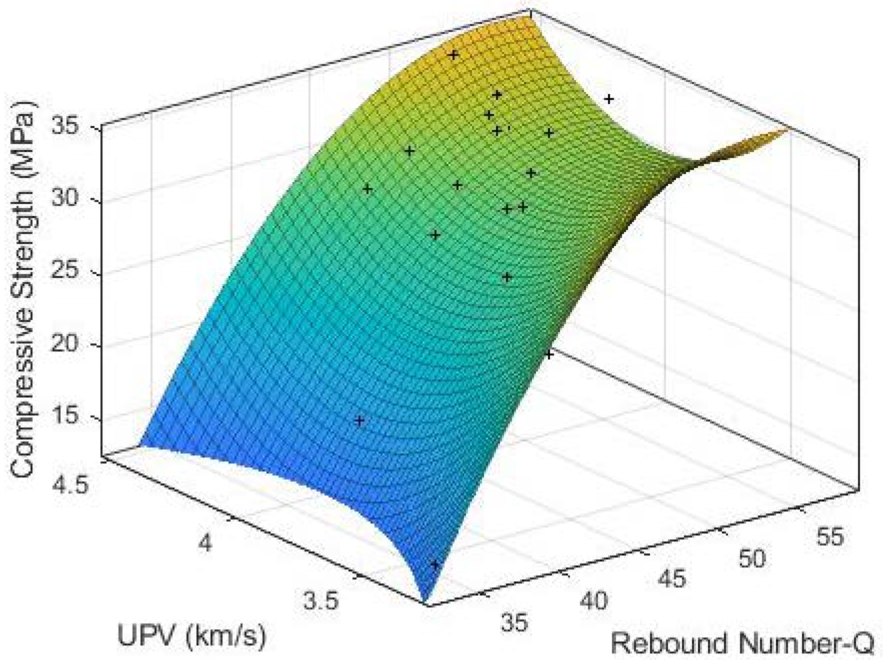


Figure 3. 68: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJ (D).

Figure 3.68 illustrates the 3-D combined SonReb method for Rebound number-Q vs UPV vs Compressive strength and like the Rebound-R the data dispersion requires to have double polynomial correlation curves to reach the higher and improved R-square value. According to Table 3.19, there is a 12 % increase in R-square value while using double polynomial correlation compared using linear correlation curves. In addition, the analysis reveals that there is approximately 100 % increase in R-square value comparing combined SonReb method and 2-D UPV vs. Compressive strength Poly. 2nd degree correlation`s R-square values which are occurs due to weak values which were found for UPV vs. Compressive strength correlations.

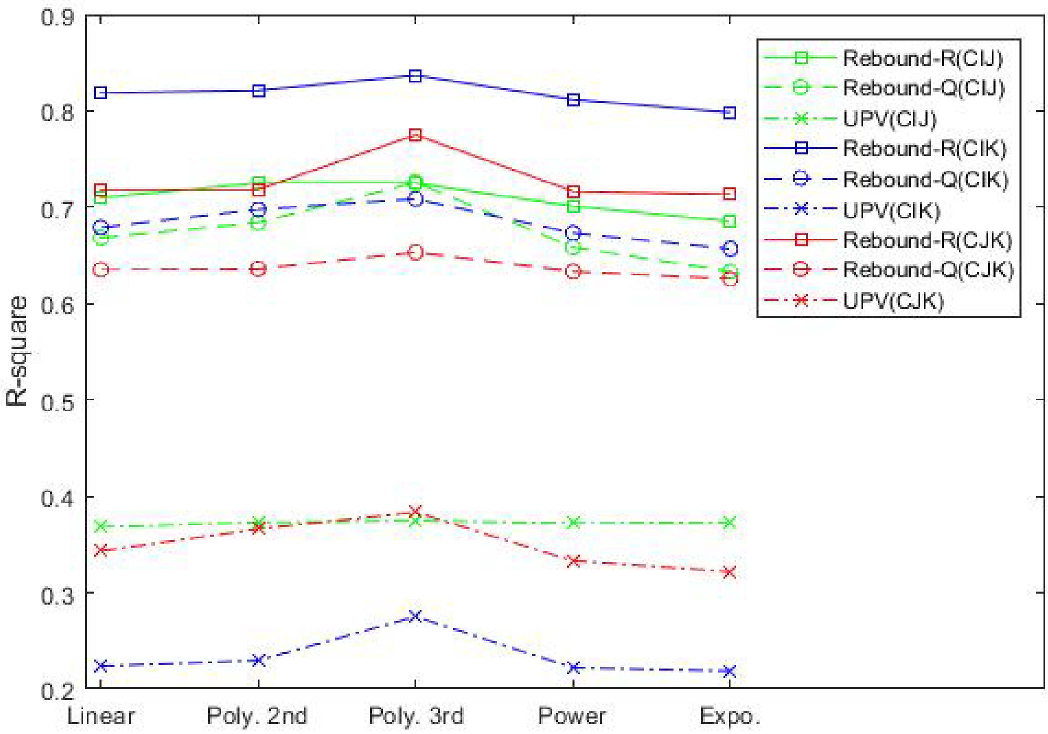


Figure 3. 69: R-square values for different equations, methods, and sets of couple cores (D).

The R-square values of four different sets and three various methods were illustrated in Fig. 3.69 for five different correlation equation (regression) types for building D. The behavior of curves in the intended figure, demonstrates that most of the sets and methods behave like each other; however, there are some differences such as high rate increase from Poly. 2nd degree result to Poly. 3rd degree result which was shown for Rebound-R (CJK), UPV (CIK), UPV (CJK), and Rebound-Q (CIJ) which dramatically depends on the way that the data dispersed for each correlation. In addition, this phenomena is usual for the UPV measurement correlations due to their special data dispersion.

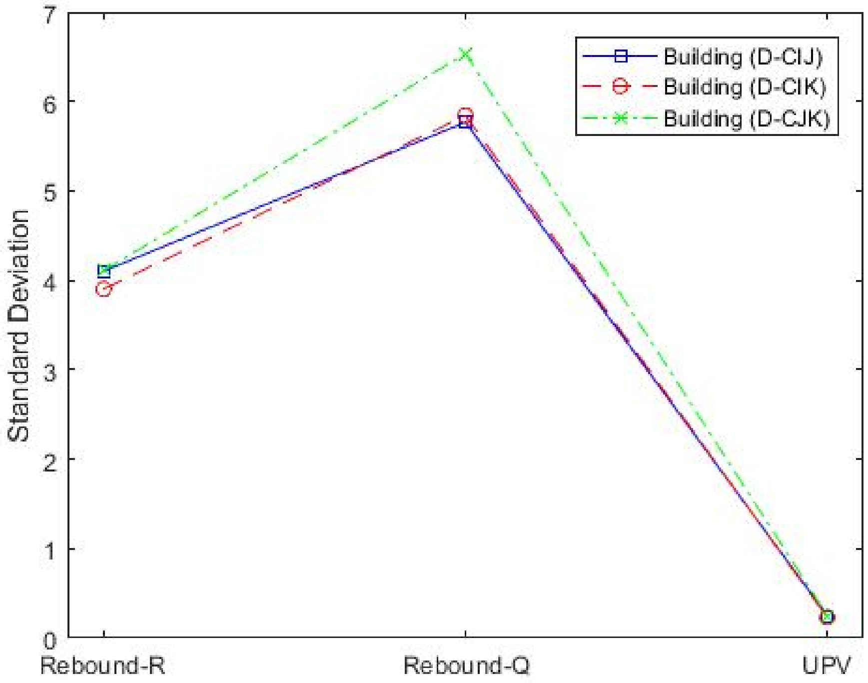


Figure 3. 70: Standard deviation of different sets of couple cores (D).

There is an increase in the standard deviation magnitude in Rebound-Q compared Rebound-R and it is almost same with the previous buildings sets. In addition, there is almost 50 % increase in average for Rebound-Q compared Rebound-R which was observed in Fig. 3.70 and determined in Table 3.19 for different sets. Furthermore, the D-CJK set illustrates the highest standard deviation for Rebound-Q; however, the other two sets demonstrates almost equal amount for this type of method`s standard deviation.

3.2.2.5 Second scenario-building All

In this part the sets and correlations which was derived based on second scenario was demonstrated in various tables and figures for All building case.

Table 3. 20: R-square and standard deviation values of different equations and methods of couple cores for building (All).

NDT Method	Equation type	CI & CJ		CI & CK		CJ & CK	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.7477	4.3118	0.6770	4.0613	0.5192	4.2399
	Poly. 2nd	0.7512		0.6901		0.5193	
	Poly. 3rd	0.7543		0.6915		0.5246	
	Power	0.7372		0.6615		0.5181	
	Expo.	0.7172		0.6377		0.5112	
Rebound-Q	Linear	0.7317	6.3594	0.7067	6.0746	0.4931	6.4653
	Poly. 2nd	0.7438		0.7234		0.5001	
	Poly. 3rd	0.7457		0.7261		0.5182	
	Power	0.7191		0.6917		0.4892	
	Expo.	0.6935		0.6631		0.4725	
UPV	Linear	0.4229	0.3747	0.4081	0.3527	0.2500	0.3399
	Poly. 2nd	0.4229		0.4085		0.2691	
	Poly. 3rd	0.4448		0.4389		0.2738	
	Power	0.4209		0.4040		0.2559	
	Expo.	0.4128		0.3937		0.2616	
SonReb (R)	R 1st , V 1st	0.7553	-	0.7039	-	0.5264	-
	R 2nd , V 2nd	0.7641		0.7232		0.5537	
SonReb (Q)	Q 1st , V 1st	0.7376	-	0.7228	-	0.4963	-
	Q 2nd , V 2nd	0.7586		0.7456		0.5369	

Based on the results which are obtained based on Table 3.20 considering R-square and standard deviation values, CIJ set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for all cases.

Table 3. 21: Correlation equations of CIJ set for building (All).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.345R - 23.11$	0.7477	4.3118
	Poly. 2nd	$F = -0.01666R^2 + 2.543R - 44.34$	0.7512	
	Poly. 3rd	$F = -0.002934R^3 + 0.304R^2 - 8.989R + 92.07$	0.7543	
	Power	$F = 0.02945R^{1.882}$	0.7372	
	Expo.	$F = 4.059\ \exp(0.05017R)$	0.7172	
Rebound-Q	Linear	$F = 0.9212Q - 17.79$	0.7317	
	Poly. 2nd	$F = -0.01512Q^2 + 2.358Q - 51.27$	0.7438	6.3594
	Poly. 3rd	$F = -0.0007472Q^3 + 0.09193Q^2 - 2.676Q + 26.39$	0.7457	
	Power	$F = 0.04472\ Q^{1.646}$	0.7191	
	Expo.	$F = 5.225\ \exp(0.03325Q)$	0.6935	
UPV	Linear	$F = 12.42\ V - 26.19$	0.4229	
	Poly. 2nd	$F = 0.009844\ V^2 + 12.33\ V - 26.01$	0.4229	
	Poly. 3rd	$F = -8.506\ V^3 + 109.3\ V^2 - 451.2V + 623.7$	0.4448	0.3747
	Power	$F = 1.5\ V^{1.981}$	0.4209	
	Expo.	$F = 3.845\ \exp(0.4511V)$	0.4128	
SonReb (R)	R 1st , V 1st	$F = 1.219R + 2.268V - 28$	0.7553	-
	R 2nd , V 2nd	$F = 3.127R - 10.82\ V - 0.03732R^2 + 0.1797RV + 0.8295V^2 - 34.7$	0.7641	
SonReb (Q)	Q 1st , V 1st	$F = 0.8407Q + 2.053V - 22.53$	0.7376	-
	Q 2nd , V 2nd	$F = 3.157Q - 25.85V - 0.01738Q^2 - 0.1605QV + 4.24V^2 - 18.52$	0.7586	

Table 3.21 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data dispersion of CIJ set of the building (All) for Rebound number-R is suitable for a better correlation compared previous sets and buildings and as it is observed in Fig. 3.71 and both EN 13791 curves and Poly. 2nd correlation curves could properly cover the data and it was proven by the R-square value of 0.751 for Poly. 2nd degree correlation which provides a highly reliable correlation. In addition, according to Table 3.21, the other correlations demonstrates high magnitude for R-square value, which proves that even by using linear correlation the reliable correlation with acceptable R-square value could be obtained.

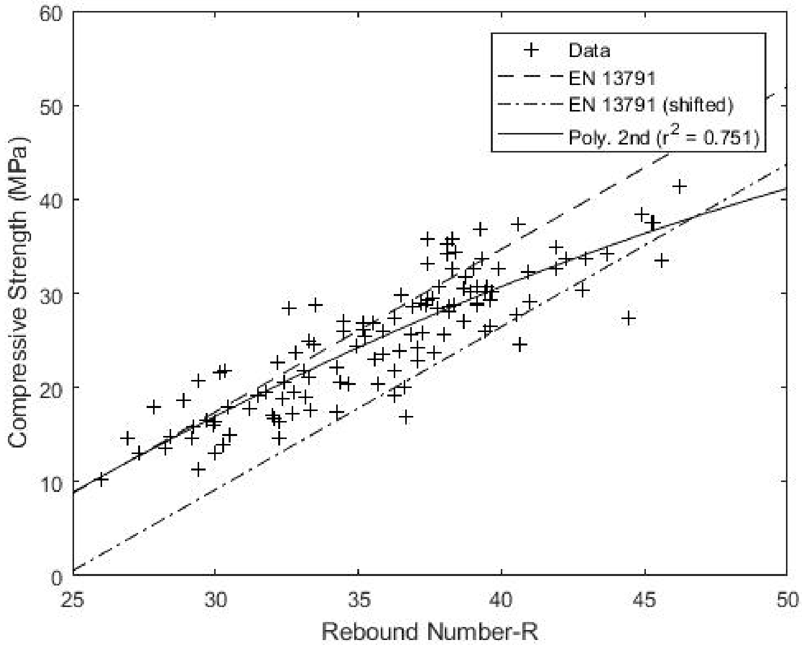


Figure 3. 71: Correlation: Rebound R vs. Compressive Strength of set CIJ (All).

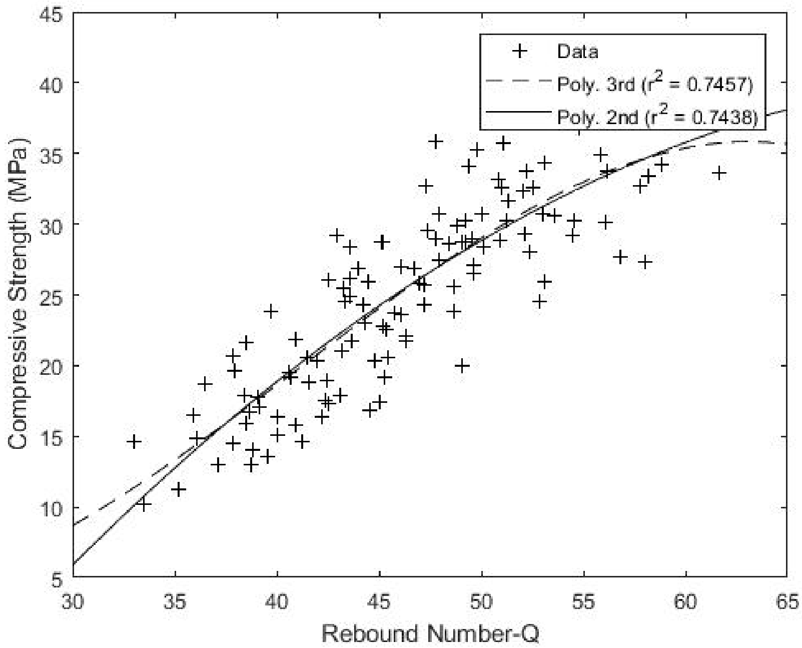


Figure 3. 72: Correlation: Rebound Q vs. Compressive Strength of set CIJ (All).

Figure 3. 72 illustrates the Poly. 2nd and Poly. 3rd degree correlations for Rebound-Q vs Compressive strength with R-square values of 0.7438 and 0.7457 respectively. Although the R-square values have a few differences with each other and even with linear and power correlations' R-square values (see Table 3.21), the curve shape in Fig. 3.72 demonstrates that the Poly. 2nd correlation curves could provide proper cover

over the intended data and are more simple than Poly. 3rd degree correlation thus, it could be strongly acceptable and reliable for this set of data. In addition, data dispersion for this set of data illustrates acceptable propagation with almost no abnormal dispersion which helps to have high R-square values even by using linear correlations.

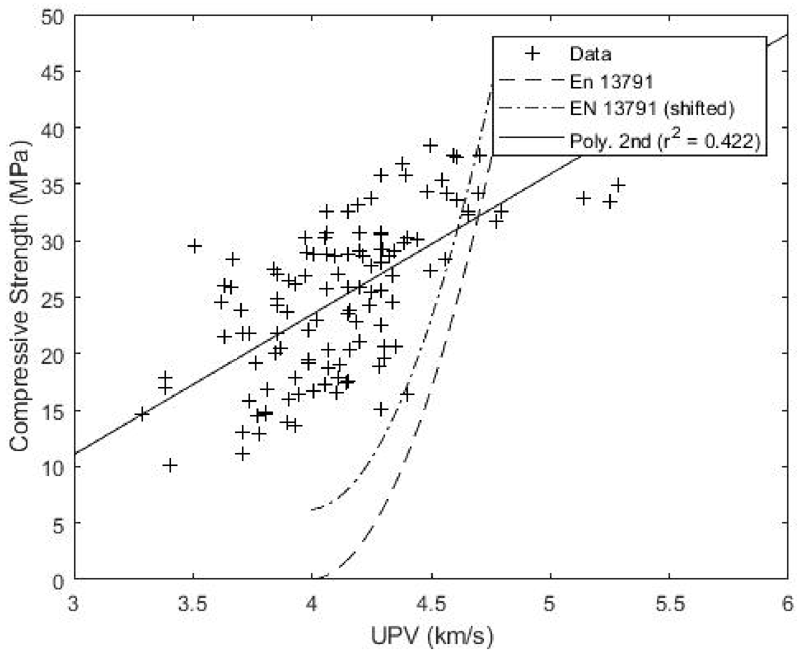


Figure 3. 73: Correlation: UPV vs. Compressive Strength of set CIJ (All).

In some special case when the data dispersion is not in polynomial shape- which is suitable for EN 13791 suggested curve- and the compressive strength values are in high values the EN 13791 curve and it`s shifted curve could not cover the data and the correlation curves by the standards are not reliable anymore as it is observed in Fig 3.73. However, the Poly. 2nd correlation curve by Matlab software could properly cover the data due to using an inverse type of this polynomial which is more suitable for this data dispersion and the R-square value reach to the 0.5380 which is a higher value compared other UPV measurements correlations.

The plate which was derived using the combined correlation of Rebound-R vs UPV vs Compressive strength in Fig. 3.74. The shape and slope of both curves demonstrate that the polynomial curve is the best option for this data dispersion; however, using the linear curve for UPV side could be useful due to the shape of a polynomial plate which is so close to linear than polynomial. In addition, based on the results which were observed in Table 3.21 there is an 80 % increase comparing combined SonReb method and UPV measurements 2-D correlations.

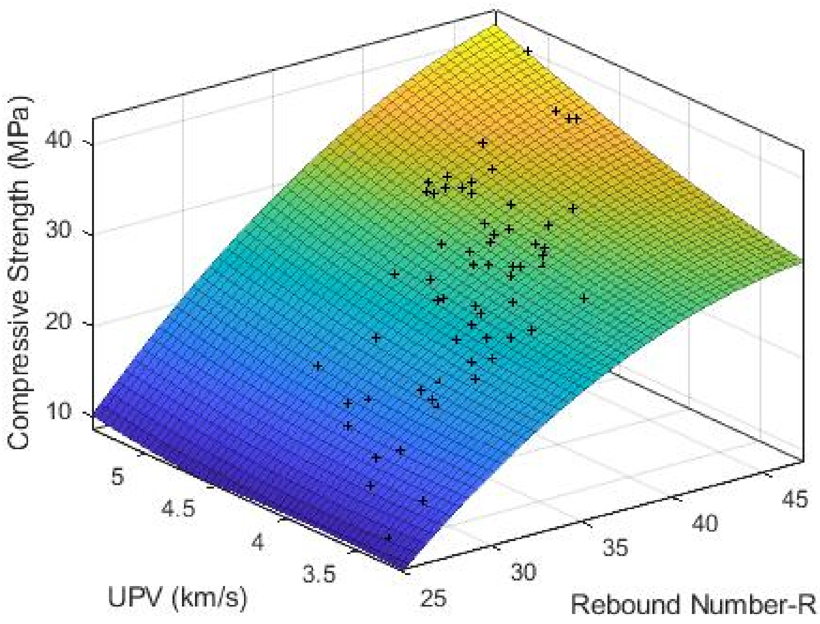


Figure 3. 74: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of set CIJ (All).

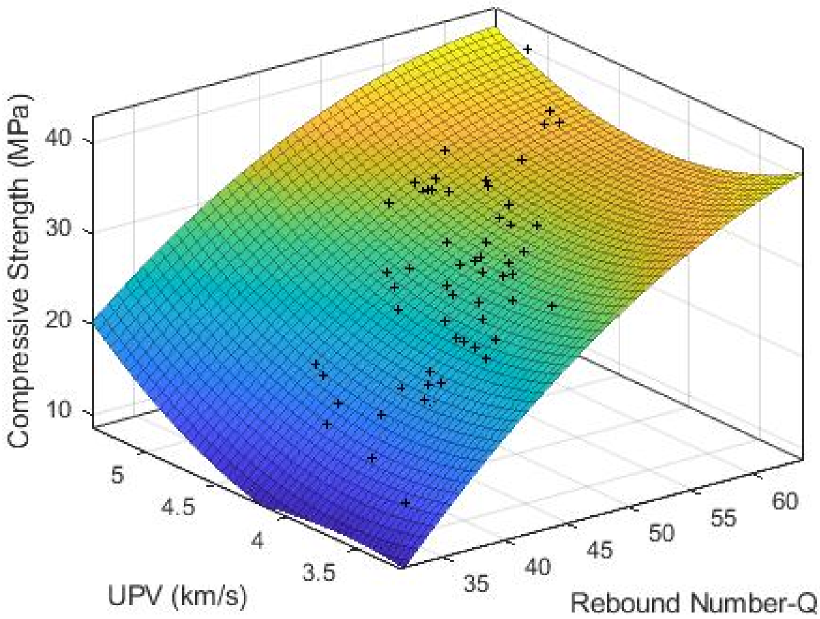


Figure 3. 75: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of set CIJ (All).

Figure 3.75 illustrates the combined SonReb method for Rebound-Q vs. UPV. Vs compressive strength. The plate was properly cover the data and provides the high reliable results which help to improve the accuracy on the estimation of intended concrete compressive strength using 3-D correlation curves. In addition, there is an 80 % difference between combined SonReb method`s R-square value and UPV vs. Compressive strength correlation's R-square values. Furthermore, there is a few difference between linear and polynomial combined methods (2.8 %) which is negligible considering the simplicity of linear plate comparing polynomial plate in SonReb correlation.

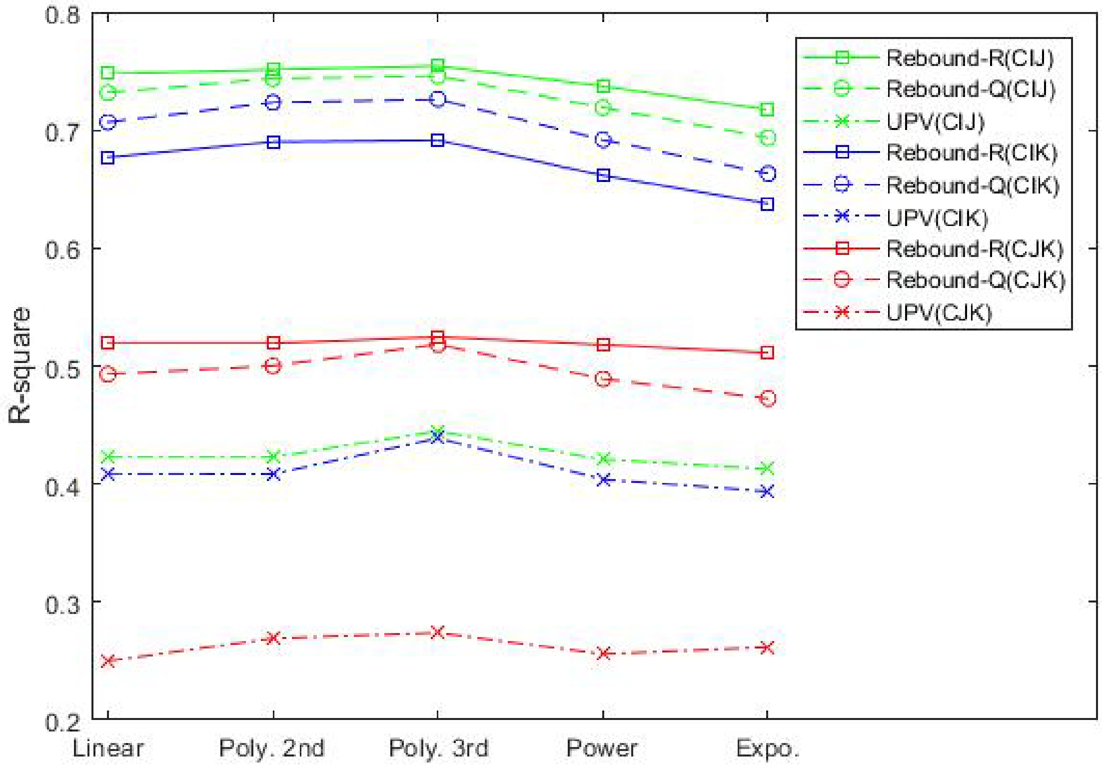


Figure 3. 76: R-square values for different equations, methods, and sets of couple cores (All).

There is a logical increase from linear to Poly. 2nd degree and then a high slope increase to the Poly. 3rd degree correlation`s R-square values. Then, there is a decrease from Poly. 3rd to Power and then straight continue with an almost equal amount to exponential correlation's R-square value. The R-square values were illustrated in Fig. 3.76 for all four different sets and three NDT methods and the changes of R-square values was observed in the above mentioned figure. In addition, except the UPV (CIJ) and UPV (CIK) which demonstrate a higher rise to Poly. 3rd degree correlation`s R-square value, in the other sets there is a few increase among equation types which is not normal considering other buildings and scenarios.

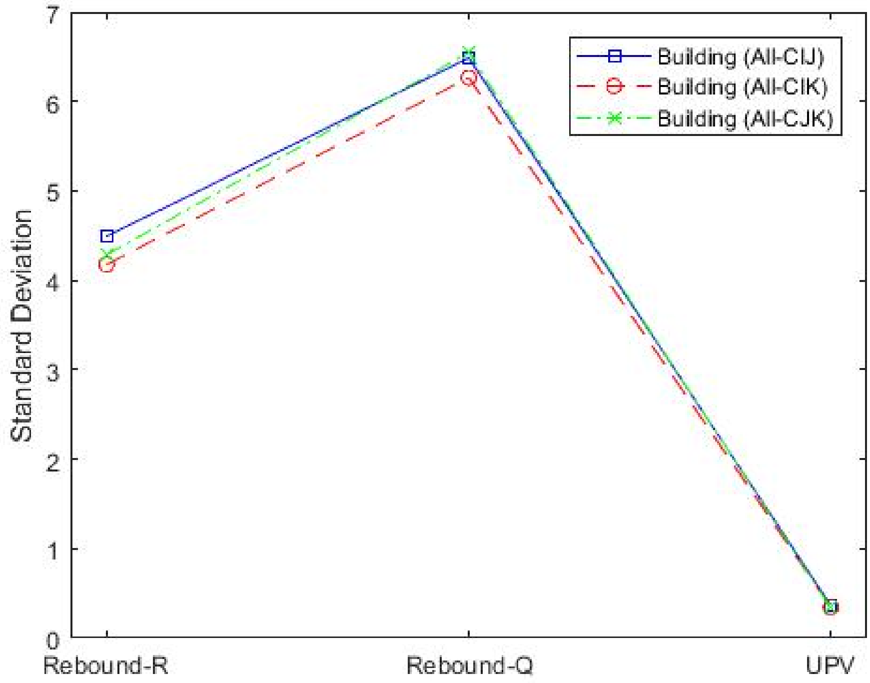


Figure 3. 77: Standard deviation of different sets of couple cores (All).

The slope of change between Rebound-R to Rebound-Q and Rebound-Q to UPV for all sets are approximately the same. Furthermore, the standard deviation for Rebound-Q of CJK set in this building reaches the highest amount among the sets and other buildings same set and method (see Fig. 3.77) which indicates the reason that why the R-square values are not much greater than Rebound-R, R-square values. However, the highest standard deviation for Rebound-R is for CIJ set.

3.2.2.6 Data analysis

The analysis of all evaluation and comparison of obtained values based on each set of five different data was assessed and discussed in this section based on equation and method which was used for each set.

The correlation results (R-square values) was observed in Fig 3.78 for all different couple cores sets in all four buildings and considering all together as one case called All for the four different sets in each case.

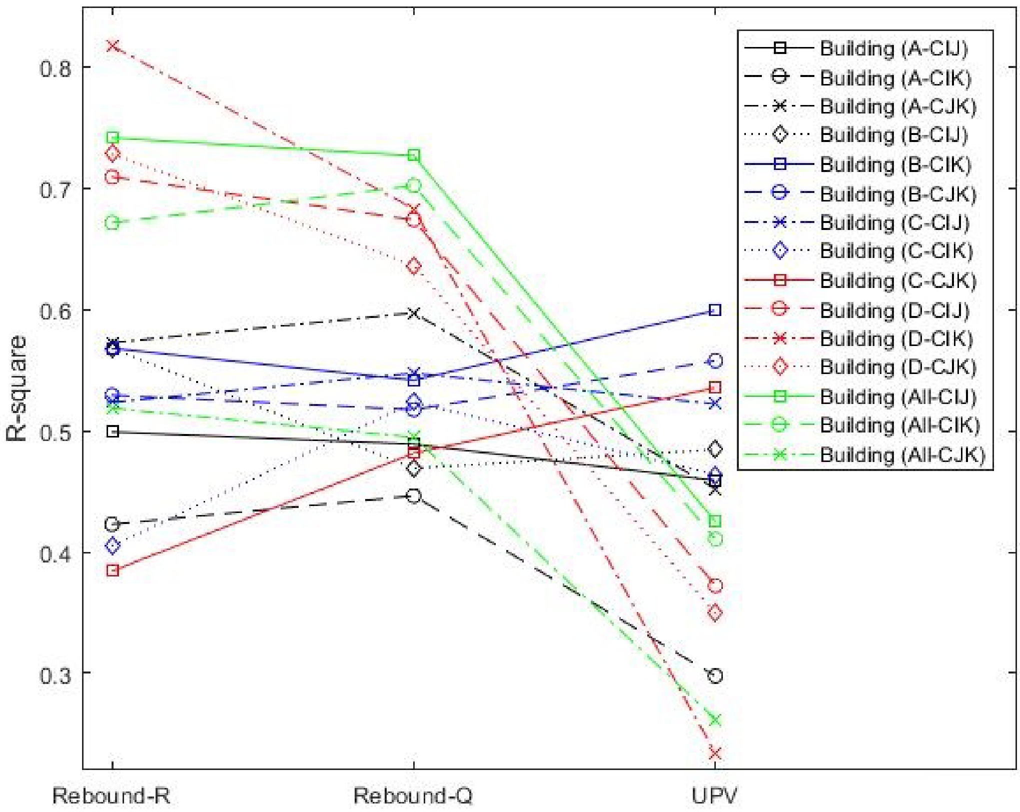


Figure 3. 78: R-square values for different sets based on methods of couple cores.

The R-square values illustrate that the behavior of results changes from set to set and building to building; however, considering the overall view in Fig. 3.78 it could be concluded that there are a few increases from Rebound-R to Rebound-Q and a great decrease from Rebound-Q to UPV R-square values. In addition, considering the simplicity factor in implementing the NDT methods, using either Rebound-R or Rebound-Q seems more logical due to the results which was obtained during this section analysis and based on the R-square results which were illustrated in the intended figure.

The R-square values changes were illustrated in Fig. 3.79 for all three various sets in three NDT methods based on five different equation types. It could be strongly concluded that considering only R-square values, there are a few increases from linear correlation to the Poly. 2nd degree correlation than a great increase with high rate toward Poly. 3rd degree correlation; after this point, it was observed that there is a sudden reduction to the power correlation and then a few decreases to the exponential correlation R-square value.

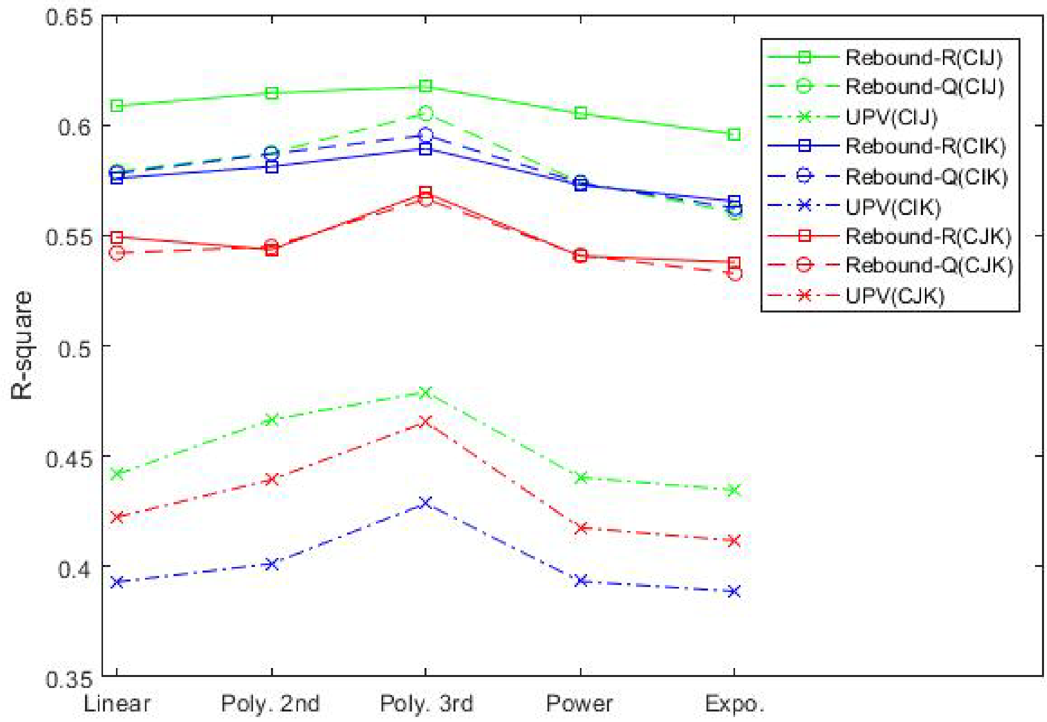


Figure 3. 79: R-square values for different sets based on equations of couple cores.

Thus, if the simplicity of equation was neglected during a process it is strongly suggested to use Poly. 3rd degree correlation, but if the simplicity is a major factor in one project based on the results observed in Fig. 3.79, Poly. 2nd degree is a suitable correlation which should be chosen.

Figure 3.80 demonstrates the changes in standard deviation magnitude for all four sets, four buildings and, one All case based on three NDT methods which were used in this project. The behavior and rate of changes observed in previous standard deviation figures and in Fig. 3.80 for all shows that there is a slight increase from Rebound-R to Rebound-Q and then a reduction with the high rate from Rebound-Q to UPV standard deviation magnitude. In addition, All-CJK set has the highest and B-CIJ set has the lowest standard deviation for the Rebound-Q method; moreover, All-CIJ has the highest and All-CIK has the lowest standard deviation for the Rebound-R method. The UPV measurements are so close to each other with small differences.

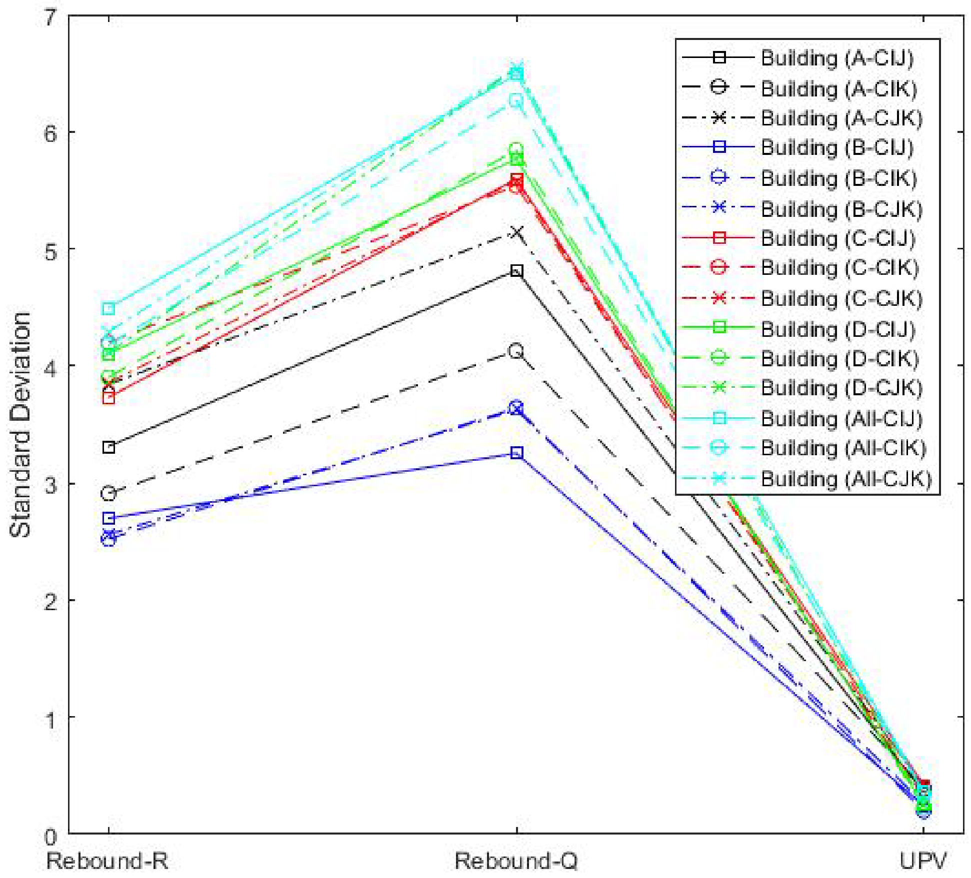


Figure 3. 80: Standard deviation of different sets of couple cores based on method.

3.2.3 Third scenario (taking three cores in each story)

In this scenario all cores which was taken from a building was evaluated, in each story of 15-story buildings, 3 cores were considered and the total number of 45 cores was selected to finding out the intended correlations for each of four different building and one special all cases set.

3.2.3.1 Third scenario-building A

Table 3.22 demonstrates the different R-square values for various type of equations and methods which was considered in this project to evaluate the results.

The correlation equations (regressions) was find out for linear, Poly. 2nd, Poly. 3rd, power, and exponential equation types and their r-square values associated with standard deviations was illustrated in Table 3.22

Table 3. 22: Correlation equations and R-square values of three cores for building (A).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.234R - 18.38$	0.4920	3.3604
	Poly. 2nd	$F = 0.0068R^2 + 0.736R - 9.36$	0.4924	
	Poly. 3rd	$F = -0.0083R^3 + 0.933R^2 - 33.31R + 403.9$	0.5034	
	Power	$F = 0.0602R^{1.693}$	0.4923	
	Expo.	$F = 5.075\exp(0.04517R)$	0.4874	
Rebound-Q	Linear	$F = 0.896Q - 14.79$	0.5062	4.6937
	Poly. 2nd	$F = -0.00087Q^2 + 0.978Q - 16.71$	0.5062	
	Poly. 3rd	$F = -0.0013Q^3 + 0.334Q^2 - 14.98Q + 234$	0.5110	
	Power	$F = 0.0731Q^{1.538}$	0.5054	
	Expo.	$F = 6.037\exp(0.318Q)$	0.4995	
UPV	Linear	$F = 9.624V - 12.16$	0.3973	0.3873
	Poly. 2nd	$F = 3.309V^2 - 17.19V + 41.66$	0.4050	
	Poly. 3rd	$F = 2.561V^3 - 27.85V^2 + 108.4V - 125.9$	0.4060	
	Power	$F = 3.392V^{1.476}$	0.3996	
	Expo.	$F = 6.095\exp(0.363V)$	0.4034	
SonReb (R)	R 1st , V 1st	$F = 0.888R + 4.921V - 25.61$	0.5572	-
	R 2nd , V 2nd	$F = 1.7R - 61.22V - 0.06R^2 + 0.934RV + 3.855V^2 + 91.24$	0.5956	
SonReb (Q)	Q 1st , V 1st	$F = 0.658Q + 4.423V - 21.64$	0.5545	-
	Q 2nd , V 2nd	$F = 0.96Q - 28.72V + 0.016Q^2 - 0.45QV + 6.65V^2 + 37.85$	0.5685	

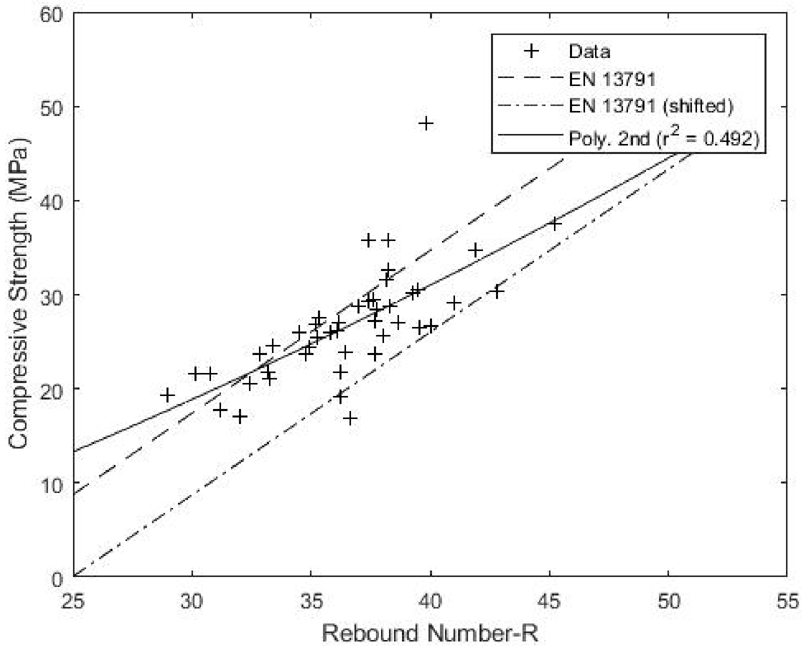


Figure 3. 81: Correlation: Rebound R vs. Compressive Strength of three cores (A).

The obtained data from Rebound-R measurements and compressive strength tests demonstrate that the data is not well dispersed compared other buildings; however, the related correlations illustrates suitable R-square values. Based on Fig. 3.81 the Poly. 2nd degree curve has almost the same performance comparing EN 13791.

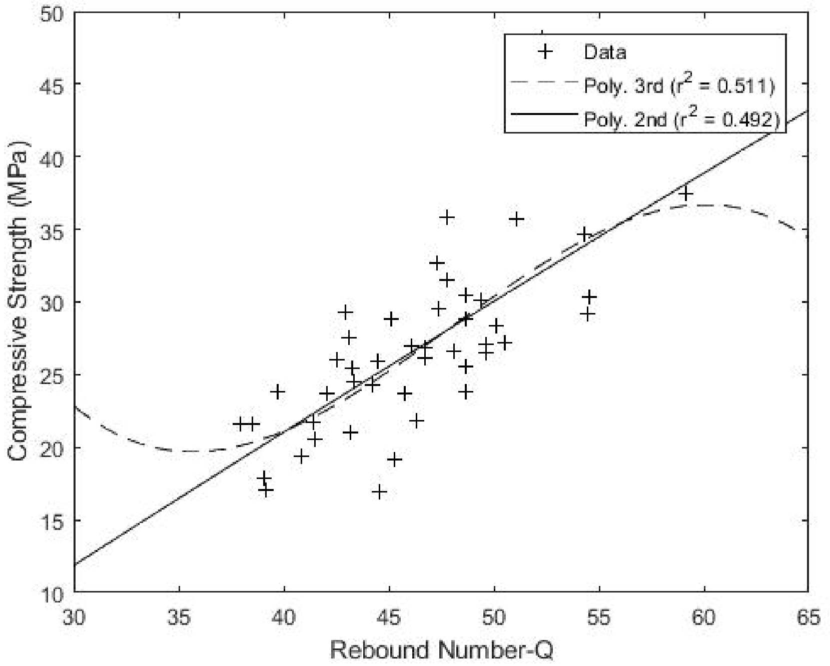


Figure 3. 82: Correlation: Rebound Q vs. Compressive Strength of three cores (A).

Despite the Rebound-R data dispersion condition, the data separation for the Rebound-Q is in the better condition compared the intended one. According to Fig. 3.82 the correlation curves which was illustrated by Poly. 2nd and Poly. 3rd are so close together to the obtained R-square values (0.492 and 0.511 respectively) for each curve. However, Poly. 3rd degree shows better results due to results which was illustrated in Table 3.22.

The UPV measurements for the set of building A shows better results for UPV-Compressive strength correlations compared other sets and building using inverse Poly. 2nd degree curve with the R-square value of 0.4050 which is shown in Fig. 3.83. However, the number of data which are sited on the range which was determined by the En 13791 standard is lower than other sets and most of the UPV measurements are lower than 4 which is out of the intended range. Thus, the inverse Poly. 2nd degree correlation curves shows the most proper results in the intended set.

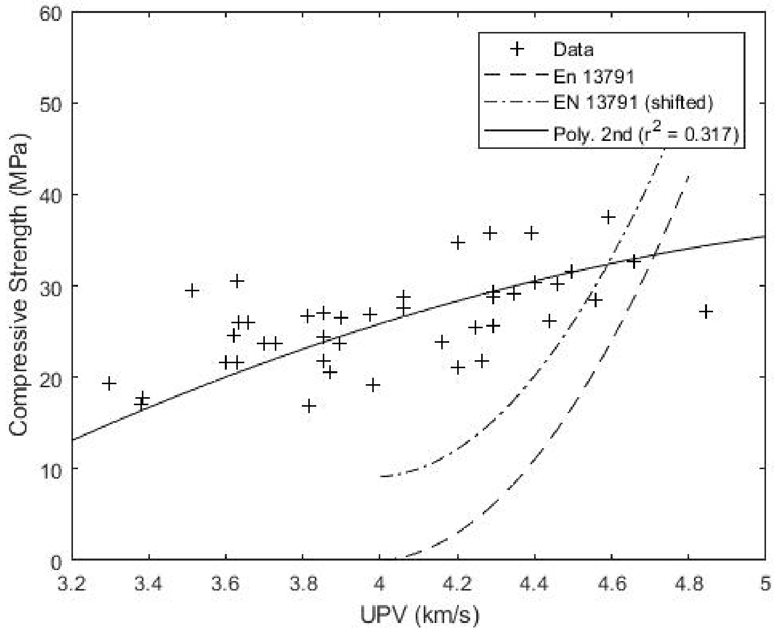


Figure 3. 83: Correlation: UPV vs. Compressive Strength of three cores (A).

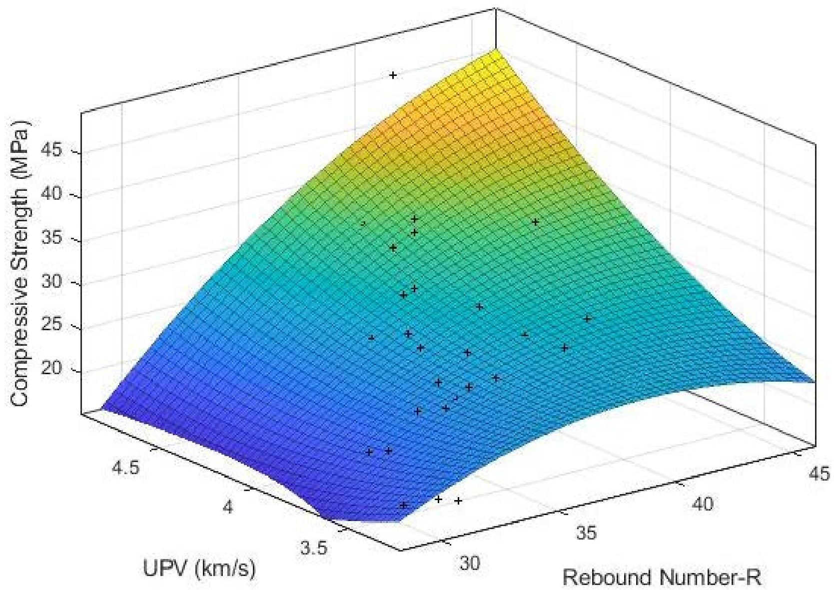


Figure 3. 84: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of three cores (A).

The combined method for building A was observed in Fig. 3.84 and the related curves demonstrate the double polynomial curve in both directions which helps to reach better correlation in 3-D condition-the double linear correlation has almost no positive effect and shows no improvement due to data special dispersion- with a higher R-square value which demonstrates a great improvement considering the values which were obtained for Rebound-R (see Table 3.22).

Figure 3.85 illustrates the 3-D combined SonReb method for Rebound number-Q vs. UPV vs. Compressive strength and like the Rebound-R the data dispersion requires to have double polynomial correlation curves to reach the higher and improved R-square value. Table 3.22 shows that there is a rise in R-square value while using double polynomial correlation compared using linear correlation curves. In addition, the analysis reveals that there is a slight increase in R-square value comparing combined SonReb method and normal Poly. 2nd degree correlation`s R-square values.

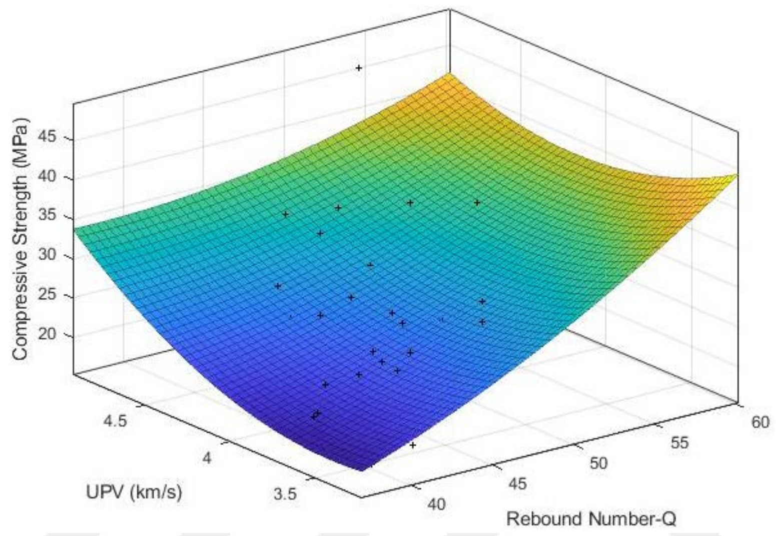


Figure 3. 85: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of three cores (A).

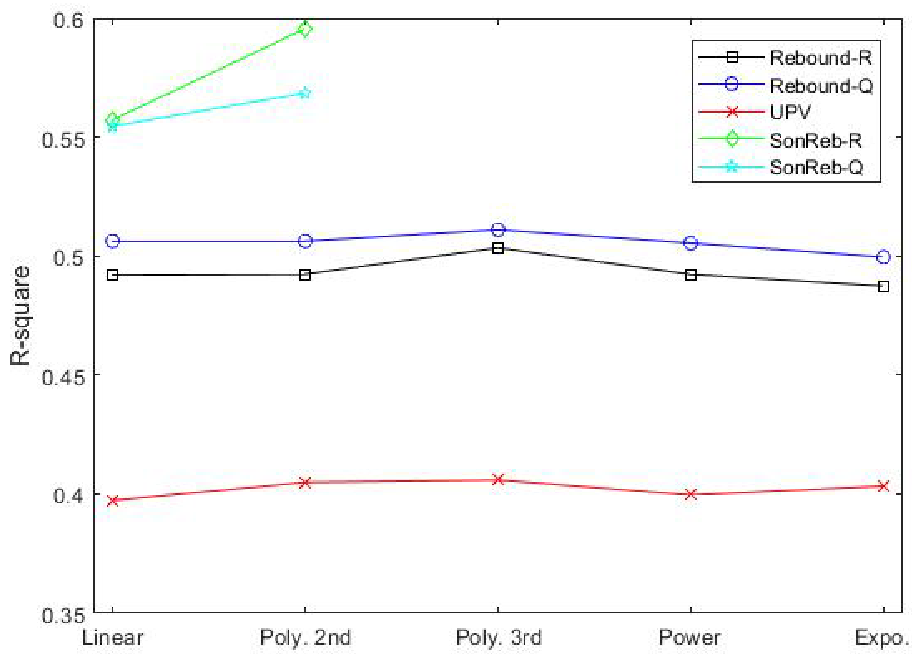


Figure 3. 86: R-square values based on equations of three cores (A).

The R-square values of four different sets and three various methods was illustrated in Fig. 3.86 for five different correlation equation (regression) types for building A. The behavior of curves in this figure, demonstrates that most of the methods behave like each other; however, there are (i) the slight increase of R-square value in Poly. 3rd degree equation in some cases, and (ii) a high rate increase from linear SonReb to the polynomial SonReb R-square values.

3.2.3.2 Third scenario-building B

Table 3.23 demonstrates the different R-square values for various type of equations and methods which was considered in this project to evaluate the results.

Table 3. 23: Correlation equations and R-square values of three cores for Building (B).

NDT Method	Equation type	Correlation Equation	$\mathbf{r^2}$	SD
Rebound- R	Linear	$F = 1.044R - 15.69$	0.5650	2.5814
	Poly. 2nd	$F = 0.0123R^2 + 0.264R - 3.419$	0.5657	
	Poly. 3rd	$F = -0.0126R^3 - 1.186R^2 + 37.83R - 393.7$	0.5730	
	Power	$F = 0.0233R^{1.913}$	0.5657	
	Expo.	$F = 2.588\exp(0.0597R)$	0.5648	
Rebound-Q	Linear	$F = 0.724Q - 11.69$	0.4999	3.5021
	Poly. 2nd	$F = -0.00318Q^2 + 0.973Q - 16.56$	0.5001	
	Poly. 3rd	$F = 0.0083Q^3 - 0.9819Q^2 + 38.78Q - 500.3$	0.5171	
	Power	$F = 0.0329Q^{1.697}$	0.4986	
	Expo.	$F = 3.092\exp(0.0427Q)$	0.4959	
UPV	Linear	$F = 10.77V - 25.67$	0.5120	0.2383
	Poly. 2nd	$F = -5.417V^2 + 53.21V - 108.5$	0.5285	
	Poly. 3rd	$F = -23.92V^3 + 270.9V^2 - 1007V + 1240$	0.5549	
	Power	$F = 0.58V^{2.448}$	0.4972	
	Expo.	$F = 1.506\exp(0.609V)$	0.4856	
SonReb (R)	R 1st , V 1st	$F = 0.7073R + 6.394V - 30.55$	0.6868	-
	R 2nd , V 2nd	$F = -4.44R + 49.29V + 0.117R^2 - 0.589RV - 3.027V^2 - 33.8$	0.7229	
SonReb (Q)	Q 1st , V 1st	$F = 0.457Q + 7.015V - 29$	0.6496	-
	Q 2nd , V 2nd	$F = -1.662Q + 36.07V + 0.057Q^2 - 0.616QV - 0.6V^2 - 44.68$	0.6710	

In addition, results was illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values (see Table 3.23).

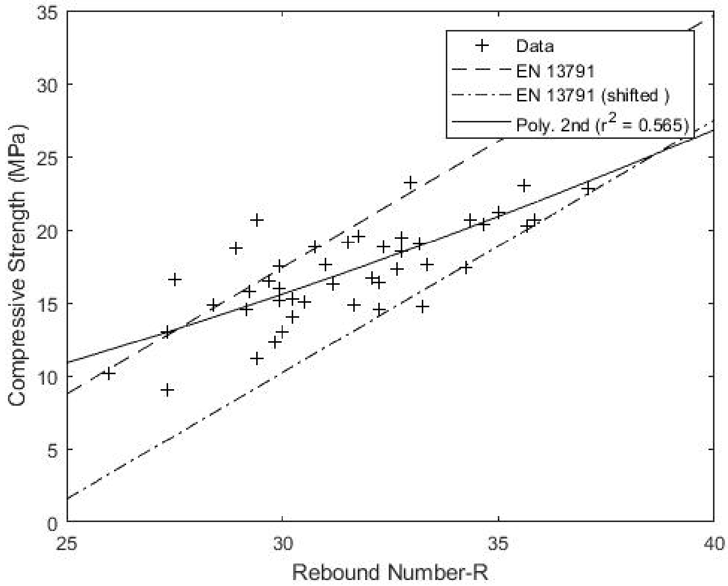


Figure 3. 87: Correlation: Rebound R vs. Compressive Strength of three cores (B).

The data for Rebound-R and Compressive strength obtained from NDT measurements and experimental compression tests respectively was provided and the intended data correlations using both EN 13791 standard and Poly. 2nd degree correlation curves were drawn in Fig. 3.87. The data dispersion was in a proper condition along the both EN 13791 suggested curve for the intended data and for the Poly. 2nd degree correlation curves with the R-square value of 0.5657 which is a reliable value for the Rebound-R considering other buildings. Thus, the more core leads to more reliable results.

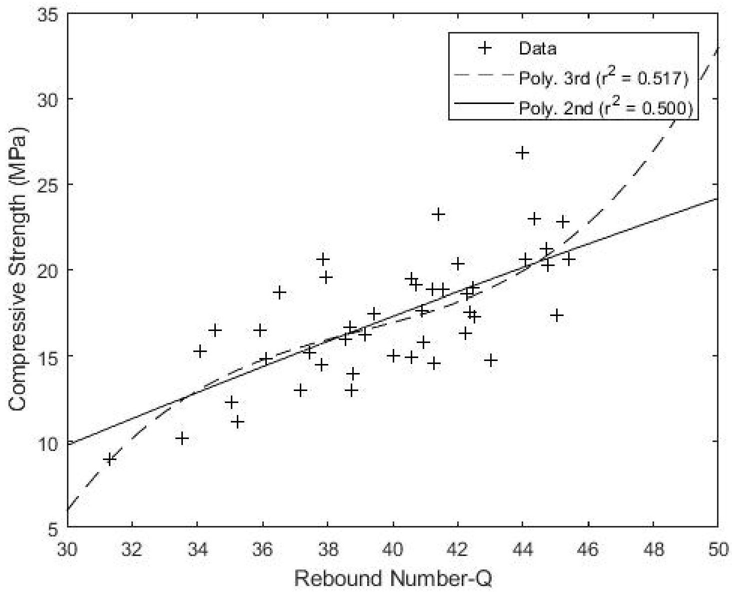


Figure 3. 88: Correlation: Rebound Q vs. Compressive Strength of three cores (B).

Based on observations in Fig. 3.88 both Poly. 2nd and Poly. 3rd degree correlation curves lay on each other in this section due to the special dispersion of data in the section. The data was suitably distributed around the correlation curves which leads to high R-square values for both Poly. 2nd degree and Poly. 3rd degree (0.5, and 0.517 respectively). In addition, in this data correlation, the dispersion is approximately proper close to intended correlation equations.

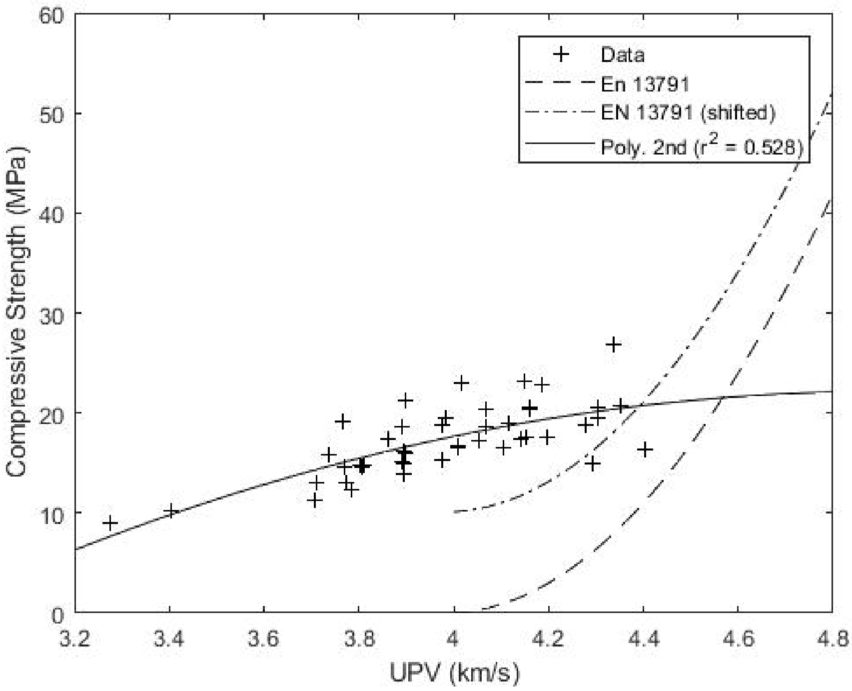


Figure 3. 89: Correlation: UPV vs. Compressive Strength of three cores (B).

EN 13791 standard suggested curve and shifted curve was drawn for results between 4 and 4.8 based on standard suggestion; however, Polynomial 2nd degree correlation curves was fitted for all of the data. In order to the special dispersion of UPV measurements data which is more compatible with the equation and the curve suggested by EN 13791 standard, the other correlation curves could not cover the data properly and the obtained R-square value is not such strong value to consider for concrete compressive strength estimation. The Poly. 2nd degree correlation illustrates the more suitable correlation considering all data even out of range which was mentioned at EN 13791 (see Fig 3.89).

The improvement in R-square value in Fig. 3.90 indicates the importance and effectiveness of combined SonReb method and using the 3-D correlation with a plate which covers most of the data is the reason for this enhancement in the R-square value.

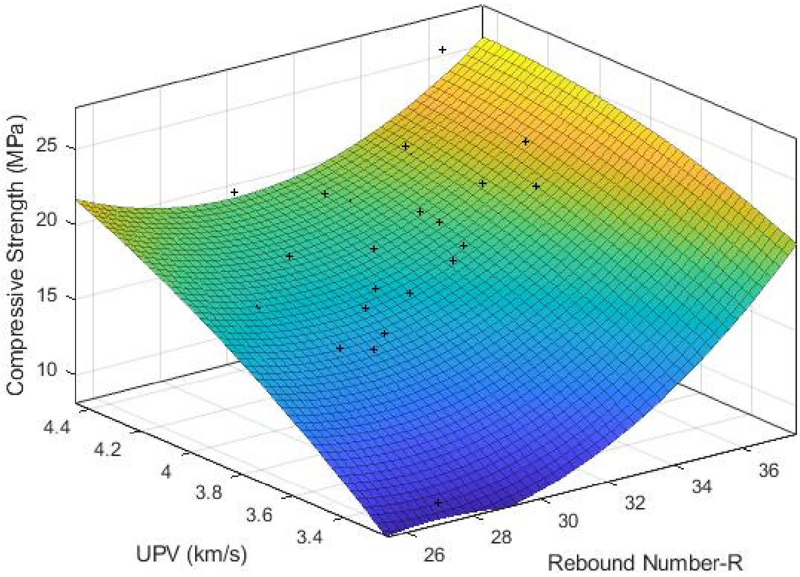


Figure 3. 90: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of three cores (B).

Fig 3. 90 illustrates that approximately the curve for UPV data is in polynomial shape; however, the other curve which is in Rebound-R straight is much linear than polynomial. Table 3.23 demonstrates that there is a 36.7 % increase compared with UPV-Compressive strength correlation`s R-square value. In addition, there is a 27 % increase in comparing Rebound-R results with SonReb results which was obtained for Rebound-R vs. Compressive strength correlation.

Despite the Rebound-R combined correlation for this section and set, the combined correlation for Rebound-Q due to the data distribution which was observed in Fig. 3.91 requires double polynomial curves to cover the data and fit the plate to reach the best result for correlation equation and R-square value. Furthermore, there are a few increases in comparing Rebound-Q R-square results with SonReb results and this happens due to the high R-square value which was derived for Rebound-Q vs. Compressive strength correlation. Moreover, there is 27 % increase in R-square value compared with UPV vs. Compressive strength correlation`s result (see Table 3.23).

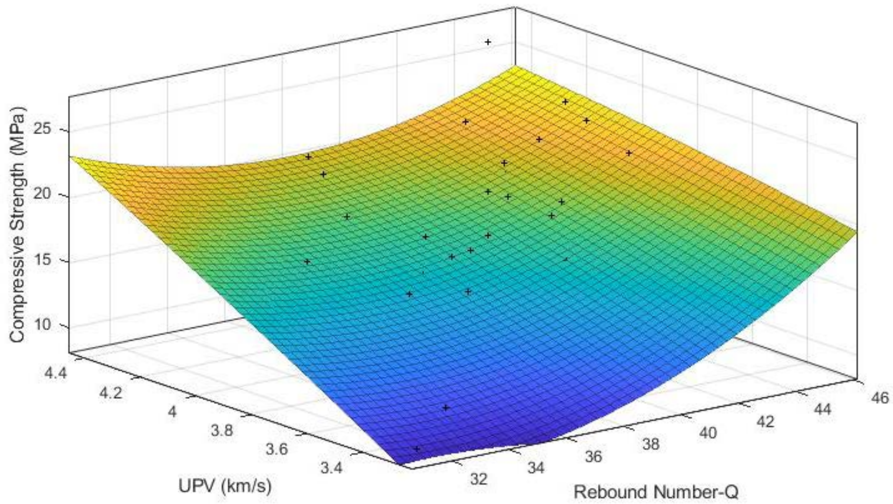


Figure 3. 91: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of three cores (B).

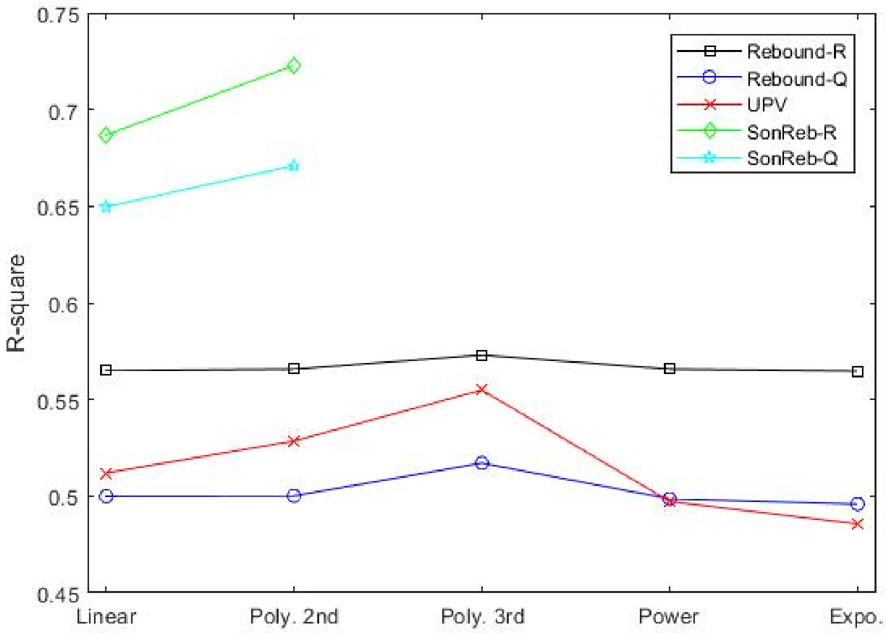


Figure 3. 92: R-square equation based results of three cores (B).

The evaluation of results was provided based on Table 3.23 and Fig. 3.92 for obtaining the best outcome considering R-square values. It reveals that Poly. 3rd degree has the best results. The curves in Fig. 3.88 shows that the behavior of change in R-square values among five different equation and three different NDT methods are close to each other; however, in some cases that data distribution is special and require polynomial curve to reach the proper fit and high R-square value, the R-square value increase with high rate toward Poly. 3rd degree correlation and this occurs mostly in UPV vs. Compressive strength correlation due to the special data dispersion which was observed in previous figures and even EN 13791 suggest the special polynomial curve for UPV correlation. In addition, power and poly. 2nd degree equations have the same performance and using either of them is logical.

3.2.3.3 Third scenario-building C

Table 3.24 illustrates the different R-square values for various type of equation which was considered in this project to evaluate the results.

Table 3. 24: Correlation equations and R-square values of three cores for Building (C).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.782R + 0.325$	0.4442	4.0569
	Poly. 2nd	$F = 0.0038R^2 + 0.489R + 5.908$	0.4444	
	Poly. 3rd	$F = 0.00454R^3 - 0.5187R^2 + 20.33R - 243.1$	0.4499	
	Power	$F = 0.819R^{0.99}$	0.4442	
	Expo.	$F = 11.3\exp(0.0256R)$	0.4440	
Rebound-Q	Linear	$F = 0.6059Q - 0.2134$	0.5241	5.6886
	Poly. 2nd	$F = -0.00985Q^2 + 1.619Q - 25.92$	0.5297	
	Poly. 3rd	$F = 0.0019Q^3 - 0.3026Q^2 + 16.44Q - 273.8$	0.5368	
	Power	$F = 0.601Q^1$	0.5241	
	Expo.	$F = 11.42\exp(0.0192Q)$	0.5158	
UPV	Linear	$F = 8.956V - 9.013$	0.4925	0.3730
	Poly. 2nd	$F = -3.717V^2 + 42.15V - 82.57$	0.5146	
	Poly. 3rd	$F = -10.63V^3 + 139V^2 - 591.7V + 849.9$	0.5497	
	Power	$F = 4.634V^{1.269}$	0.4891	
	Expo.	$F = 8.918\exp(0.2774V)$	0.4744	
SonReb (R)	R 1st , V 1st	$F = 0.4096R + 5.895V - 11.26$	0.5568	-
	R 2nd , V 2nd	$F = 0.349R + 31.92V + 0.0345R^2 - 0.588RV - 0.365V^2 - 67.8$	0.5784	
SonReb (Q)	Q 1st , V 1st	$F = 0.3787Q + 4.697V - 9.377$	0.5859	-
	Q 2nd , V 2nd	$F = 0.658Q + 24.43V + 0.0092Q^2 - 0.28QV - 0.574V^2 - 59.95$	0.5973	

Moreover, Table 3.24 shows the intended results associated with standard deviation values for each test method. The combined SonReb method improves the results of both Rebound-R, Rebound-Q and UPV values. In addition, the standard deviations were just obtained for Rebound-R, Rebound-Q, and UPV measurements.

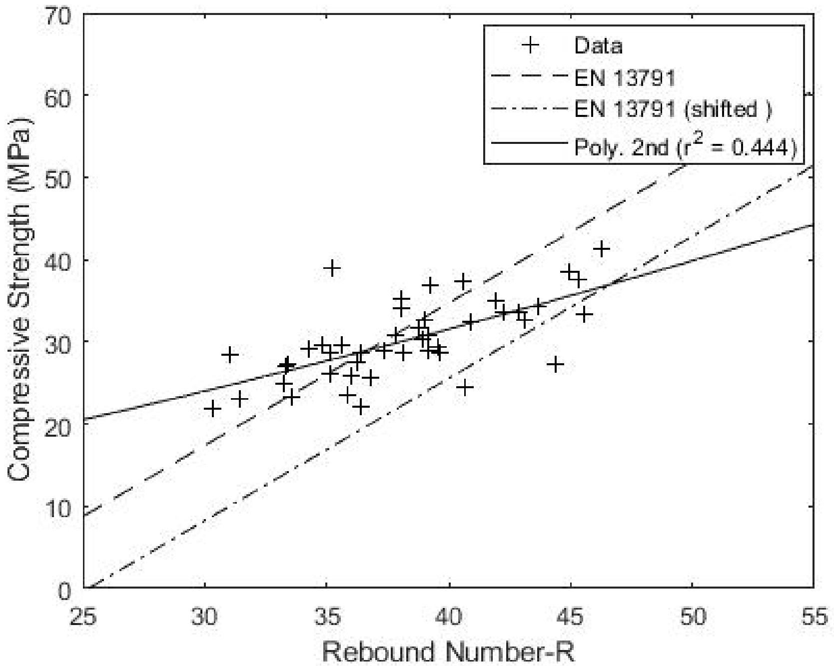


Figure 3. 93: Correlation: Rebound R vs. Compressive Strength of three cores (C).

Despite the lowest measurement of Rebound-R which is associated with high compressive strength comparing the nearby points (data), the data dispersion demonstrates the proper fit with both EN 13791 standards suggested curves and with Poly. 2nd degree correlation curves which is mostly close to the linear shape and the R-square value demonstrates the low value (0.444) due to improper data dispersion (see Fig 3.93).

The proper values of R-square for both Poly. 2nd and Poly. 3rd degree correlations (0.529, and 0.536 respectively) demonstrates that the data dispersion in this analysis was almost properly distributed and the intended correlation leads to the high reliable equation for concrete strength estimation in building C; however, considering the simplicity factor due to close results of both intended correlations using Ploy. 2nd seem more logical (see Fig. 3.94).

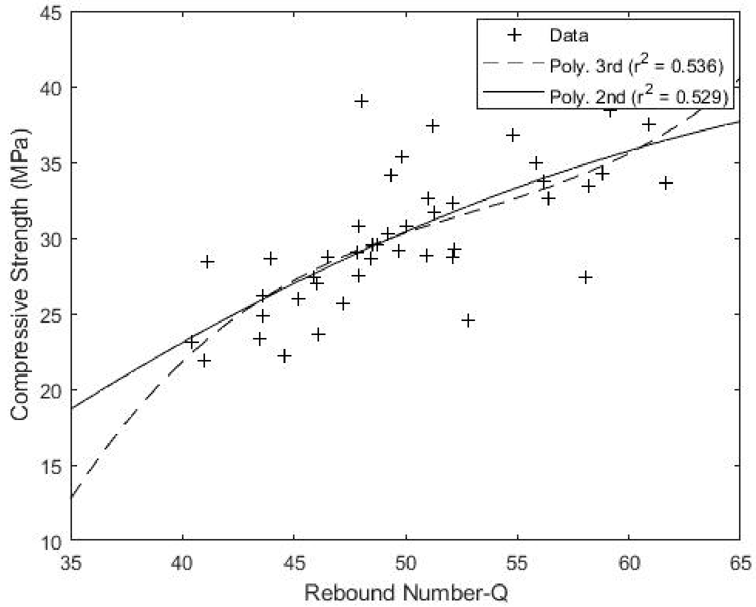


Figure 3. 94: Correlation: Rebound Q vs. Compressive Strength of three cores (C).

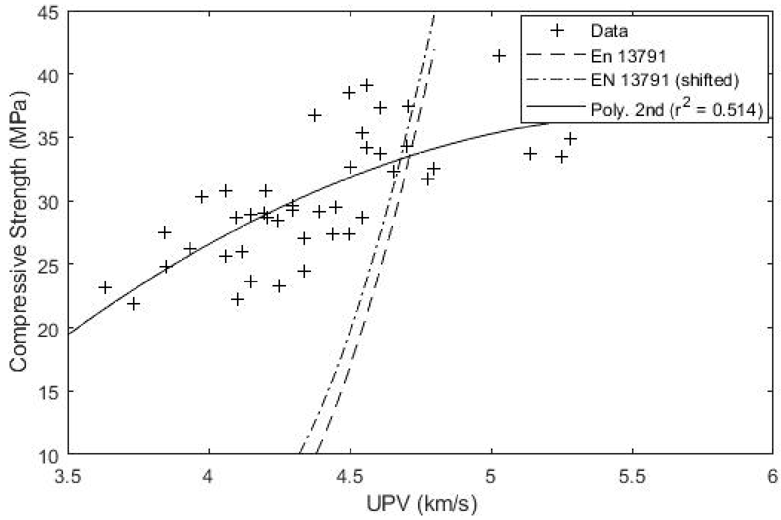


Figure 3. 95: Correlation: UPV vs. Compressive Strength of three cores (C).

Despite the EN 13791 standard curve for this set of data the EN 13791 shifted curve could reach the data and cover some part of it with proper proximity. However, the Poly. 2nd degree correlation curve with R-square 0.514 have better support due to no limits- there is a limit for the standard which requires data between 4-4.8- thus the Poly. 2nd degree reach better results considering that the data is somehow compacted and the dispersion of the data is not that much longitudinal like the previous sets (see Fig. 3.95).

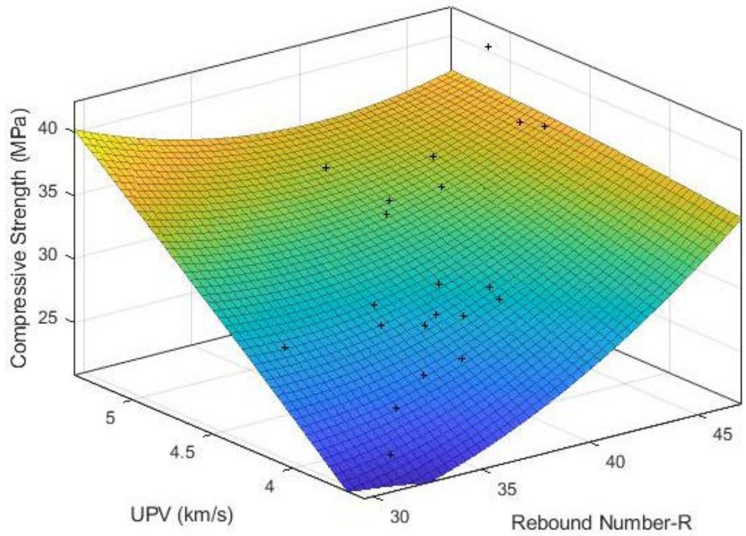


Figure 3. 96: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of three cores (C).

The combined method could significantly improve the results of correlation and related regressions with higher R-square values in this set of data for Rebound-R, UPV, and Compressive strength. According to the data which was demonstrated in Table 3.24 there is an approximately 30 % increase compared with Rebound-R and about 12.4 % increase compared with UPV`s Poly. 2nd degree 2-D correlation`s R-square value. Fig. 3.96 illustrates that there is much data compaction in the final part of UPV measurements.

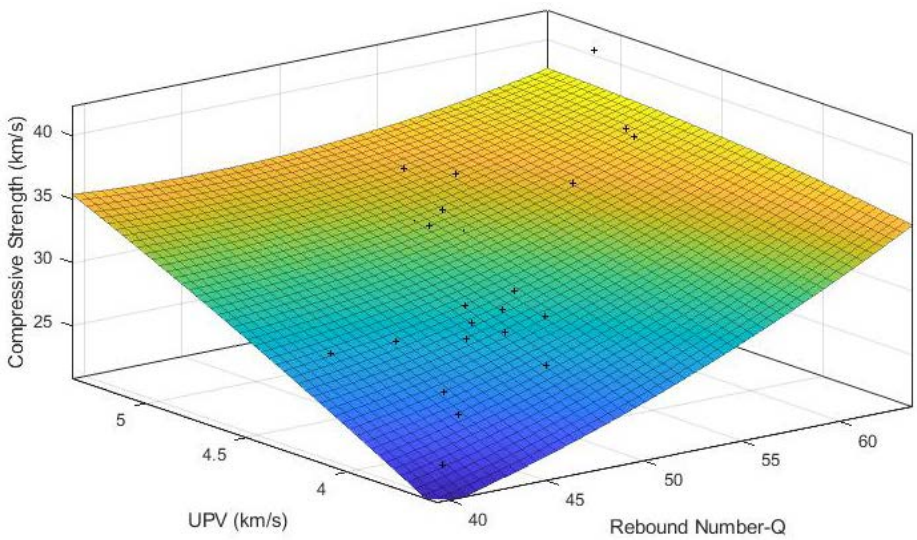


Figure 3. 97: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of three cores (C).

There is a proper cover of correlation plate in combined SonReb method for Rebound-Q vs. UPV vs. Compressive strength which was observed in Fig. 3.97. The both Rebound-Q and UPV sides help to cover the data in both sides to rise the R-square value. Moreover, there is an approximately 13 % increase compared with Rebound-Q and about 16.7 % rise compared with UPV`s Poly. 2nd degree 2-D correlation`s R-square value (see Table 3.24).

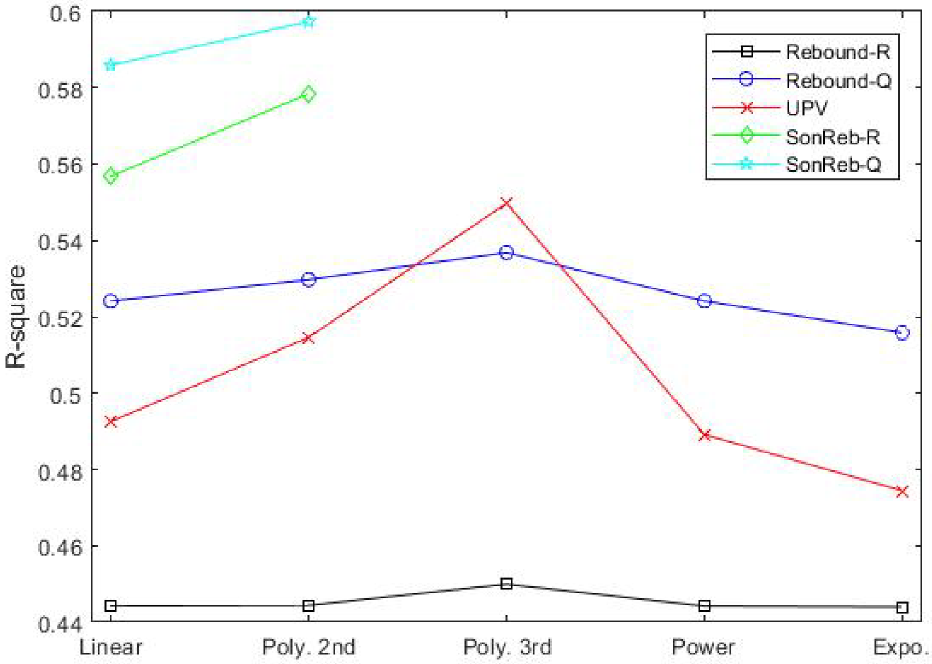


Figure 3. 98: R-square equation based results of three cores (C).

Figure 3.98 shows the changes which were occurred for the R-square values in each method type of each different sets for different five equation types. There is an increase almost in every method-set line from linear to Poly. 2nd degree and then increase with higher slope than the previous step toward Poly. 3rd degree equation correlations R-square values. After this there is sharp decline toward power then continue almost slight toward Exponential equation`s R-square value. SonReb values rise from linear to Poly. 2nd in all correlations.

3.2.3.4 Third scenario-building D

Table 3.25 shows the different R-square values for various type of equation and methods which was considered in this project to evaluate the results.

Table 3. 25: Correlation equations and R-square values of three cores for Building (D).

NDT Method	Equation type	Correlation Equation	$\mathbf{r^2}$	SD
Rebound- R	Linear	$F = 1.213R - 16.68$	0.7335	4.0366
	Poly. 2nd	$F = -0.017R^2 + 2.417R - 37.67$	0.7368	
	Poly. 3rd	$F = 0.00859R^3 - -0.934R^2 + 34.71R - 412.4$	0.7622	
	Power	$F = 0.0809R^{1.62}$	0.7277	
	Expo.	$F = 5.295\exp(0.0448R)$	0.7167	
Rebound-Q	Linear	$F = 0.7616Q - 10.07$	0.6517	6.0615
	Poly. 2nd	$F = -0.0123Q^2 + 1.947Q - 38.13$	0.6613	
	Poly. 3rd	$F = -3.34 \times 10^{-5}Q^3 - 0.0076Q^2 + 1.729Q - 34.83$	0.6613	
	Power	$F = 0.139Q^{1.356}$	0.6464	
	Expo.	$F = 7.021\exp(0.02742Q)$	0.6293	
UPV	Linear	$F = 13.13V - 26.95$	0.3143	0.2441
	Poly. 2nd	$F = -3.569V^2 + 41.67V - 83.73$	0.3178	
	Poly. 3rd	$F = -11.42V^3 + 131.4V^2 - 487.1V + 603$	0.3223	
	Power	$F = 1.569V^{2.012}$	0.3102	
	Expo.	$F = 3.547\exp(0.4924V)$	0.3050	
SonReb (R)	R 1st , V 1st	$F = 1.105R + 3.332V - 26.52$	0.7479	-
	R 2nd , V 2nd	$F = 3.723R - 52.21V + 0.0043R^2 - 0.708RV + 9.88V^2 - 39.52$	0.7539	
SonReb (Q)	Q 1st , V 1st	$F = 0.7029Q + 2.358V - 16.93$	0.6579	-
	Q 2nd , V 2nd	$F = 4.206Q - 86.2V + 0.0092Q^2 - 0.0054QV - 0.714V^2 + 14.9$	0.6717	

In addition, the intended results were illustrated in Fig. 3.24 associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data dispersion of this set (building D) for Rebound number-R is suitable for a better correlation compared previous sets and buildings and as it is observed in Fig. 3.99 both EN 13791 curves and Poly. 2nd correlation curve could properly cover the data and it was proven by the R-square value of 0.7368 for Poly. 2nd degree correlation. In addition according to Table 3.25 the other correlations demonstrates high magnitude for R-square value which could be used considering other factors based on the project ends.

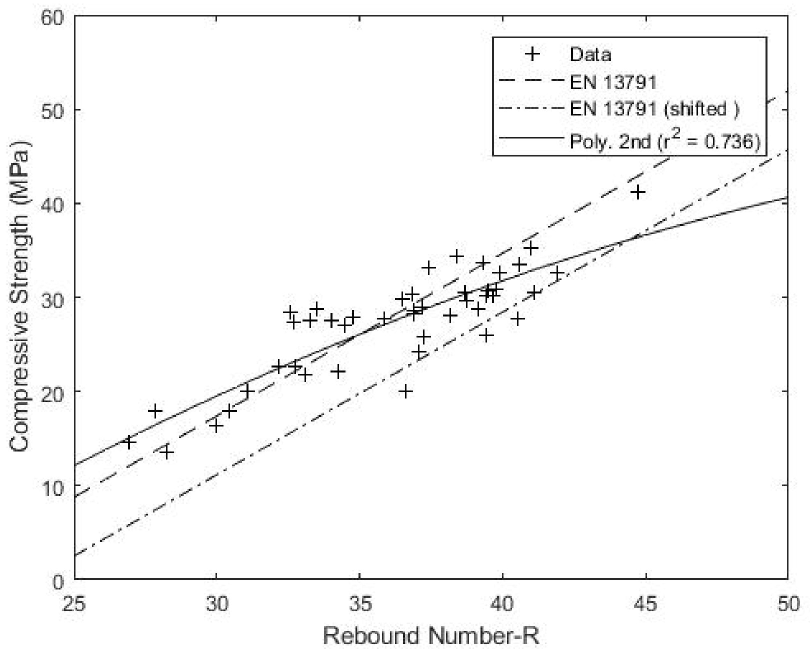


Figure 3. 99: Correlation: Rebound R vs. Compressive Strength of three cores (D).

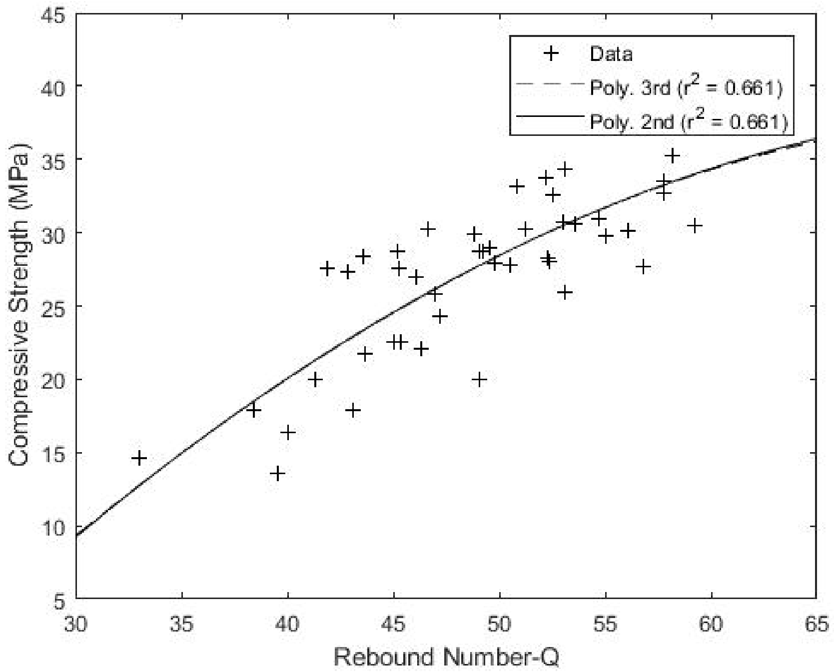


Figure 3. 100: Correlation: Rebound Q vs. Compressive Strength of three cores (D).

Figure 3.100 illustrates the Poly. 2nd and Poly. 3rd degree correlations for Rebound-Q vs Compressive strength with R-square values of both 0.6613. There is almost no difference in using Poly. 2nd degree and Poly. 3rd degree correlation curve for this set of data. However, simplicity and time factors require to use Poly. 2nd degree while the accuracy is same between the. In addition, due to a proper R-square value and very simple regression, the linear correlation could be implemented also.

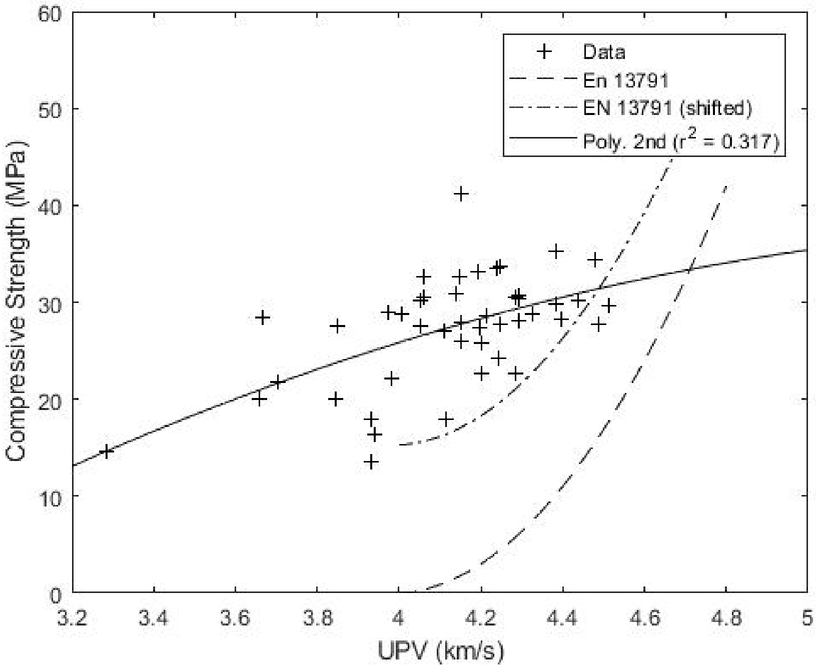


Figure 3. 101: Correlation: UPV vs. Compressive Strength of three cores (D).

In some special case when the data dispersion is not in polynomial shape- which is suitable for EN 13791 suggested curve- and the compressive strength values are in high values the EN 13791 curve and it`s shifted curve could not cover the data and the correlation curves by the standards are not reliable anymore as it is observed in Fig 3.101. However, the Poly. 2nd correlation curve by Matlab software could properly cover the data due to using inverse type of this polynomial which is more suitable for this data dispersion and the R-square value reach to the 0.317 which is better result compared EN 13791 suggested curve and regression.

The plate which was derived using the combined correlation of Rebound-R vs UPV vs Compressive strength in Fig. 3.102. The shape and slope of both curves demonstrate that the polynomial curve is the best option for this data dispersion and the results were observed in Table 3.25 which indicates that there is a smooth rise while using polynomial curves instead of using a linear plate for this data correlation. The R-square values for linear and polynomial correlation curves are 0.7479 and 0.7539 respectively.

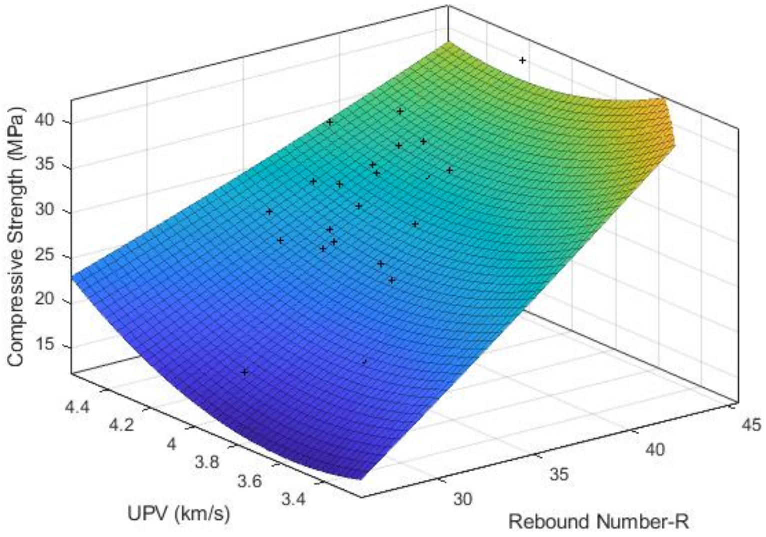


Figure 3. 102: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of three cores (D).

The shape of the plate is approximately close to the Rebound-R combined SonReb correlation (Fig. 3.102); however, there is reduction at final part of SonReb-R plate but there is almost no reduction at the end section of SonReb-Q plate, which shows the difference in data dispersion between the Rebound-Q combined SonReb correlation and the previous one (see Fig. 3.103).

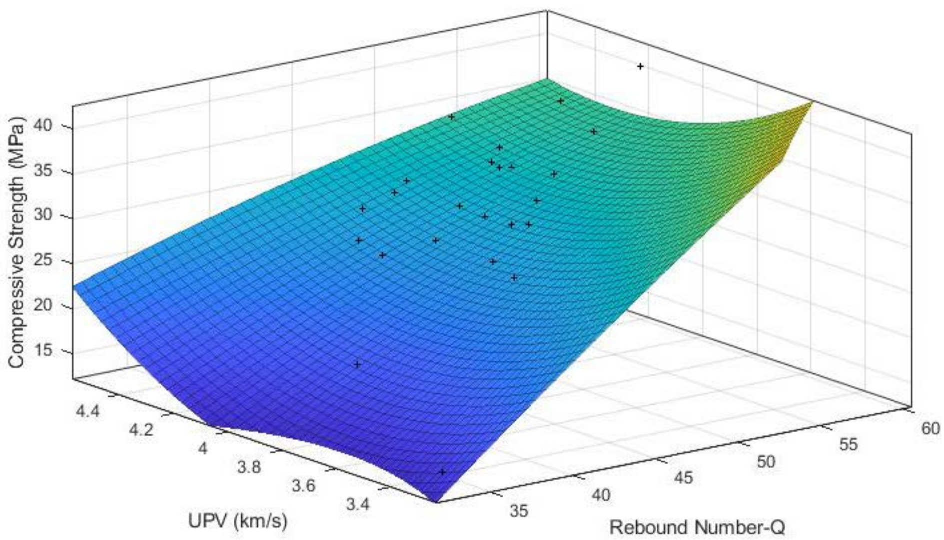


Figure 3. 103: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of three cores (D).

In addition, polynomial correlation is also the proper option for the intended data because there is 2 % increase compared linear one; however, if the simplicity of equations and curves was considered, using linear correlation is more reliable because the difference between linear and polynomial correlations`s R-square values is not such a great amount and could be neglected easily considering the simplicity of the linear plate.

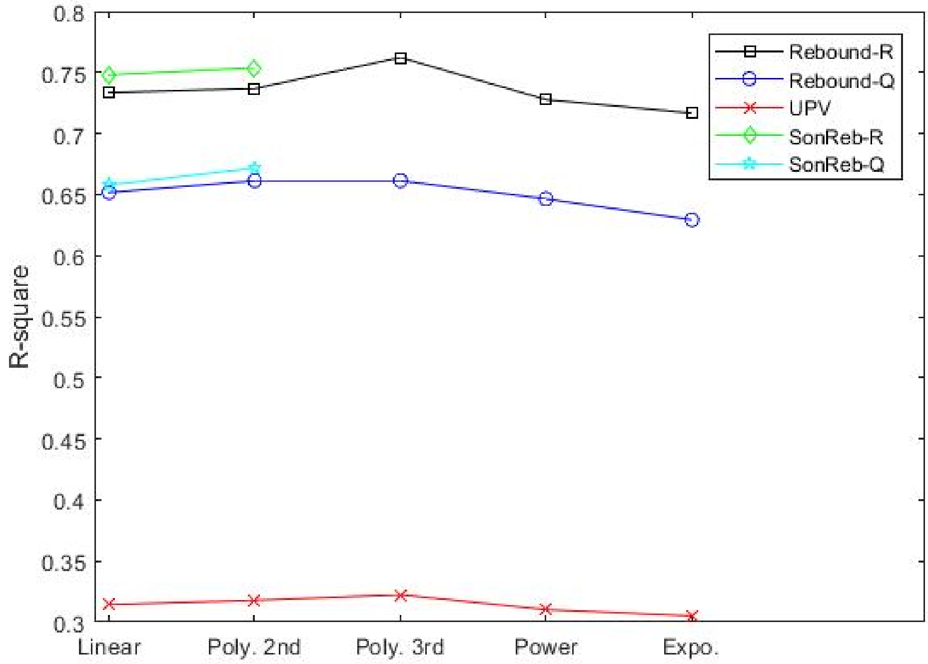


Figure 3. 104: R-square equation based results of three cores (D).

There is a logical increase from linear to Poly. 2nd degree and then a higher slope rise compared previous one to the Poly. 3rd degree correlation`s R-square values. Then, there is a reduction from Poly. 3rd to Power and then straight continue with an almost equal amount to exponential correlation's R-square value. The R-square values were illustrated in Fig. 3.104 for all four different sets and three NDT methods and the changes of R-square values was observed in this figure.

3.2.3.5 Third scenario-building All

Table 3.26 demonstrates the different R-square values for various type of equation and methods which was considered in this project to evaluate the results.

Table 3. 26: Correlation equations and R-square values of three cores for Building All.

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.355R - 22.92$	0.6955	4.3217
	Poly. 2nd	$F = -0.0245R^2 + 3.117R - 54.08$	0.7019	
	Poly. 3rd	$F = -0.00103R^3 + 0.0857R^2 - 0.835R - 7.422$	0.7022	
	Power	$F = 0.03351R^{1.852}$	0.6840	
	Expo.	$F = 4.23\exp(0.04966R)$	0.6645	
Rebound-Q	Linear	$F = 0.9157Q - 17.11$	0.7027	6.4287
	Poly. 2nd	$F = -0.0164Q^2 + 2.462Q - 52.88$	0.7173	
	Poly. 3rd	$F = -0.00076Q^3 - 0.912Q^2 - 2.521Q + 22.82$	0.7194	
	Power	$F = 0.05179Q^{1.612}$	0.6897	
	Expo.	$F = 5.435\exp(0.03277Q)$	0.6632	
UPV	Linear	$F = 12.83V - 27.67$	0.4103	0.3506
	Poly. 2nd	$F = 0.0755V^2 + 12.2V - 26.36$	0.4103	
	Poly. 3rd	$F = -7.602V^3 + 96.9V^2 - 395.3V + 540.4$	0.4275	
	Power	$F = 1.379V^{2.047}$	0.4083	
	Expo.	$F = 3.584\exp(0.4702V)$	0.4004	
SonReb (R)	R 1st , V 1st	$F = 1.162R + 3.751V - 31.55$	0.7165	-
	R 2nd , V 2nd	$F = 4.075R - 13.53V - 0.0173R^2 - 0.4057RV + 3.848V^2 - 47.62$	0.7271	
SonReb (Q)	Q 1st , V 1st	$F = 0.8064Q + 3.02V - 24.52$	0.7154	-
	Q 2nd , V 2nd	$F = 3.317Q - 25.3V - 0.012Q^2 - 0.3299QV + 5.237V^2 + 5.237$	0.7353	

The intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values (see Table 3.26).

Figure 3.105 demonstrates the curve which is suggested by the EN 13791 standard considering the data which was obtained from compressive tests and NDT measurements. In addition, the EN 13791 (shifted) curve is the curve shifted from the main curve to consider more accuracy based on EN 13791. Furthermore, the Poly. 2nd curve in this figure which was drawn using Matlab software demonstrates better proximity to the obtained data with R-square value of 0.7019.

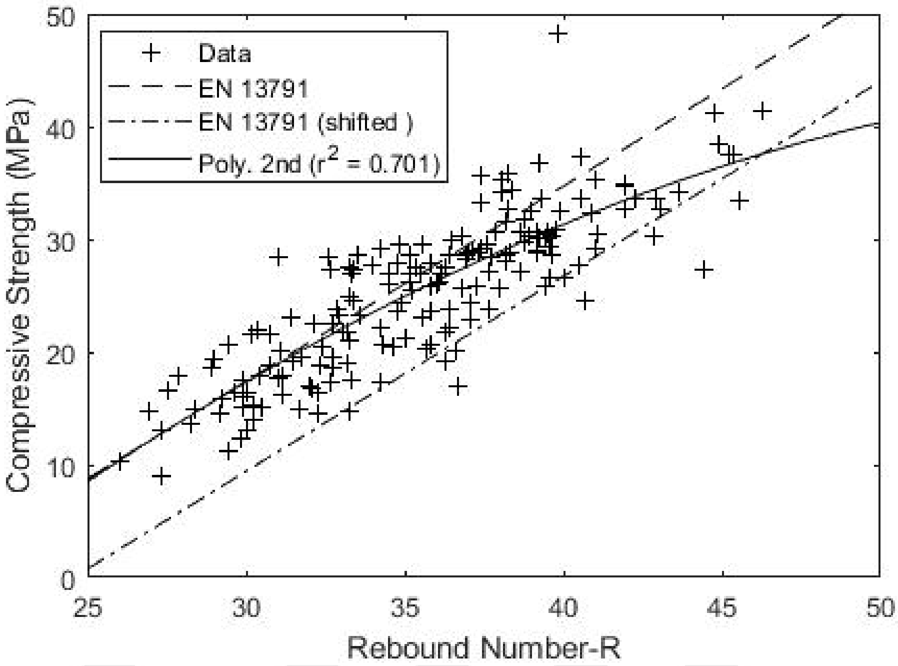


Figure 3. 105: Correlation: Rebound R vs. Compressive Strength of three cores (All).

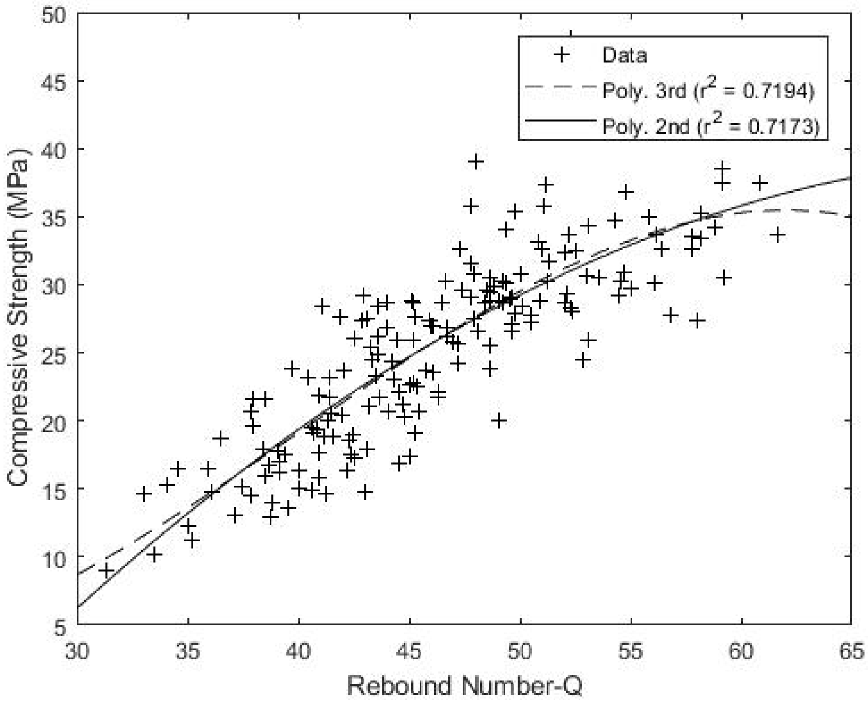


Figure 3. 106: Correlation: Rebound Q vs. Compressive Strength of three cores (All).

It was mentioned previously that, there is a lack of information for Silver Schmidt hammer (Q type) in the EN 13791 standard thus, there is no suggested equation and curve for data obtained from measurements using this hammer. In order to comparison Poly. 2nd and poly. 3rd degree correlations were shown in Fig. 3.106 and the results demonstrate that due to the dispersion of data there is almost no difference in using poly. 2nd or poly. 3rd degree curves and intended regressions; however, in order to the simplicity of poly. 2nd degree in equation this curve suggested to use for estimate the concrete strength at the studied case (building All).

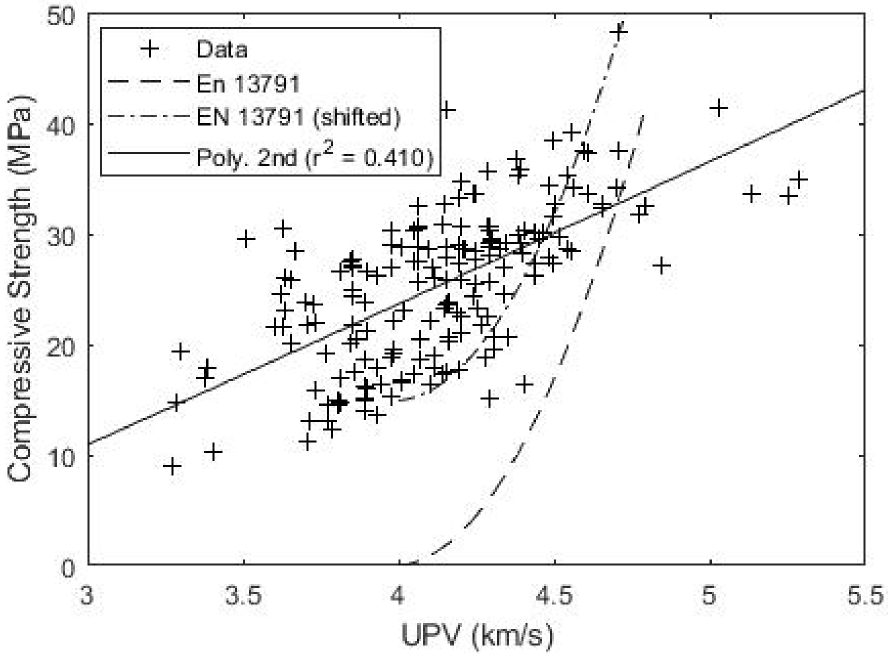


Figure 3. 107: Correlation: UPV vs. Compressive Strength of three cores (All).

The data dispersion leads to the approximately linear correlation between UPV measurements and compressive strength and it was observed from the poly. 2nd degree curve which is close to the linear shape than polynomial shape. In addition, in order to standard limits both of standards curves (main curve and the shifted one) was calculated and drawn between 4 and 4.8 using the measurements which was obtained between this range; however, the poly. 2nd degree which covers all of measurements and the related compressive strengths, derived based on all obtained data from 3.6 to 4.85 (km/s) of UPV measurements (see Fig 3.107).

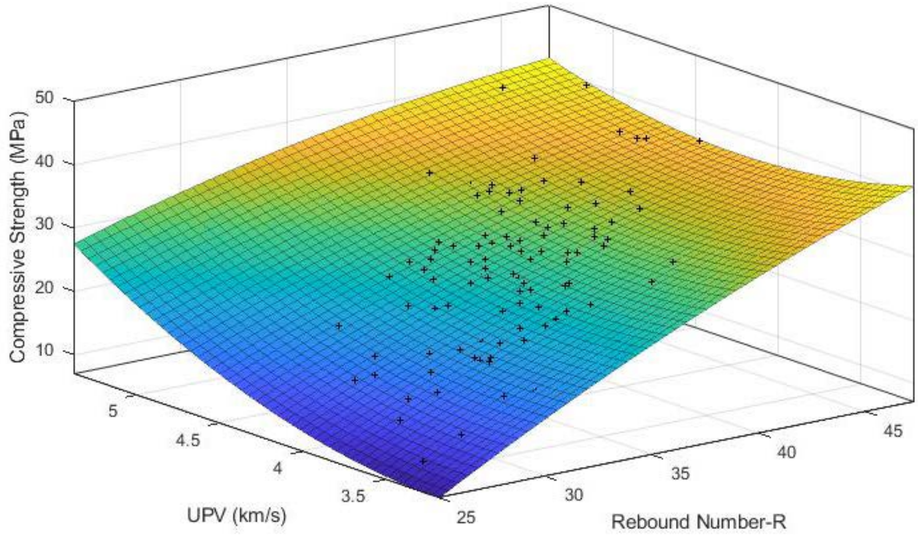


Figure 3. 108: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of three cores (All).

The combined SonReb method significantly increases the accuracy and the R-square value for the correlation using UPV, Rebound Number-R and Compressive Strength measurements due to using 3-D correlation using intended data. As it is illustrated in Fig. 3.108 the correlation which was derived using three different data increase the R-square by 10.36 % compared with Rebound-R (see Table 3.26).

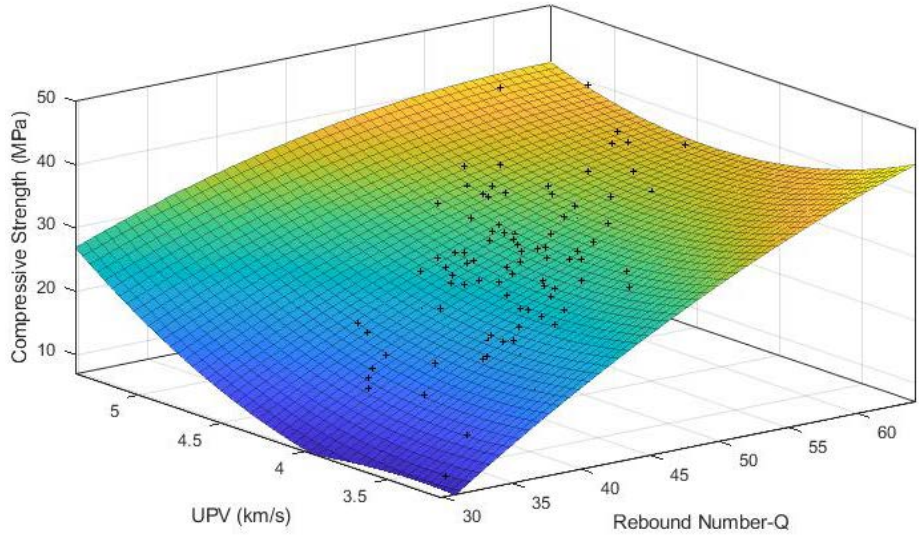


Figure 3. 109: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of three cores (All).

The combined SonReb method has better results and higher efficiency in Rebound-Q compared Rebound-R and it was observed in Fig. 3.109 and the equations and intended R-square values prove this in Table 3.26. However, it has less increase comparing the Poly. 2nd degree of Rebound-Q correlations. This occurs due to the higher R-square value of Rebound-Q than Rebound-R data 2-D correlations with compressive strength.

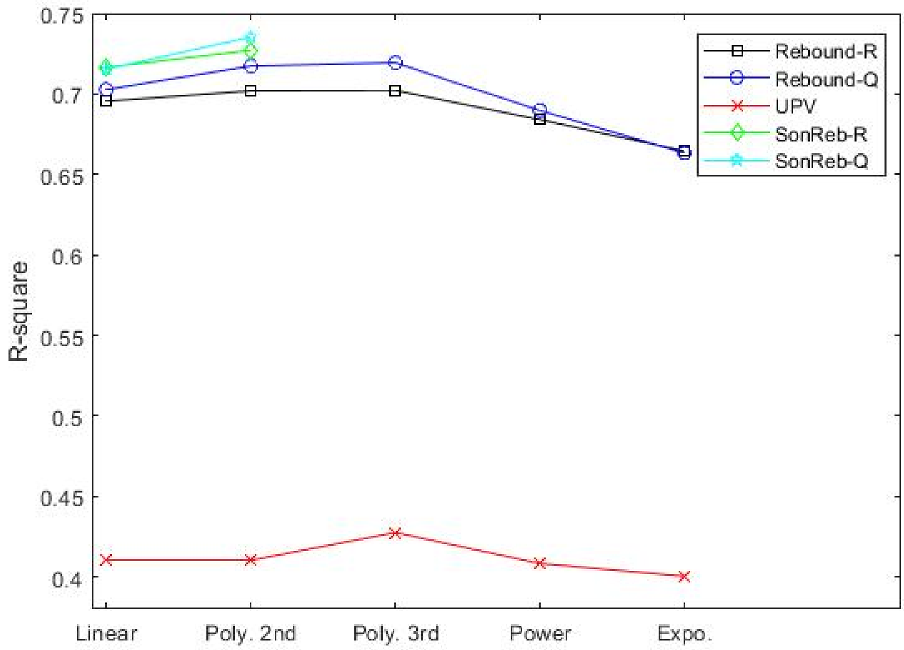


Figure 3. 110: R-square equation based results of three cores (All).

The R-square values for all core sets for All building case was shown in Fig. 3.106 based on all five different equations which was used for correlations and regressions using three different NDT methods. As it is observed in Fig. 3.106 the R-square values for Poly. 3rd degree correlation reaches the highest amount compare other four correlation equation. In addition, the increase in R-square value from linear to Poly. 2nd correlation is too smooth with a small rate then a rise to Poly. 3rd degree correlation R-square value and then decrease from Poly. 3rd to power and expo. correlations was illustrated in the intended figure. Furthermore, there is a small increase from Linear to Poly. 2nd degree SonReb correlation results and like other sets the UPV results demonstrate the lowest amount comparing other NDT methods.

3.2.3.6 Data analysis

The data (R-square values) which was obtained from the previous correlations was analayzed in this section based on (i) Method, and (ii) Equation respectively.

Method based analysis

In this section results obtained for R-square value was compared based on each non-destructive method for all four buildings and in the case that all data was considered for correlation.

The mean value of R-square results for each building and also for all data was calculated for each method of five various equation and results was shown in Figure 3.111.

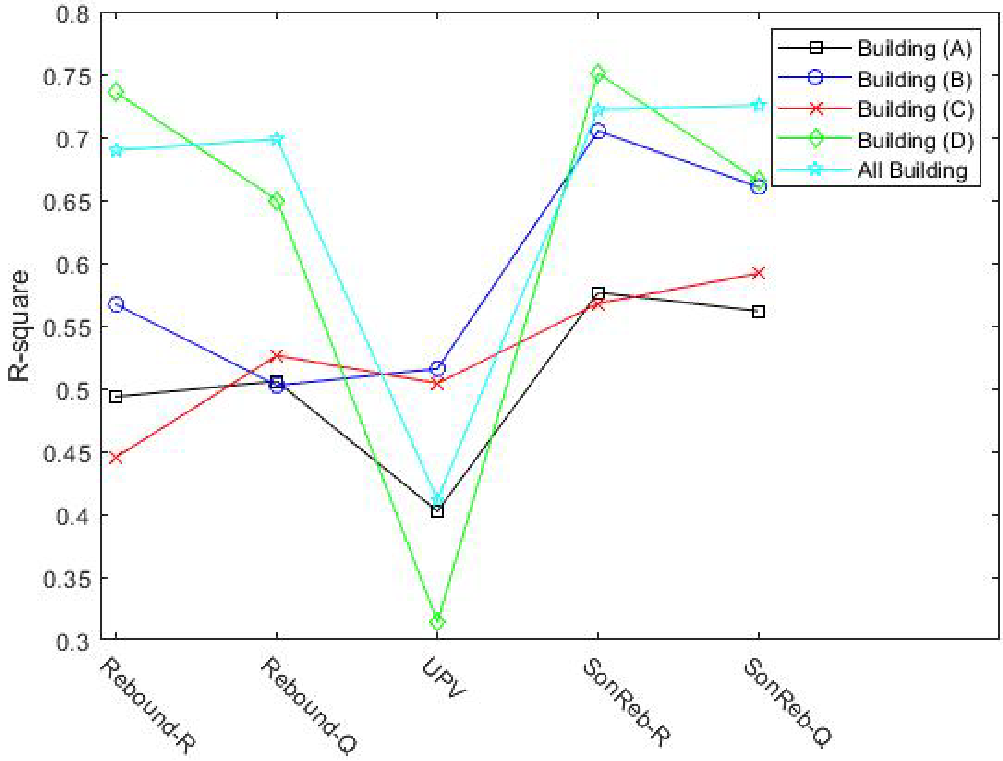


Figure 3. 111: R-square method based results of three cores (All).

The correlation results (R-square values) was observed in Fig 3.107 for all different single core sets in all four buildings and considering all together as one case called All for the four different sets in each case. The R-square values illustrate that the behavior of results changes from set to set and building to building; however, considering the overall view in Fig. 3.111 it could be concluded that there is a few increases from Rebound-R to Rebound-Q and a great decrease from Rebound-Q to UPV R-square values and then a rice to SonReb-R and SonReb-Q occurs based on the correlation which was derived using the intended data. In addition, considering the simplicity factor in implementing the NDT methods, using either Rebound-R or Rebound-Q seems more logical due to the results which were obtained during this section analysis and based on the R-square results which was illustrated in Fig. 3.111.

Equation based analysis

The mean value of R-square results for each method was calculated for each equation type and results were shown in Figure 3.108 based on every three different methods. It is observed that Rebound-R reached the best result (Higher R-square value) and UPV obtained the lowest values. However, it does not literally mean that Rebound-R has better results than Rebound-Q while the standard deviation of data was not considered as a factor in a comparison.

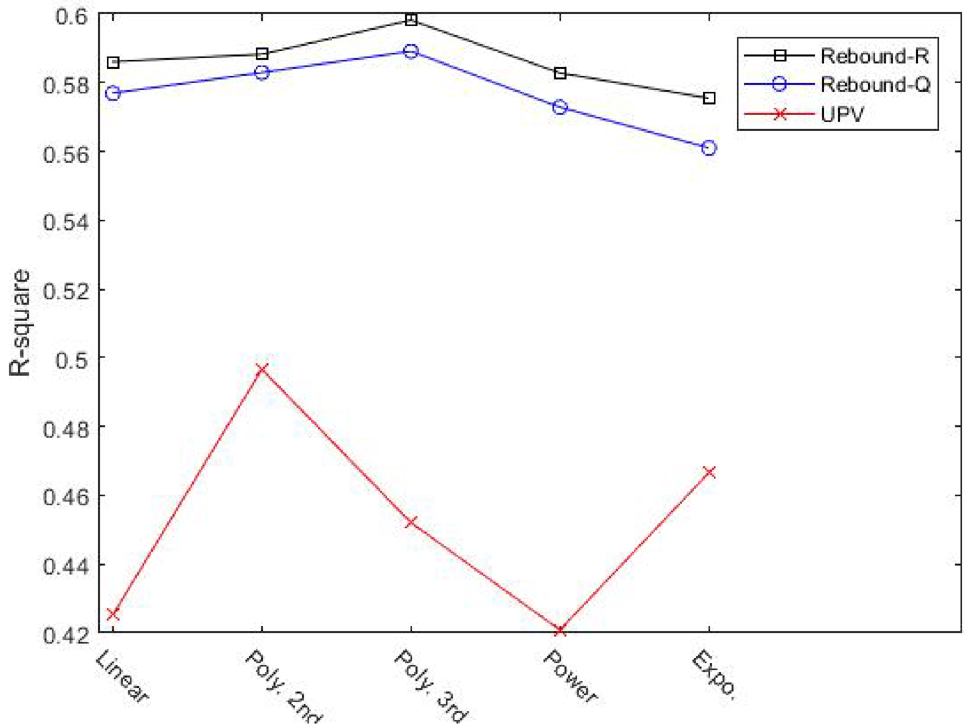


Figure 3. 112: R-square equation based results of three cores (All).

The R-square values changes was illustrated in Fig. 3.112 for all four various building in three NDT methods based on five different equation types. It could be strongly concluded that considering only R-square values, there are a few increases from linear correlation to the Poly. 2nd degree correlation then, a great increase with high rate toward Poly. 3rd degree correlation; after this point, it was observed that there is a sudden reduction to the power correlation and then a few decreases to the Exponential correlation R-square value. Thus, if the simplicity of equation was neglected during a process it is strongly suggested to use Poly. 3rd degree correlation, but if the simplicity is an important factor in one project Poly. 2nd degree is a suitable correlation (based on the results observed in Fig. 3.112). However, due to special dispersion for UPV data which was also considered by EN 13791 standard, the Poly. 2nd degree correlation s demonstrates better results for this NDT method.

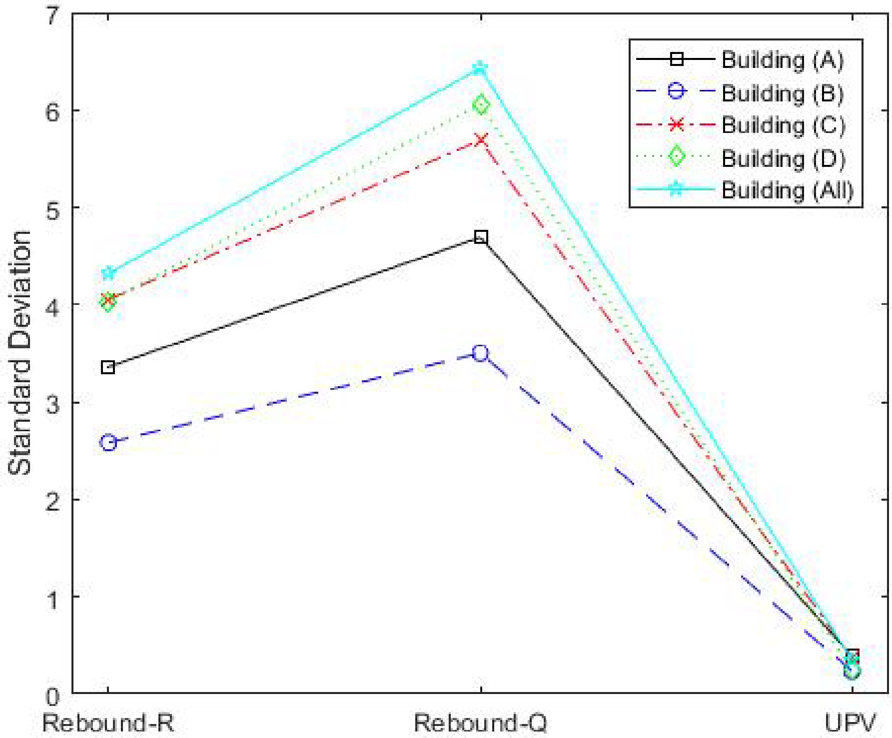


Figure 3. 113: Standard deviation of three cores based on method.

Figure 3.113 illustrates the changes in standard deviation magnitude for all four buildings, and one All case set based on three NDT methods which were used in this project. The behavior and rate of changes observed in previous standard deviation figures and in Fig. 3.113 for all shows that there is a slight increase from Rebound-R to Rebound-Q and then a reduction with high rate from Rebound-Q to UPV standard deviation magnitude.

3.2.4 Fourth scenario (story based study)

In this scenario correlations and related analysis was provided using the number of cores which was taken from three different selection criteria based on story number. The sets contain 2-story, 4-story, and 8-story data which was selected considering economic and the work difficulty factors.

3.2.4.1 Fourth scenario-building A

In this part, the sets and correlations which was derived based on the fourth scenario was demonstrated in various tables and figures for building A.

Table 3. 27: R-square and standard deviation values of different equations and methods of story based analysis for building (A).

NDT Method	Equation type	2-story		4-story		8-story	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.4679	2.6783	0.5690	2.6997	0.4877	3.3397
	Poly. 2nd	0.5755		0.6366		0.4880	
	Poly. 3rd	0.6052		0.6537		0.4886	
	Power	0.4695		0.5639		0.4879	
	Expo.	0.4608		0.5515		0.4874	
Rebound-Q	Linear	0.3148	3.8618	0.4428	3.6429	0.4335	4.1354
	Poly. 2nd	0.6249		0.5269		0.4436	
	Poly. 3rd	0.6293		0.5709		0.4488	
	Power	0.3226		0.4410		0.4327	
	Expo.	0.3050		0.4277		0.4234	
UPV	Linear	0.0033	0.1520	0.3118	0.1731	0.2007	0.3192
	Poly. 2nd	0.3700		0.4031		0.2026	
	Poly. 3rd	0.7273		0.6254		0.2545	
	Power	0.0022		0.3046		0.2004	
	Expo.	0.0034		0.2945		0.1984	
SonReb (R)	R 1st , V 1st	0.4841	-	0.5811	-	0.4877	-
	R 2nd , V 2nd	1		0.7614		0.5630	
SonReb (Q)	Q 1st , V 1st	0.3151	-	0.4882	-	0.4382	-
	Q 2nd , V 2nd	1		0.8138		0.6143	

Based on the results which are obtained based on Table 3.27 considering R-square and standard deviation values, the 4-story set was selected as optimum set among the four sets and correlation curves and regression equations was demonstrated for this set of couple cores for building A.

Table 3. 28: Correlation equations of 4-story set for building (A).

NDT Method	Equation type	Correlation Equation	$\mathbf{r^2}$	SD
Rebound- R	Linear	$F = 0.979R - 10.39$	0.5690	2.6997
	Poly. 2nd	$F = -0.1486R^2 + 11.75R - 204.6$	0.6366	
	Poly. 3rd	$F = 0.0413R^3 - 4.61R^2 + 171.7R - 2109$	0.6537	
	Power	$F = 0.1723R^{1.387}$	0.5639	
	Expo.	$F = 6.349\exp(0.03781R)$	0.5515	
Rebound-Q	Linear	$F = 0.6402Q - 3.501$	0.4428	3.6429
	Poly. 2nd	$F = -0.0908Q^2 + 8.737Q - 182.8$	0.5269	
	Poly. 3rd	$F = 0.02627Q^3 - 3.601Q^2 + 164.5Q - 2478$	0.5709	
	Power	$F = 0.3588\ Q^{1.118}$	0.4410	
	Expo.	$F = 8.304\exp(0.02469Q)$	0.4277	
UPV	Linear	$F = 11.31\ V - 17.07$	0.3118	0.1731
	Poly. 2nd	$F = -25.56\ V^2 + 201.5V - 370.1$	0.4031	
	Poly. 3rd	$F = 212.4\ V^3 - 2396\ V^2 + 9001V - 1.124 \times 10^{-4}$	0.6254	
	Power	$F = 2.993\ V^{1.615}$	0.3046	
	Expo.	$F = 5.113\exp(0.4261V)$	0.2945	
SonReb (R)	R 1st , V 1st	$F = 0.8643R + 2.865V - 16.95$	0.5811	-
	R 2nd , V 2nd	$F = 19.98R - 45.9V + 0.046R^2 - 6.058RV + 35.84V^2 - 267.5$	0.7614	
SonReb (Q)	Q 1st , V 1st	$F = 0.7444Q + 3.433V - 21.68$	0.4882	-
	Q 2nd , V 2nd	$F = 15.03Q + 25.06V + 0.0711Q^2 - 5.6QV + 30.23V^2 - 368.9$	0.8138	

Table 3.28 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

Despite the few numbers of data for Rebound-R which is associated with high compressive strength comparing the nearby points (data), the data dispersion in Fig. 3.114 demonstrates the proper fit with both EN 13791 standards suggested curves and with Poly. 2nd degree correlation curves are properly derived due to the dispersion of data.

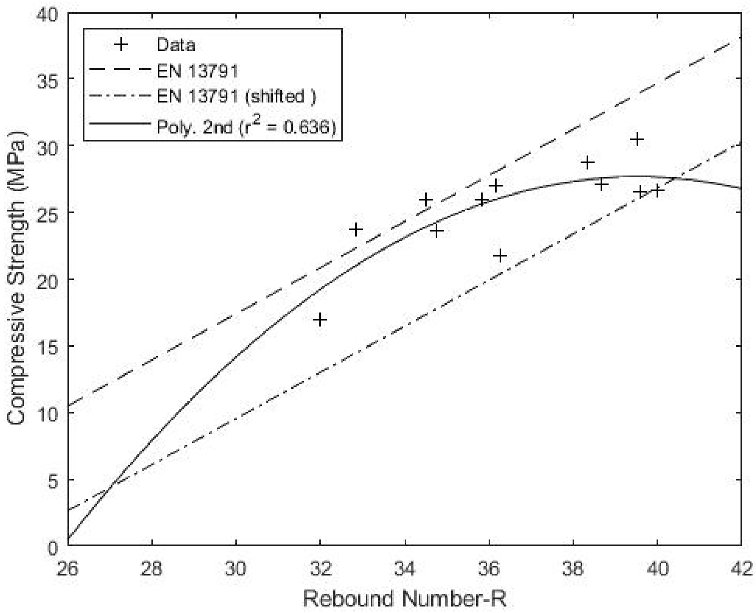


Figure 3. 114: Correlation: Rebound R vs. Compressive Strength of 4-story set (A).

The data was dispersed in such case that even with linear shape of correlation curve the R-square value still stays in a high amount of 0.636 which is the greatest amount comparing the other sets and buildings R-square values for Rebound-R measurements and intended correlations (see Fig. 3.114).

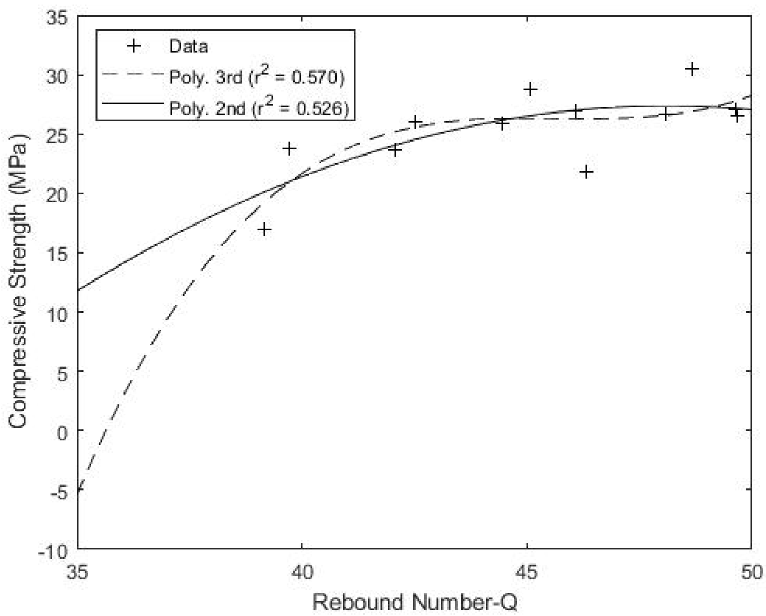


Figure 3. 115: Correlation: Rebound Q vs. Compressive Strength of 4-story set (A).

The high values of R-square for both Poly. 2nd and Poly. 3rd degree correlations (0.526, and 0.570 respectively) demonstrates that the data dispersion in this analysis was properly distributed and the intended correlation leads to the high reliable equation for concrete strength estimation in building A. In addition, it is been founded that the correlation using linear curve is even reliable and acceptable for this set of data (see Fig. 3.115).

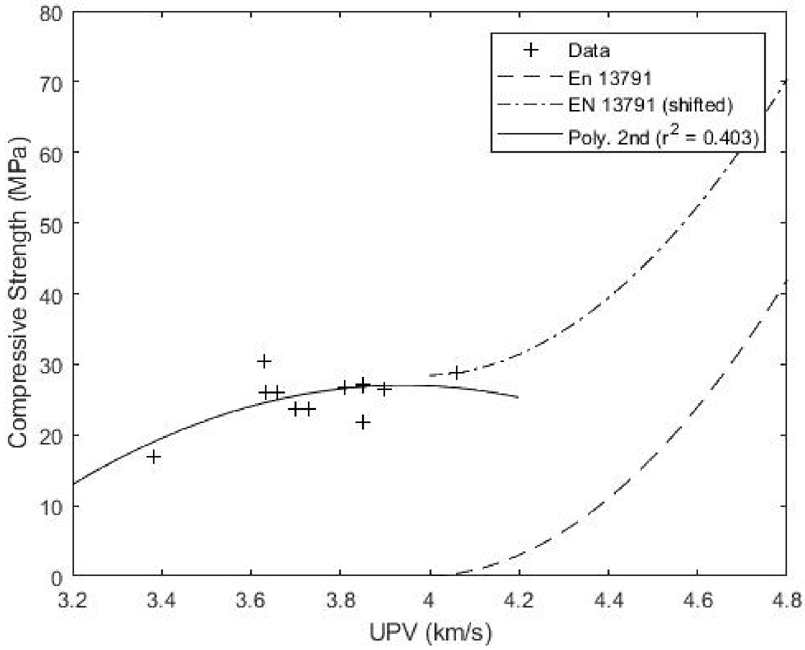


Figure 3. 116: Correlation: UPV vs. Compressive Strength of 4-story set (A).

Despite the EN 13791 standard curve for this set of data the EN 13791 shifted curve could reach the data and cover one data with proper proximity. However, the Poly. 2nd degree correlation curve with R-square 0.403 have better support due to no limits- there is a limit for the standard which requires data between 4-4.8- thus the Poly. 2nd degree reach better results considering that the data is somehow compacted and the dispersion of the data is not that much longitudinal like the previous sets (see Fig. 3.116).

The combined method could significantly improve the results of correlation and related regressions with higher R-square values in this set of data for Rebound-R, UPV, and Compressive strength. According to the data which was demonstrated in Table 3.28 there is an approximately 20 % increase compared with Rebound-R and about 89 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value. Fig. 3.116 illustrates that the data tends to stay in high values and it leads to high compaction of data at upper parts.

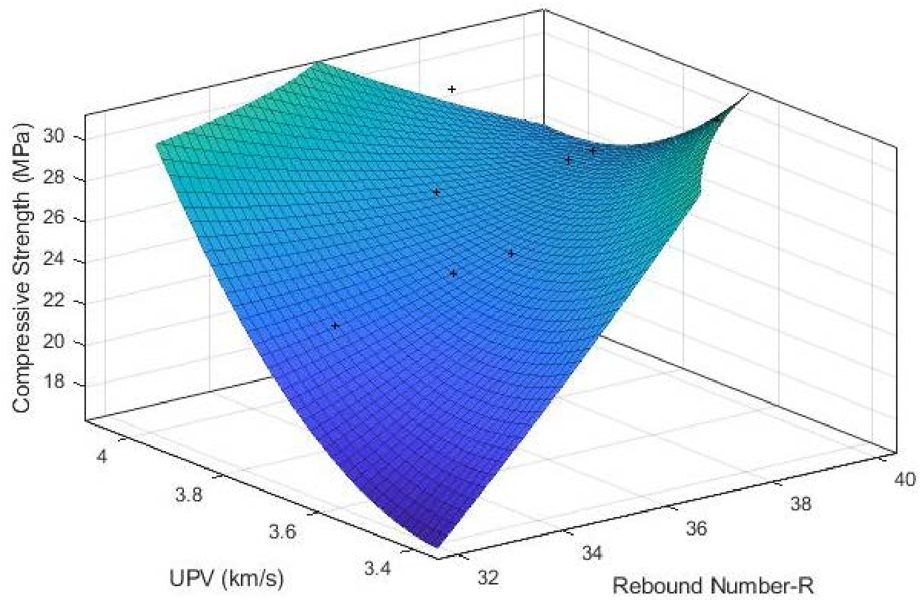


Figure 3. 117: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of 4-story set (A).

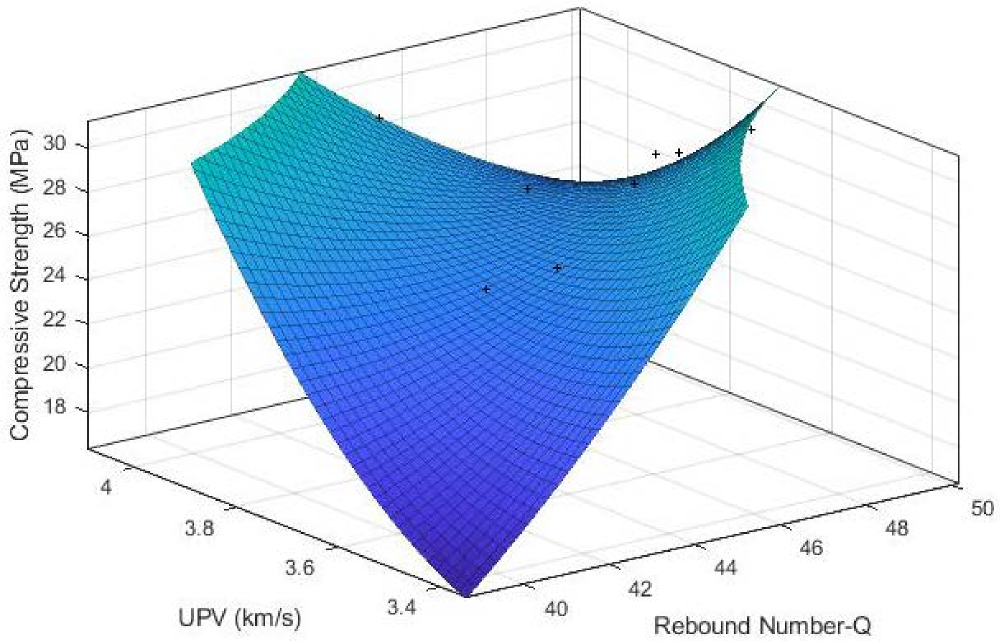


Figure 3. 118: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of 4-story set (A).

There is a proper cover of correlation plate in combined SonReb method for Rebound-Q vs. UPV vs. Compressive strength which was observed in Fig. 3.117. The both Rebound-Q and UPV sides help to cover the data in both sides to increase the R-square value. Moreover, there is an approximately 54 % increase compared with Rebound-Q and about a 100 % increase compared with UPV`s Poly. 2nd degree correlation`s R-square value (see Table 3.28).

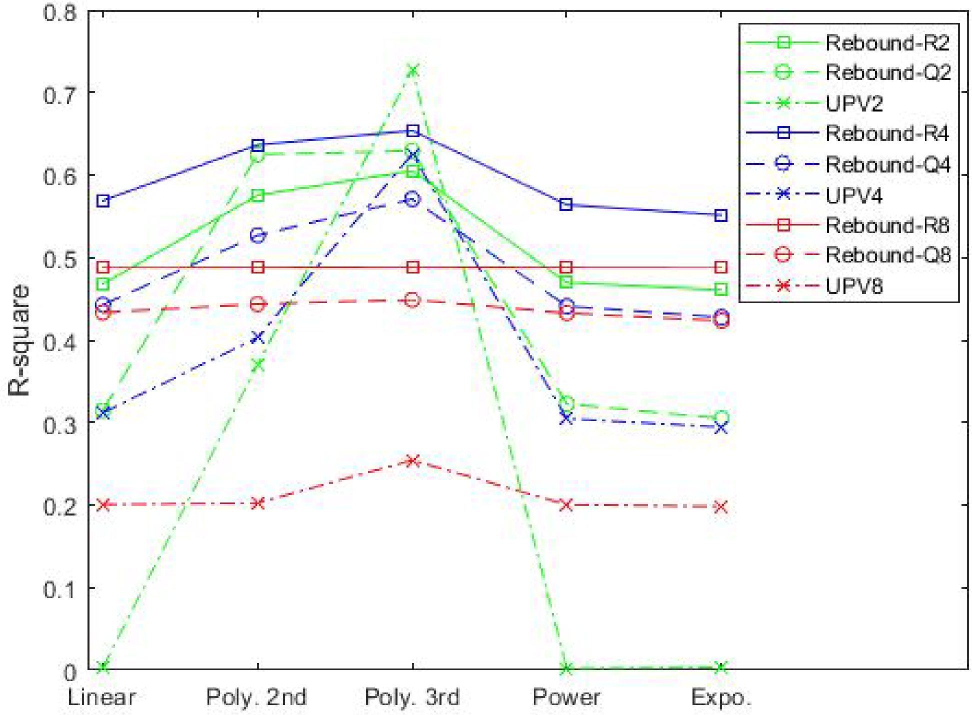


Figure 3. 119: R-square values for different equations, methods, and sets story based analysis (A).

Figure 3.119 demonstrates the changes which were occurred for the R-square values in each method type of each different sets for different five equation types. There is an increase almost in every method-set line from linear to Poly. 2nd degree and then increase with higher slope than the previous step toward Poly. 3rd degree equation correlations R-square values. After this there is sharp decline toward power then continue almost slight toward Exponential equation`s R-square value. However, there is a special set called UPV2, in this set due to the special distribution of data which is most compatible with polynomial curves the R-square values have great differences between linear, power, expo. and polynomial correlations; this phenomenon was also illustrated for other sets but with lower rates.

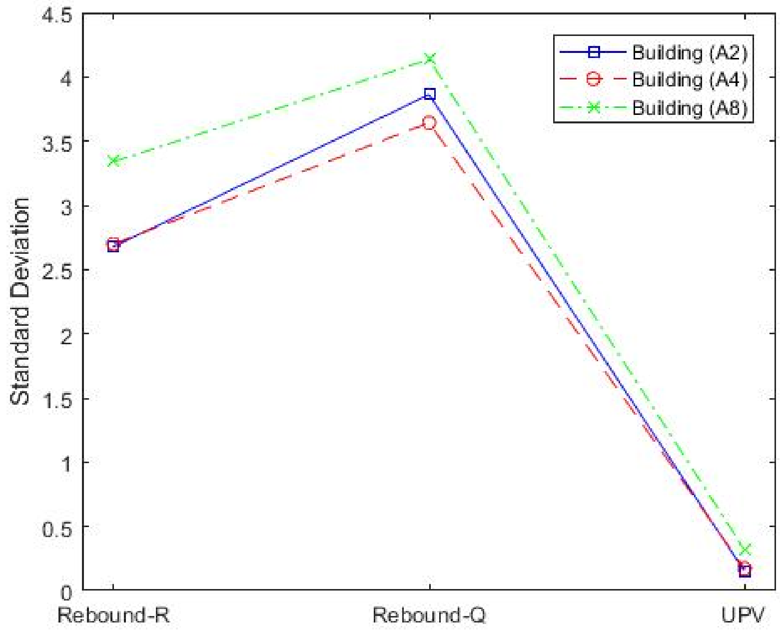


Figure 3. 120: Standard deviation of different sets of story based analysis (A).

All of the sets almost has an equal rate in increase of standard deviation from Rebound-R to Rebound-Q and the same rate in deflection from Rebound-Q to UPV. The 2-story and 4-story sets have almost the same standard deviations for Rebound-R measurements and UPV measurements; however, this value is different for Rebound-Q measurements (see Fig. 3.120).

3.2.4.2 Fourth scenario-building B

In this part the sets and correlations which was derived based on the fourth scenario was demonstrated in various tables and figures for building B.

Table 3. 29: R-square and standard deviation values of different equations and methods of story based analysis for building (B).

NDT Method	Equation type	2-story		4-story		8-story	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.4316	1.4733	0.4301	1.9967	0.5684	2.2858
	Poly. 2nd	0.4348		0.4800		0.5727	
	Poly. 3rd	0.7024		0.4806		0.5786	
	Power	0.4277		0.4388		0.5634	
	Expo.	0.4257		0.4450		0.5576	
Rebound-Q	Linear	0.3021	2.8952	0.4563	2.4175	0.5012	3.4882
	Poly. 2nd	0.5063		0.4598		0.5034	
	Poly. 3rd	0.5769		0.5185		0.5051	
	Power	0.2929		0.4525		0.4982	
	Expo.	0.2825		0.4485		0.4921	
UPV	Linear	0.7627	0.1951	0.6919	0.1726	0.433	0.2259
	Poly. 2nd	0.765		0.6941		0.486	
	Poly. 3rd	0.795		0.7079		0.5483	
	Power	0.7586		0.6881		0.4134	
	Expo.	0.7574		0.6866		0.3958	
SonReb (R)	R 1st , V 1st	0.7727	-	0.6934		0.6189	-
	R 2nd , V 2nd	1		0.7165		0.6537	
SonReb (Q)	Q 1st , V 1st	0.7663	-	0.7278		0.5877	-
	Q 2nd , V 2nd	1		0.8140		0.6124	

Based on the results which are obtained based on Table 3.29 considering R-square and standard deviation values, the 4-story set was selected as optimum set among the three sets and correlation curves and regression equations was demonstrated for this set of story-based analysis for building B.

Table 3. 30: Correlation equations of 4-story set for building (B).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.074R - 17.78$	0.4301	1.9967
	Poly. 2nd	$F = 0.235R^2 - 13.34R + 202.2$	0.4800	
	Poly. 3rd	$F = -0.01518R^3 + 1.615R^2 - 55.03R + 621$	0.4806	
	Power	$F = 0.006767R^{2.251}$	0.4388	
	Expo.	$F = 1.564\exp(0.07364R)$	0.445	
Rebound-Q	Linear	$F = 0.9141Q - 21.1$	0.4563	2.4175
	Poly. 2nd	$F = -0.03809Q^2 + 3.907Q - 79.61$	0.4598	
	Poly. 3rd	$F = -0.07321Q^3 + 8.578Q^2 - 333.2Q + 4307$	0.5185	
	Power	$F = 0.002165\ Q^{2.404}$	0.4525	
	Expo.	$F = 1.358\ \exp(0.06054Q)$	0.4485	
UPV	Linear	$F = 15.76\ V - 45.4$	0.6919	0.1726
	Poly. 2nd	$F = -8.237\ V^2 + 80.58\ V - 172.7$	0.6941	
	Poly. 3rd	$F = 189.5\ V^3 - 2235\ V^2 + 8796\ V - 1.153 \times 10^{-4}$	0.7079	
	Power	$F = 0.09943\ V^{3.73}$	0.6881	
	Expo.	$F = 0.3974\ \exp(0.9456V)$	0.6866	
SonReb (R)	R 1st , V 1st	$F = 0.09743R + 14.91V - 45.14$	0.6934	-
	R 2nd , V 2nd	$F = 30.24R - 4.048V + 0.2699R^2 - 12.4RV + 53.87V^2 - 483.6$	0.7165	
SonReb (Q)	Q 1st , V 1st	$F = 0.3325Q + 12.8V - 47.36$	0.7278	-
	Q 2nd , V 2nd	$F = 23.96Q - 37.38V + 0.08175Q^2 - 7.971QV + 48.55V^2 - 421.9$	0.8140	

Table 3.30 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results was illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The EN-13791 curve in Fig. 3.121 demonstrates the curve which is suggested by the EN 13791 standard considering the data which was obtained from compressive tests and NDT measurements. Furthermore, the Poly. 2nd curve in this figure which was drawn using Matlab software demonstrates better proximity to the obtained data with R-square value of 0.480; however, because of compaction in data in small length it could not be strongly concluded that this correlation curves provides higher reliability than EN-13791 suggested curves.

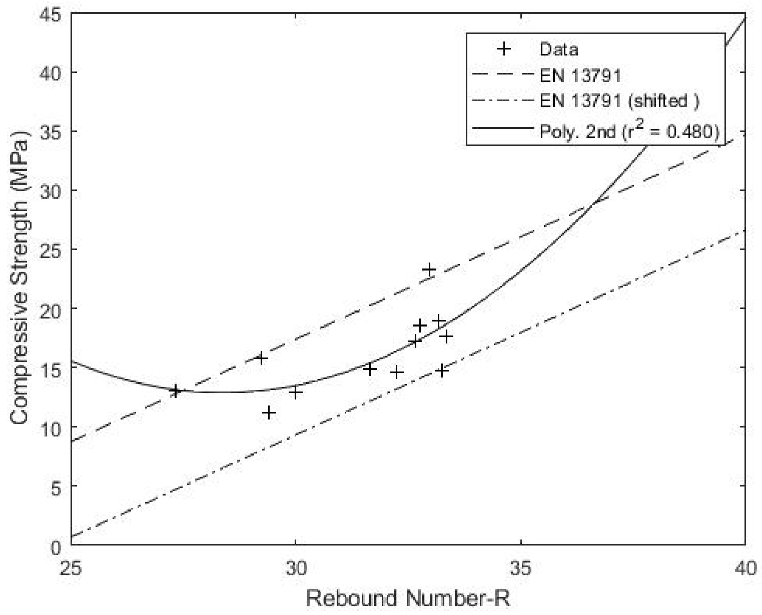


Figure 3. 121: Correlation: Rebound R vs. Compressive Strength of 4-story set (B).

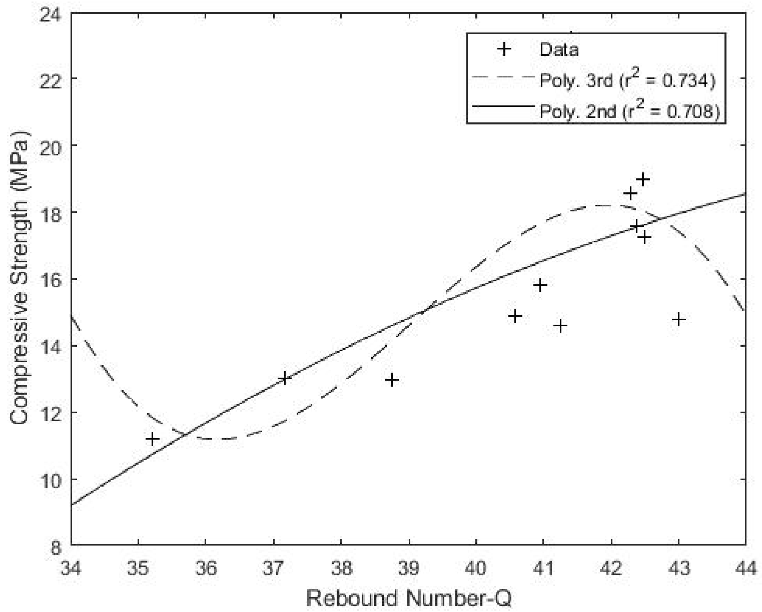


Figure 3. 122: Correlation: Rebound Q vs. Compressive Strength of 4-story set (B).

In order to comparison Poly. 2nd and poly. 3rd degree correlations were shown in Fig. 3.122 and the results demonstrate that due to the dispersion of data there are a few differences in using poly. 2nd or poly. 3rd degree curves and intended regressions (0.708, 0.734 respectively); however, in order to the simplicity of poly. 2nd degree in the equation this curve suggested using for estimate the concrete strength at the studied case also due to curves reliability (building B).

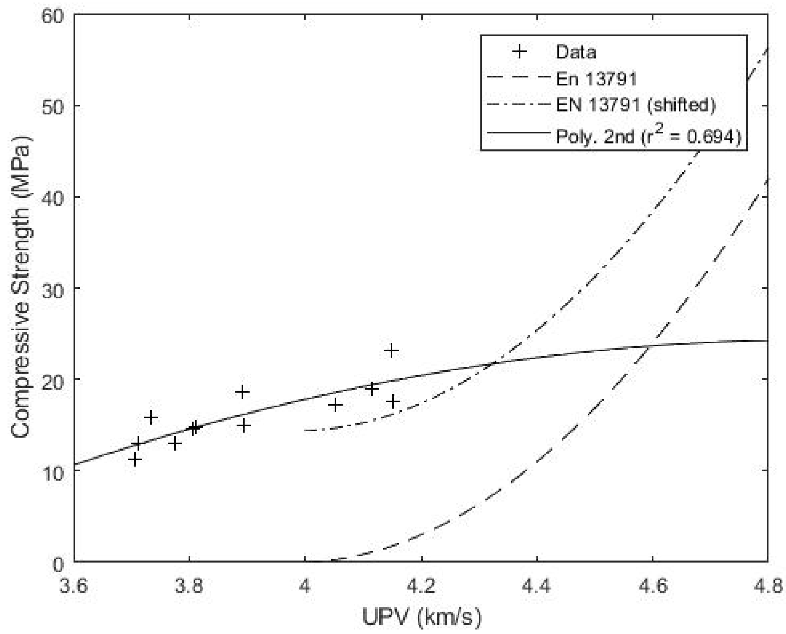


Figure 3. 123: Correlation: UPV vs. Compressive Strength of 4-story set (B).

The data dispersion leads to the approximately linear correlation between UPV measurements and compressive strength and it was observed from the poly. 2nd degree curve which is close to the linear shape than polynomial shape in the area which data exist and the correlation was derived. In addition, in order to standard limits both of standards curves (main curve and the shifted one) was calculated and drawn between 4 and 4.8 using the measurements which was obtained between this range; however, the poly. 2 degree which covers all of measurements and the related compressive strengths, derived based on all obtained data from 3.6 to 4.8 (km/s) of UPV measurements (see Fig 3.123).

The combined SonReb method significantly increases the accuracy and the R-square value for the correlation using UPV, Rebound Number-R and Compressive Strength measurements due to using 3-D correlation using intended data. As it is illustrated in Fig. 3.124 the correlation which was derived using three different data increase the R-square by 50 % compared with Rebound-R to 0.7165 (see Table 3.30).

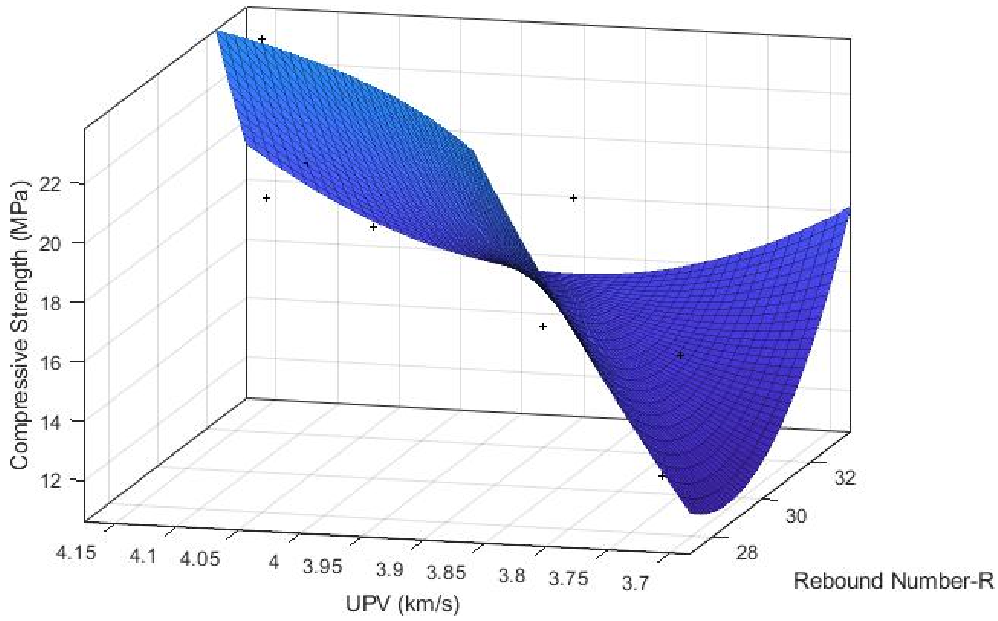


Figure 3. 124: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of 4-story set (B).

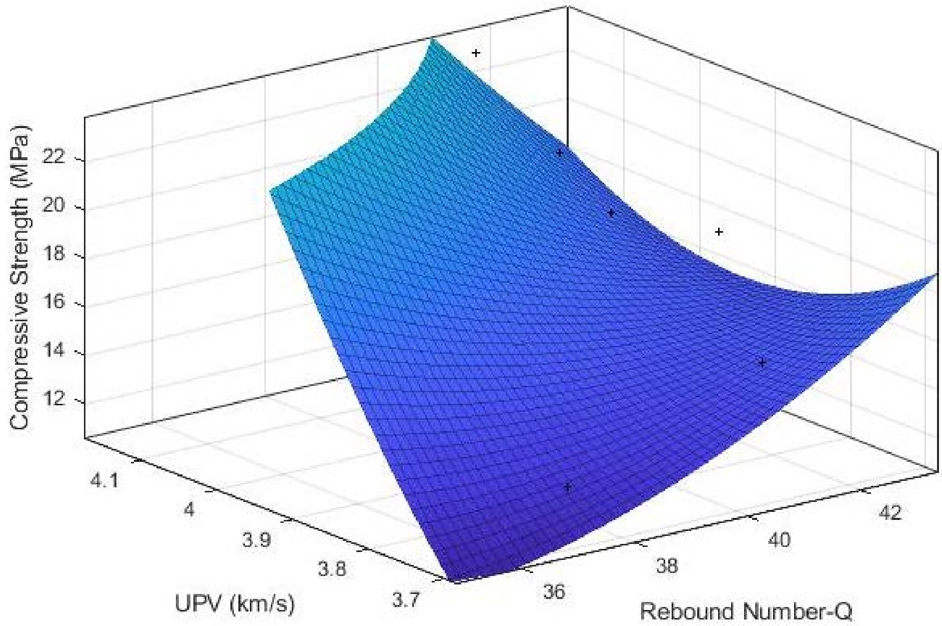


Figure 3. 125: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of 4-story set (B).

The combined SonReb method has better results and a higher effect in Rebound-Q compared Rebound-R and it was observed in Fig. 3.125 and the equations and intended R-square values prove this in Table 3.30. However, the percentage of increase comparing the Poly. 2nd degree of Rebound-Q correlations is almost the same comparing the same sets for Rebound-R SonReb correlation. This occurs due to the higher R-square value of Rebound-Q than Rebound-R data 2-D correlations with compressive strength.

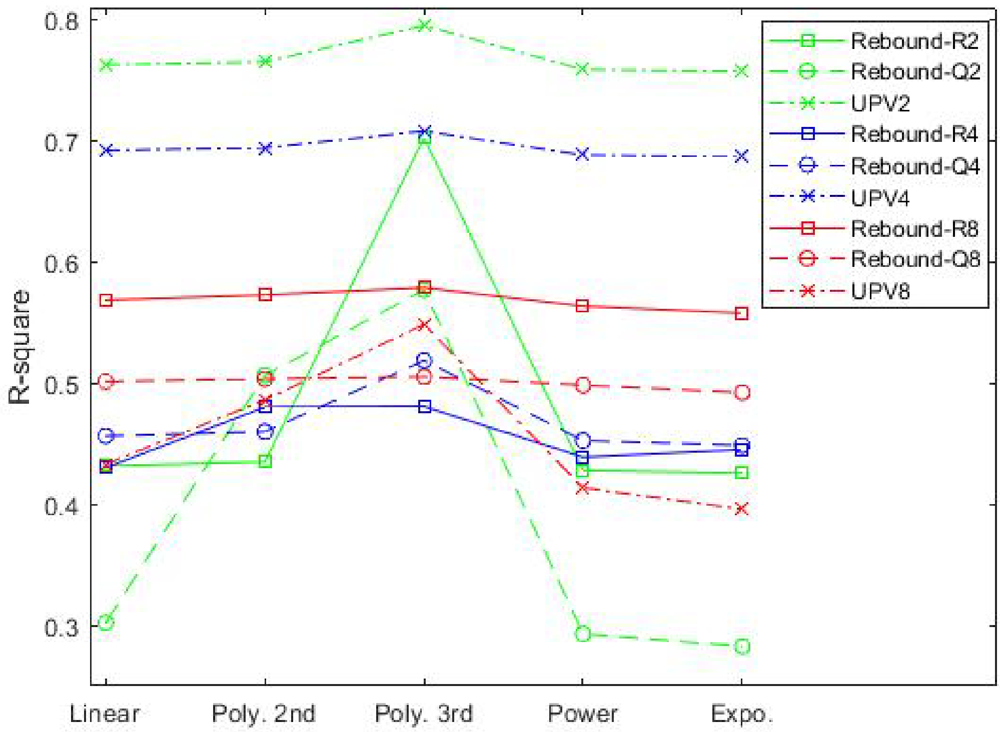


Figure 3. 126: R-square values for different equations, methods, and sets of story based analysis (B).

The R-square values for all story based sets for building B was shown in Fig. 3.125 based on all five different equations which was used for correlations and regressions for all three NDT methods. As it is observed in Fig. 3.126 the R-square values for Poly. 3rd degree correlation reaches the highest amount compare other four correlation equation type and the slop of increase is significant and higher than other sets. However, this change in slop of curves in Fig. 3.126 for some sets such as UPV4 and UPV8 is almost flat with little increase in Poly. 3rd degree correlation and it is with a higher rate for some other sets like Rebound-R2. In addition, the increase in R-square value from linear to Poly. 2nd correlation and then decrease from Poly. 3rd to power and Expo. correlations were illustrated in the intended figure which is sometimes with almost zero changes.

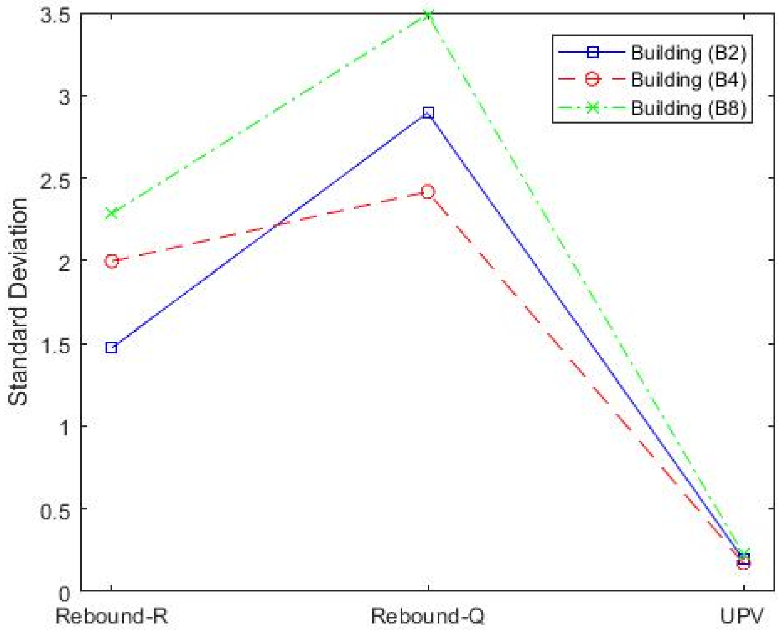


Figure 3. 127: Standard deviation of different sets of story based analysis (B).

The standard deviation for all three sets including 2-story, 4-story, and 8-story for three various methods was observed in Fig. 3.127. The amount of standard deviation for all sets shows that there is an increase in standard deviation of Rebound-Q compared with Rebound-R and maybe it is the reason that in some sets the amount of R-square value gets higher for Rebound-R type than Rebound-Q. The amount of increase for different sets differs from 30-40 % comparing Rebound-R and Rebound-Q. Furthermore, the standard deviation for UPV measurements demonstrates lower values and in order to differentiate between the amount type, the comparison could not be made for UPV measurements data and other two rebounds data. However, the behavior of changes for the 4-story set (B4) is different due to a lower amount of standard deviation for Rebound-Q of this set.

3.2.4.3 Fourth scenario-building C

In this part the sets and correlations which was derived based on the fourth scenario was demonstrated in various tables and figures for building C.

Table 3. 31: R-square and standard deviation values of different equations and methods of story based analysis for building (C).

NDT Method	Equation type	2-story		4-story		8-story	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.0100	2.8170	0.3309	3.3538	0.6518	4.1971
	Poly. 2nd	0.3279		0.5		0.6523	
	Poly. 3rd	0.6644		0.594		0.7100	
	Power	0.0122		0.3323		0.6521	
	Expo.	0.0092		0.313		0.652	
Rebound-Q	Linear	0.0008	2.5793	0.3474	3.7362	0.7076	5.7250
	Poly. 2nd	0.8677		0.5612		0.7083	
	Poly. 3rd	0.9057		0.797		0.7343	
	Power	0.0002		0.345		0.7080	
	Expo.	0.0008		0.3252		0.7072	
UPV	Linear	0.4674	0.1466	0.5394	0.3117	0.5486	0.3558
	Poly. 2nd	0.4675		0.5739		0.551	
	Poly. 3rd	0.6594		0.5967		0.5703	
	Power	0.4670		0.5452		0.5461	
	Expo.	0.4665		0.5539		0.5375	
SonReb (R)	R 1st , V 1st	0.4911	-	0.5554	-	0.6954	-
	R 2nd , V 2nd	1		0.8005		0.7045	
SonReb (Q)	Q 1st , V 1st	0.4984	-	0.5576	-	0.7337	-
	Q 2nd , V 2nd	1		0.8327		0.7449	

Based on the results which is obtained based on Table 3.31 considering R-square and standard deviation values, 8-story set was selected as optimum set among the three sets and correlation curves and regression equations was demonstrated for this set of story-based analysis for building C.

Table 3. 32: Correlation equations of 8-story set for building (C).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 0.967R - 6.466$	0.6518	4.1971
	Poly. 2nd	$F = 0.005408R^2 + 0.5508R + 1.448$	0.6523	
	Poly. 3rd	$F = 0.0145R^3 - 1.664R^2 + 64.01R - 794.9$	0.7100	
	Power	$F = 0.3653R^{1.214}$	0.6521	
	Expo.	$F = 9.123\exp(0.03136R)$	0.652	
Rebound-Q	Linear	$F = 0.7386Q - 6.812$	0.7076	5.7250
	Poly. 2nd	$F = 0.003146Q^2 + 0.4159Q + 1.364$	0.7083	
	Poly. 3rd	$F = 0.00364Q^3 - 0.5563Q^2 + 28.78Q - 472.7$	0.7343	
	Power	$F = 0.2506\,Q^{1.224}$	0.7080	
	Expo.	$F = 9.162\exp(0.02364Q)$	0.7072	
UPV	Linear	$F = 10.46\,V - 15.23$	0.5486	0.3558
	Poly. 2nd	$F = -1.346\,V^2 + 22.24V - 40.81$	0.5510	
	Poly. 3rd	$F = -10.49\,V^3 + 136.7\,V^2 - 578.9V + 825.7$	0.5703	
	Power	$F = 3.397\,V^{1.487}$	0.5461	
	Expo.	$F = 7.074\exp(0.3329V)$	0.5375	
SonReb (R)	R 1st , V 1st	$F = 0.6879R + 4.42V - 15.13$	0.6954	-
	R 2nd , V 2nd	$F = -2.055R + 31.14V - 0.01265R^2 + 0.8381RV - 6.645V^2 - 21.55$	0.7045	
SonReb (Q)	Q 1st , V 1st	$F = 0.7444Q + 3.433V - 21.68$	0.7337	-
	Q 2nd , V 2nd	$F = -0.3113Q + 16.36V + 0.03557Q^2 - 0.6342QV + 2.248V^2 - 19.42$	0.7449	

Table 3.32 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data for Rebound-R and Compressive strength obtained from NDT measurements and experimental compression tests respectively was provided and the intended data correlations using both EN 13791 standard and Poly. 2nd degree correlation curves were drawn in Fig. 3.128. The data dispersion was in a proper condition along the both EN 13791 suggested curve for the intended data and for the Poly. 2nd degree correlation curves with the R-square value of 0.652 which is a reliable value for the Rebound-R considering other buildings.

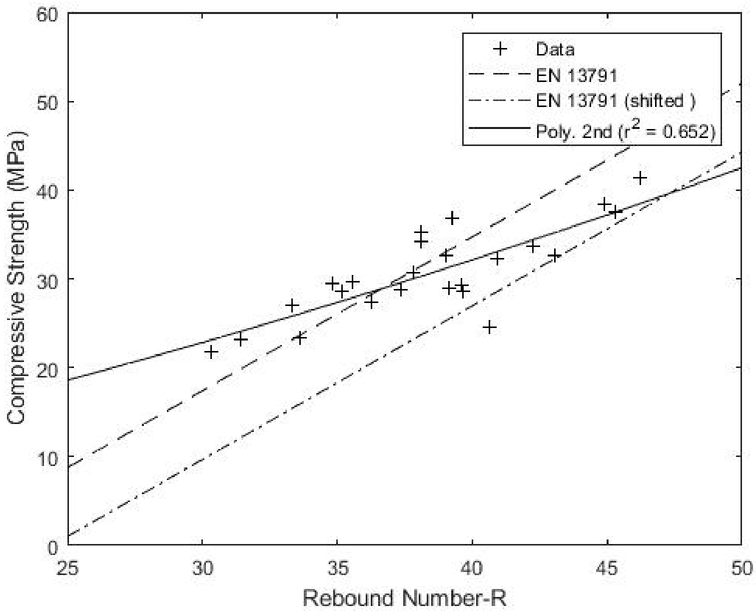


Figure 3. 128: Correlation: Rebound R vs. Compressive Strength of 8-story set (C).

Thus, Poly. 2nd degree curve due to Y-axis beginning point could cover the data better than standards suggested curves which trie to reach to the sources of coordinates.

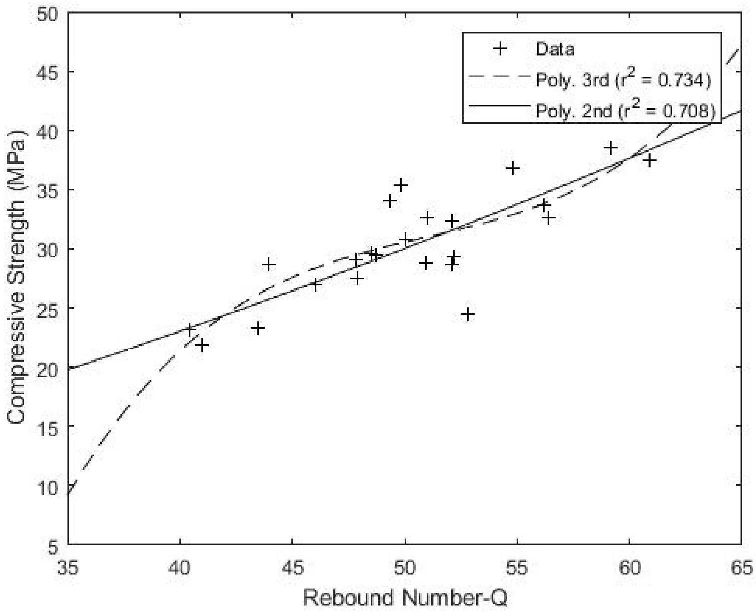


Figure 3. 129: Correlation: Rebound Q vs. Compressive Strength of 8-story set (C).

Based on observations in Fig. 3.129 both Poly. 2nd and Poly. 3rd degree correlation curves continues in same path in this section due to the special dispersion of data in the section. The data was suitably distributed around the correlation curves which leads to high R-square values for both Poly. 2nd degree and Poly. 3rd degree. In addition, Poly. 3rd correlation curves could cover the data better due to data ups and downs which is most compatible with Poly. 3rd degree than Poly. 2nd.

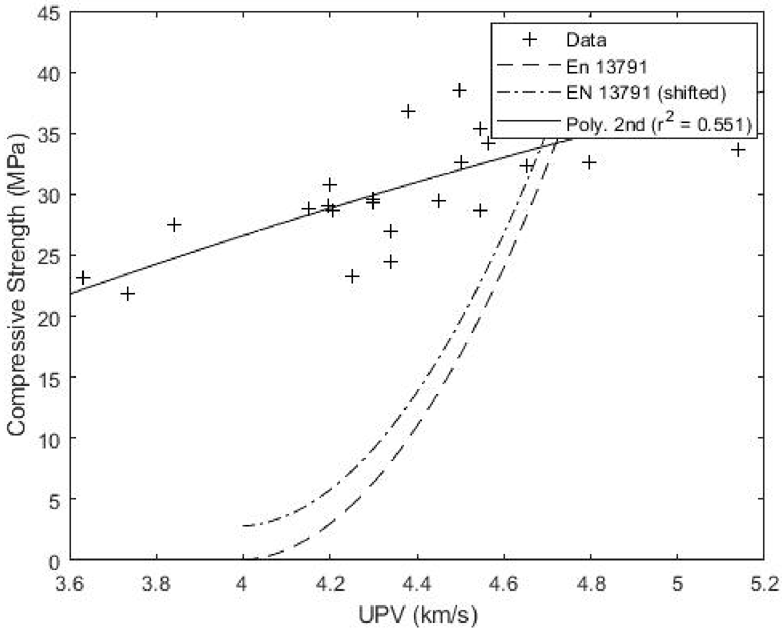


Figure 3. 130: Correlation: UPV vs. Compressive Strength of 8-story set (C).

In order to the special dispersion of UPV measurements data which is more compatible with the equation and the curve suggested by EN 13791 standard; however, in this case, the data is most compatible with the polynomial degree curves such as the correlation which was illustrated in Fig. 3.130, the other correlation curves could not cover the data properly and the obtained R-square value is not such strong value to consider for concrete compressive strength estimation.

The improvement in R-square value indicates the importance and effectiveness of combined SonReb method and using the 3-D correlation with a plate which covers most of the data is the reason for this enhancement in the R-square value. Fig 3. 131 illustrates that the curve for UPV data is in polynomial shape; however, the other curve which is in Rebound-R straight is much linear than polynomial. Table 3.32 demonstrates that there is a 27 % increase compared with UPV-Compressive strength correlation`s R-square value. In addition, there is a slight increase in comparing Rebound-R results with SonReb results and this occurs due to the high R-square value which was obtained for Rebound-R vs. Compressive strength correlation.

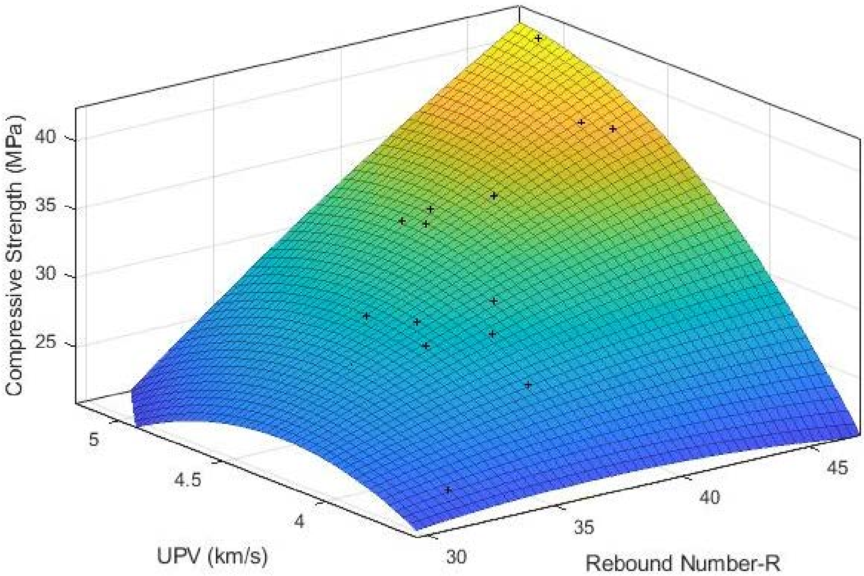


Figure 3. 131: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of 8-story set (C).

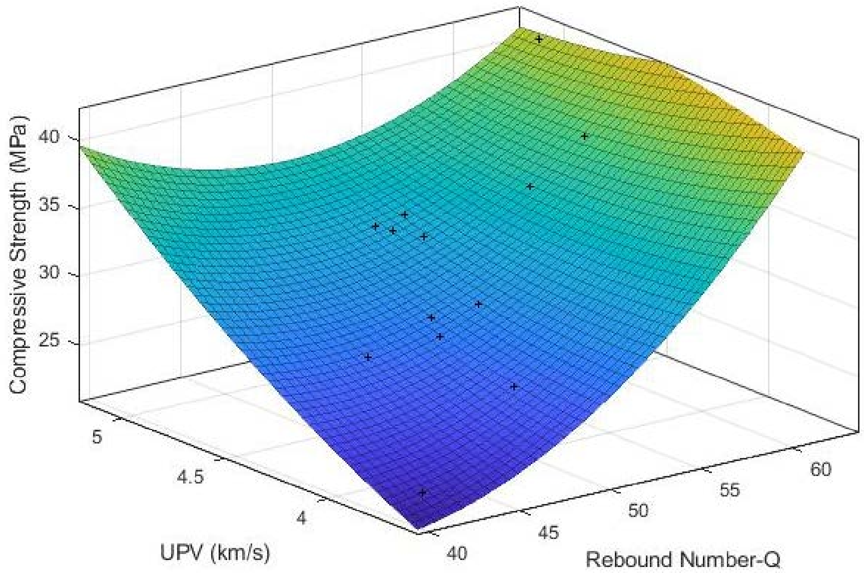


Figure 3. 132: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of 8-story set (C).

Despite the Rebound-R combined correlation for this section and set, the combined correlation for Rebound-Q due to the data distribution which was observed in Fig. 3.132 requires double polynomial curves to cover the data and fit the plate to reach the best result for correlation equation and R-square value. Furthermore, there are a few increases in comparing Rebound-Q`s R-square results with SonReb results and this happens due to the high R-square value which was derived for Rebound-Q vs.

Compressive strength correlation. Moreover, there is 31 % increase in R-square value compared with UPV vs. Compressive strength correlation`s result (see Table 3.32).

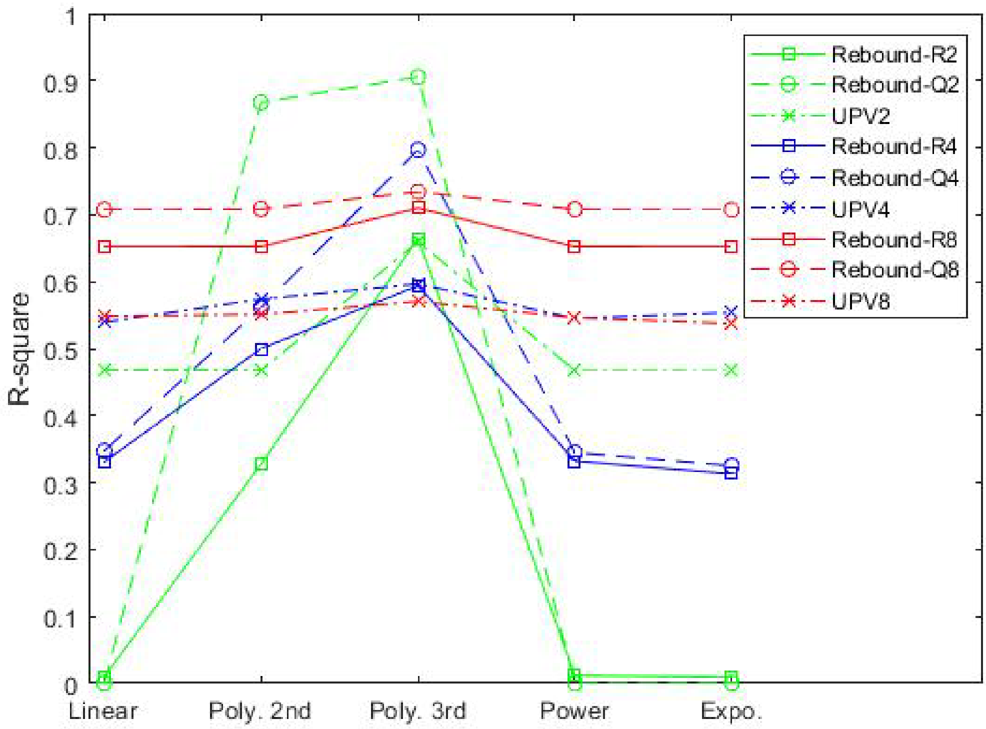


Figure 3. 133: R-square values for different equations, methods, and sets of couple cores (C).

The curves in Fig. 3.133 demonstrates that the behavior of change in R-square values among five different equation and three different NDT methods are close to each other; however, in some cases which are mostly observed for the sets with few numbers of cores, data distribution is special and require polynomial curve to reach the proper fit and high R-square value, the R-square value increase with high rate toward Poly. 2nd and Poly. 3rd degree correlation. However, this changes are not same for UPV measurements due to their special distribution which requires polynomial curves considering EN-13791 suggested curves which are polynomial curves.

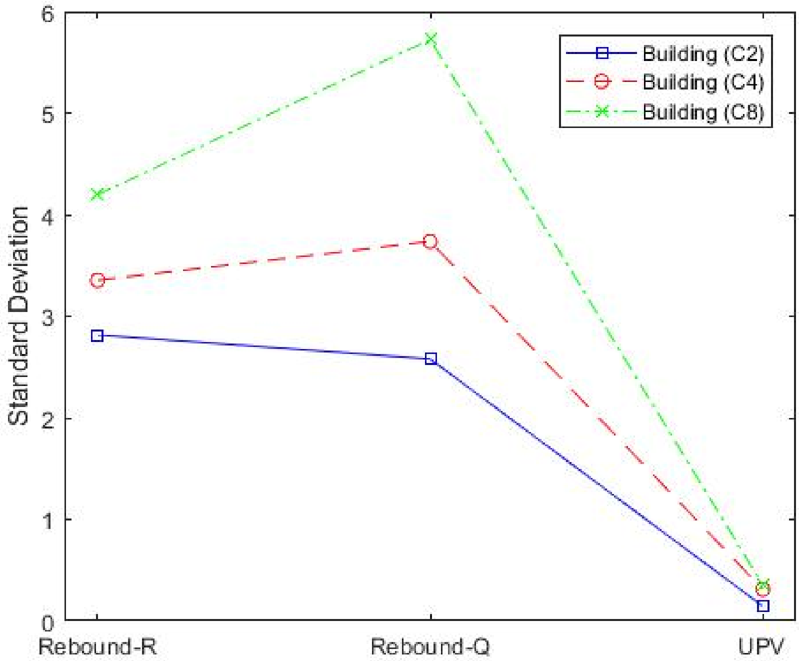


Figure 3. 134: Standard deviation of different sets of story based analysis (C).

Considering the slope of difference from method to the other method, Fig. 134 shows that there is there is a difference among sets change rate and the change in standard deviation occurs differently based on the number of data which is found in each set. It could be found that for lower number of data standard deviations demonstrates less amount and for higher number of data this amount increase (see C2 and C8 in Fig. 134) and behave like other sets in the previously studied scenarios.

3.2.4.4 Fourth scenario-building D

In this part the sets and correlations which was derived based on the fourth scenario was demonstrated in various tables and figures for building D.

Table 3. 33: R-square and standard deviation values of different equations and methods of story based analysis for building (D).

NDT Method	Equation type	2-story		4-story		8-story	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.6819	2.1080	0.6912	2.2234	0.7009	3.7950
	Poly. 2nd	0.8255		0.7821		0.7032	
	Poly. 3rd	0.8503		0.7827		0.7418	
	Power	0.6949		0.7037		0.7028	
	Expo.	0.7068		0.7198		0.7035	
Rebound-Q	Linear	0.2653	4.2883	0.3898	3.8893	0.6361	6.1793
	Poly. 2nd	0.2864		0.4091		0.6372	
	Poly. 3rd	0.3579		0.4381		0.6493	
	Power	0.2658		0.3898		0.6344	
	Expo.	0.2625		0.3942		0.6240	
UPV	Linear	0.2913	0.0859	8.1e-05	0.1693	0.4548	0.2520
	Poly. 2nd	0.5398		0.1772		0.5067	
	Poly. 3rd	0.5917		0.2939		0.5432	
	Power	0.2807		0.0002		0.4355	
	Expo.	0.2760		7.7e-05		0.4164	
SonReb (R)	R 1st , V 1st	0.8170	-	0.7169	-	0.7392	-
	R 2nd , V 2nd	1		0.8528		0.8303	
SonReb (Q)	Q 1st , V 1st	0.4523	-	0.3935	-	0.6754	-
	Q 2nd , V 2nd	1		0.5555		0.7665	

Based on the results which is obtained based on Table 3.33 considering R-square and standard deviation values, 8-story set was selected as optimum set among the three sets and correlation curves and regression equations was demonstrated for this set of story-based analysis for building D.

Table 3. 34: Correlation equations of 8-story set for building (D).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.236R - 18.51$	0.7009	3.7950
	Poly. 2nd	$F = 0.01602R^2 + 0.06472R + 2.658$	0.7032	
	Poly. 3rd	$F = -0.00925R^3 + 1.045R^2 - 37.75R + 461.2$	0.7418	
	Power	$F = 0.05601R^{1.711}$	0.7028	
	Expo.	$F = 4.937\exp(0.04573R)$	0.7035	
Rebound-Q	Linear	$F = 0.9452Q - 17.17$	0.6361	6.1793
	Poly. 2nd	$F = 0.003262Q^2 + 0.6372Q - 9.99$	0.6372	
	Poly. 3rd	$F = -0.002878Q^3 + 0.419Q^2 - 19.18Q + 301.5$	0.6493	
	Power	$F = 0.05048\,Q^{1.632}$	0.6344	
	Expo.	$F = 5.488\exp(0.03376Q)$	0.6240	
UPV	Linear	$F = 10.31\,V - 14.92$	0.4548	0.2520
	Poly. 2nd	$F = 1.776\,V^2 - 4.066V + 13.86$	0.5067	
	Poly. 3rd	$F = 5.31\,V^3 - 62.76\,V^2 + 255.6V - 331.8$	0.5432	
	Power	$F = 2.957\,V^{1.573}$	0.4355	
	Expo.	$F = 5.547\exp(0.3862V)$	0.4164	
SonReb (R)	R 1st , V 1st	$F = 0.9078R + 4.554V - 24.85$	0.7392	-
	R 2nd , V 2nd	$F = 0.9733R - 53.56V - 0.05055R^2 + 0.9401RV + 2.848V^2 + 89.06$	0.8303	
SonReb (Q)	Q 1st , V 1st	$F = 0.7444Q + 3.433V - 21.68$	0.6754	-
	Q 2nd , V 2nd	$F = 0.2585Q - 16.42V - 0.007834Q^2 + 0.3021QV + 0.7229V^2 + 29.13$	0.7665	

Table 3.34 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results was illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The obtained data from Rebound-R measurements and compressive strength tests demonstrate that the data is almost compacted compared other buildings sets; however, the related correlations illustrates high R-square values. Based on Fig. 3.135 the Poly. 2nd degree curve could properly cover all data as well as the other curves (EN 13791). The data was dispersed in a path that even linear correlation curve could acceptably cover the data and provide high reliable R-square values.

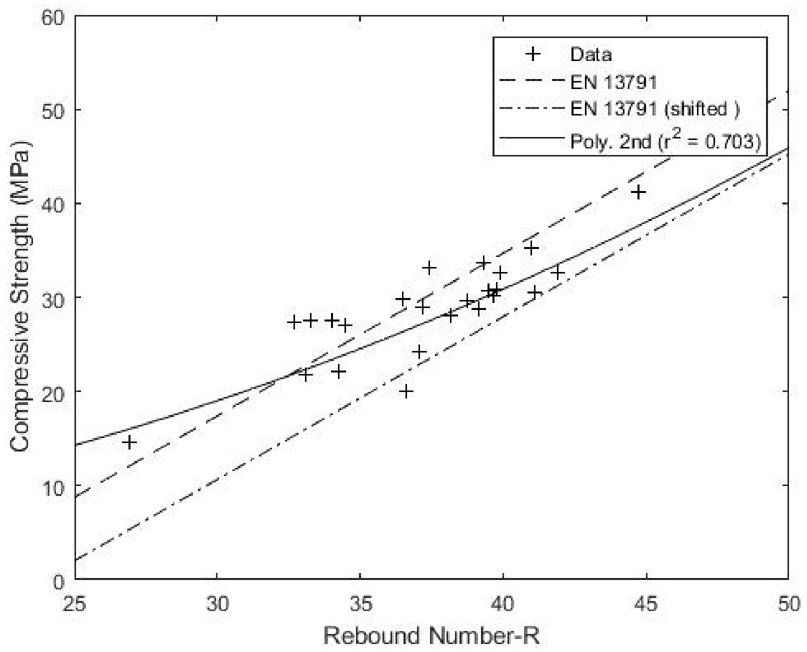


Figure 3. 135: Correlation: Rebound R vs. Compressive Strength of 8-story set (D).

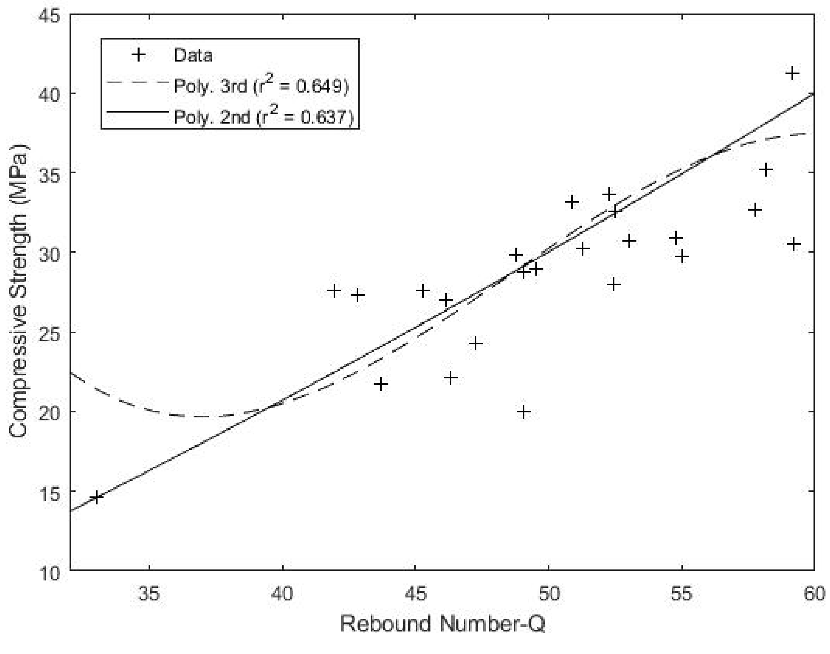


Figure 3. 136: Correlation: Rebound Q vs. Compressive Strength of 8-story set (D).

The data dispersion for the Rebound-Q data was in the path that leads both curves to stay in almost same incline and almost lay on each other. According to Fig. 3.136 the correlation curves which was illustrated by Poly. 2nd and Poly. 3rd are approximately same due to the obtained R-square values (0.637 and 0.649 respectively) for each curve. However, Poly. 3rd degree correlation could give better results due to the path that data dispersed for this set.

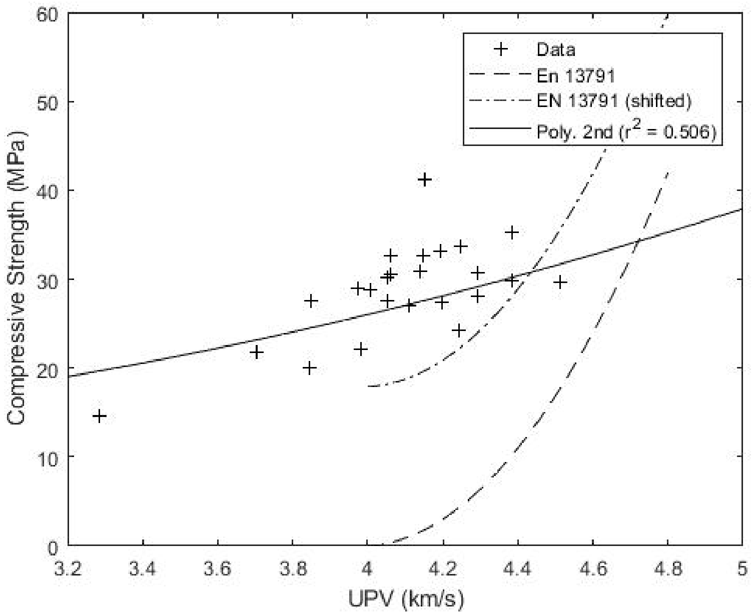


Figure 3. 137: Correlation: UPV vs. Compressive Strength of 8-story set (D).

The UPV measurements for the story based analysis in building D shows better results for UPV-Compressive strength correlations compared other sets and building using Poly. 2nd degree curve with the R-square value of 0.506 which was illustrated in Fig 3.137. However, it should be mentioned that for the part that contains data for EN 13791 range (4-4.8) the shifted EN 13791 demonstrates acceptable cover and proximity to data.

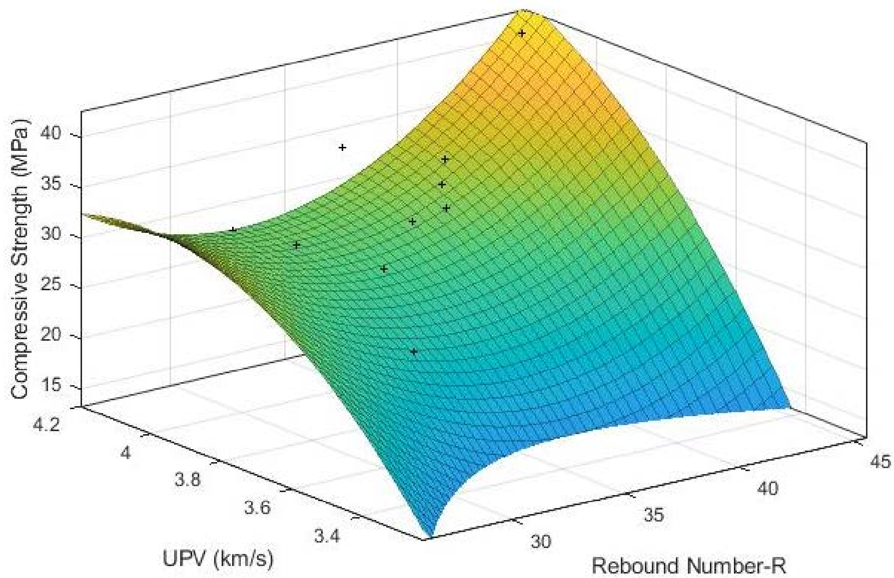


Figure 3. 138: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of 8-story set (D).

The combined method for the 8-story set of building D was observed in Fig. 3. 138 and the related curves demonstrate the double polynomial curve in both directions which helps to reach better correlation in 3-D condition-the double linear correlation has little improvement on R-square values- with higher R-square value (0.8303) which demonstrates a great improvement considering the lower values which was obtained for UPV and Rebound-R (see Table 3.34).

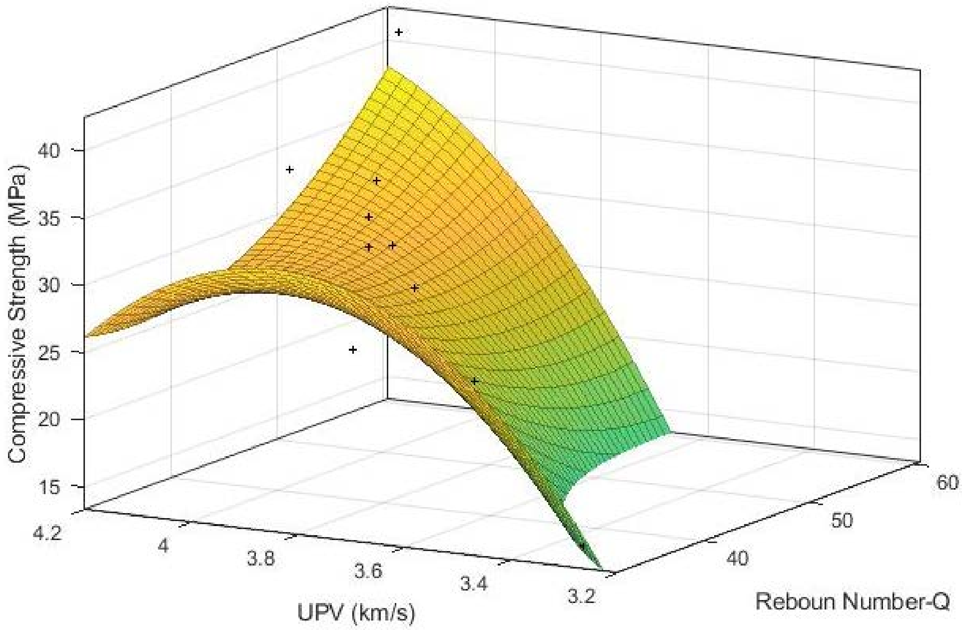


Figure 3. 139: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of 8-story set (D).

Figure 3.139 illustrates the 3-D combined SonReb method for Rebound number-Q vs UPV vs Compressive strength and like the Rebound-R the data dispersion requires to have double polynomial correlation curves to reach the higher and improved R-square value. According to Table 3.34 there is a 51 % increase in R-square value while using double polynomial correlation compared UPV-Compressive strength correlation. In addition, the analysis reveal that there is little increase in R-square value comparing combined polynomial 2.nd degree SonReb method and combined polynomial 1.st degree SonReb method.

The R-square values of four different sets and three various methods were illustrated in Fig. 3.140 for five different correlation equation (regression) types for building D. The behavior of curves in the intended figure, demonstrates that most of the sets and methods almost behave like each other; however, there are some differences such as

(i) the abnormal increase of R-square value in Poly. 2nd and Poly. 3rd degree equations of UPV-Compressive strength correlation in set UPV2 and UPV4 which occurs due to data dispersion that is not suitable for making the linear correlation and require polynomial curves, (ii) the slight increase of R-square value in Poly. 3rd degree equation in some cases, and (iii) almost no difference during equations for Rebound-Q8 which is due to higher R-square values for all equation types.

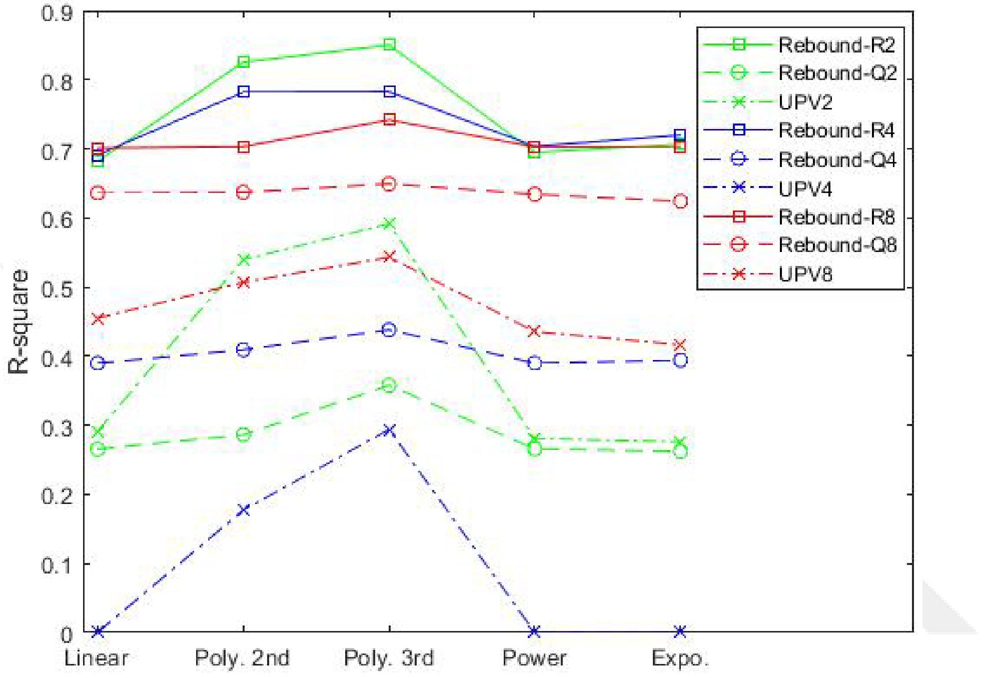


Figure 3. 140: R-square values for different equations, methods, and sets of story based analysis (D).

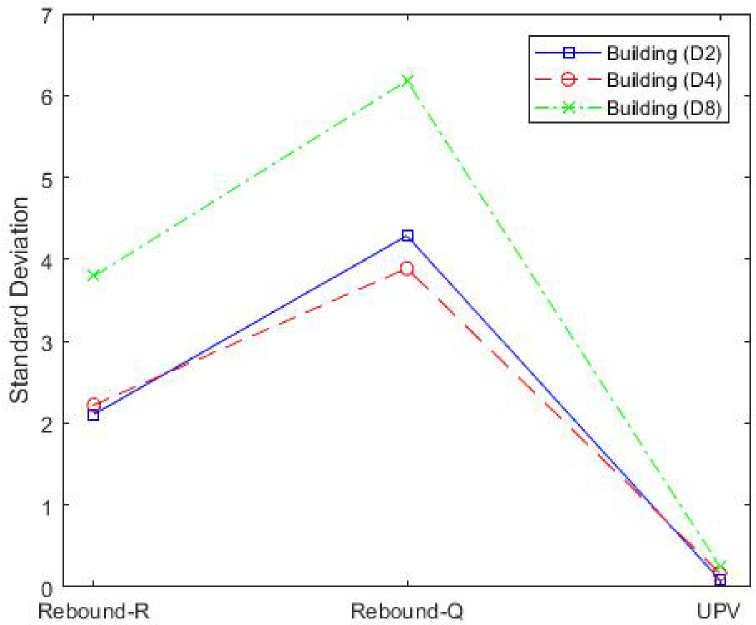


Figure 3. 141: Standard deviation of different sets of couple cores (D).

There is an increase in the standard deviation magnitude in Rebound-Q compared Rebound-R and it is almost same with the previous buildings sets. In addition, it could be found that for the lower number of data standard deviations demonstrates less amount and for a higher number of data this amount increase (see D2 and D8 in Fig. 141) and behave like other sets in the previously studied scenarios. There is almost 50 % increase between the average amount of standard deviation of D2 and D8 and the standard deviation od D8 (see Table 3.34).

3.2.4.5 Fourth scenario-building All

In this part the sets and correlations which was derived based on the fourth scenario was demonstrated in various tables and figures for All building case.

Table 3. 35: R-square and standard deviation values of different equations and methods of story based analysis for building (All).

NDT Method	Equation type	2-story		4-story		8-story	
		r^2	SD	r^2	SD	r^2	SD
Rebound- R	Linear	0.7365	3.9343	0.7617	3.9394	0.7418	4.2987
	Poly. 2nd	0.7376		0.7641		0.7423	
	Poly. 3rd	0.762		0.7642		0.7429	
	Power	0.7297		0.7517		0.7352	
	Expo.	0.7226		0.7388		0.7222	
Rebound-Q	Linear	0.6828	6.2031	0.7346	5.9556	0.7467	6.5225
	Poly. 2nd	0.7026		0.7672		0.7495	
	Poly. 3rd	0.7035		0.7672		0.7499	
	Power	0.6676		0.7153		0.738	
	Expo.	0.6427		0.6872		0.7181	
UPV	Linear	0.2147	0.2788	0.3455	0.3209	0.4172	0.3581
	Poly. 2nd	0.2188		0.3457		0.4182	
	Poly. 3rd	0.2288		0.3539		0.4239	
	Power	0.2127		0.3441		0.4181	
	Expo.	0.2095		0.341		0.4142	
SonReb (R)	R 1st , V 1st	0.7647	-	0.7902	-	0.7514	-
	R 2nd , V 2nd	0.8023		0.809		0.7564	
SonReb (Q)	Q 1st , V 1st	0.6928	-	0.7417	-	0.7516	-
	Q 2nd , V 2nd	0.7269		0.7952		0.7638	

Based on the results which is obtained based on Table 3.35 considering R-square and standard deviation values, 4-story set was selected as optimum set among the three sets and correlation curves and regression equations was demonstrated for this set of story-based analysis for all cases.

Table 3. 36: Correlation equations of 4-story set for building (All).

NDT Method	Equation type	Correlation Equation	r^2	SD
Rebound- R	Linear	$F = 1.543R - 30.35$	0.7617	3.9394
	Poly. 2nd	$F = -0.01993R^2 + 2.969R - 55.54$	0.7641	
	Poly. 3rd	$F = 0.0009249R^3 - 0.1196R^2 + 6.517R - 97.27$	0.7642	
	Power	$F = 0.009632\ R^{2.192}$	0.7517	
	Expo.	$F = 2.884\ \exp(0.05953R)$	0.7388	
Rebound-Q	Linear	$F = 1.002Q - 21.72$	0.7346	5.9556
	Poly. 2nd	$F = -0.03184Q^2 + 4.037Q - 92.92$	0.7672	
	Poly. 3rd	$F = -1.135 \times 10^{-5}Q^3 - 0.03021Q^2 + 3.96Q - 91.71$	0.7672	
	Power	$F = 0.02785\ Q^{1.768}$	0.7153	
	Expo.	$F = 4.64\ \exp(0.03573Q)$	0.6872	
UPV	Linear	$F = 12.76\ V - 26.24$	0.3455	0.3209
	Poly. 2nd	$F = -0.8587\ V^2 + 19.8V - 40.6$	0.3457	
	Poly. 3rd	$F = -12.68\ V^3 + 155\ V^2 - 615.6V + 819.4$	0.3539	
	Power	$F = 1.542\ V^2$	0.3441	
	Expo.	$F = 3.592\ \exp(0.4806V)$	0.341	
SonReb (R)	R 1st , V 1st	$F = 0.9078R + 4.554V - 24.85$	0.7902	-
	R 2nd , V 2nd	$F = 4.287R - 38.85V + 0.03318R^2 - 1.328RV + 11.22V^2 - 5.969$	0.8090	
SonReb (Q)	Q 1st , V 1st	$F = 0.9269Q + 2.304V - 27.52$	0.7417	-
	Q 2nd , V 2nd	$F = 5.903Q - 84.44V - 0.01152Q^2 - 0.9437QV + 15.88V^2 + 34.37$	0.7952	

Table 3.36 shows the different R-square values for the various type of equation which was considered in this project to evaluate and the intended results were illustrated associated with standard deviation values for each test method. The combined SonReb method improve the results of both Rebound-R, Rebound-Q and UPV values.

The data dispersion of the 4-story set of building All for Rebound number-R is suitable for a better correlation compared previous sets and buildings which is observed in Fig. 3.142, both EN 13791 curves and Poly. 2nd correlation curves could properly cover the data and it was proven by the high R-square value of 0.764 for Poly. 2nd degree correlation. In addition according to Table 3.36, the other correlations demonstrate high values for R-square value, also.

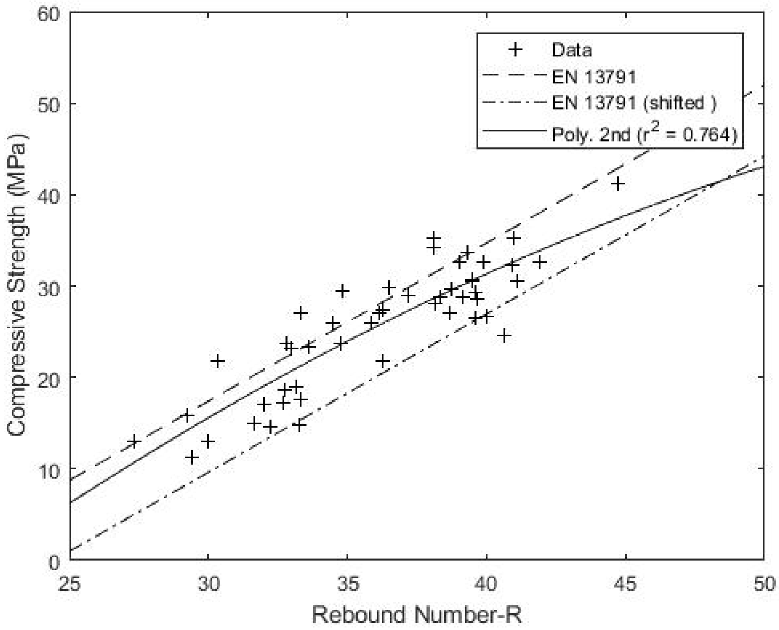


Figure 3. 142: Correlation: Rebound R vs. Compressive Strength of 4-story set (All).

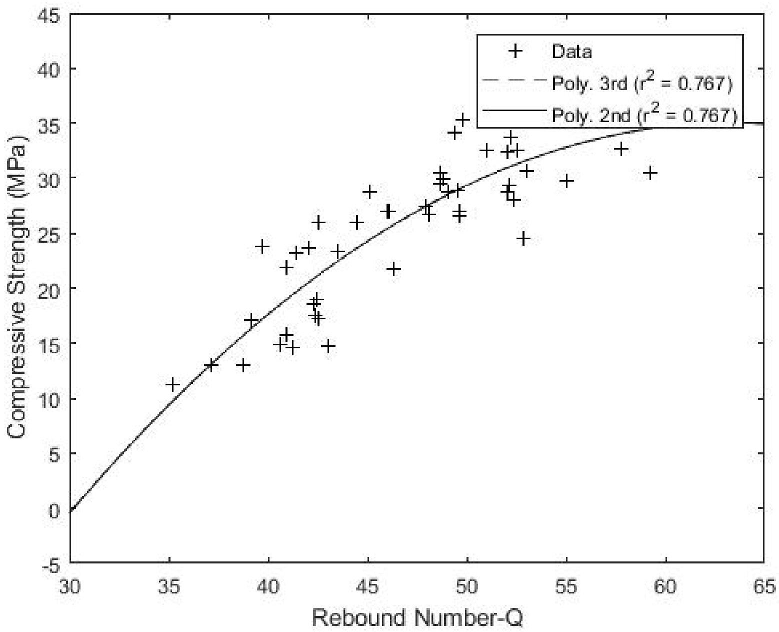


Figure 3. 143: Correlation: Rebound Q vs. Compressive Strength of 4-story set (All).

Figure 3. 143 illustrates the Poly. 2nd and Poly. 3rd degree correlations for Rebound-Q vs Compressive strength with R-square values of both 0.767. In addition, both curves are laid on each other which demonstrates no difference in using Poly. 2nd and Poly. 3rd correlations for this set of data; however, if the simplicity factor was considered for this set of data using Poly. 2nd was suggested.

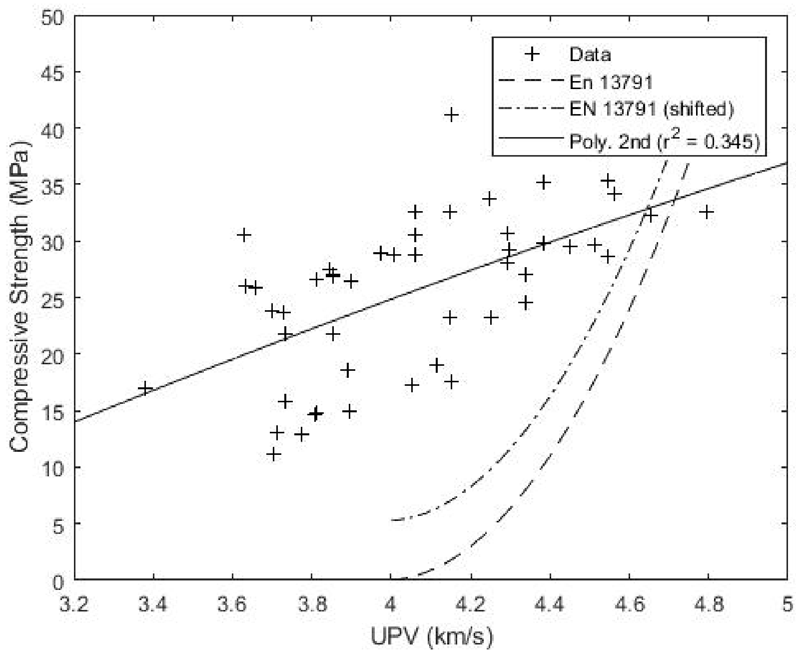


Figure 3. 144: Correlation: UPV vs. Compressive Strength of set CIJ (All).

In some special case when the data dispersion is not in polynomial shape- which is suitable for EN 13791 suggested curve- and the compressive strength values are in high values the EN 13791 curve and it`s shifted curve could not cover the data and the correlation curves by the standards are not reliable anymore as it is observed in Fig 3.144. However, the Poly. 2nd correlation curve by Matlab software could properly cover the data due to free use of this polynomial which is more suitable for this data dispersion and; however, even by using this curve the R-square value still stays in low value (0.345) due to fluctuations in compressive strength values. Furthermore, it should be considered that almost half of data was not included in EN 13791 range but they were considered in Poly. 2nd degree correlation.

The plate which was derived using the combined correlation of Rebound-R vs UPV vs Compressive strength in Fig. 3.145. The shape and slope of both curves demonstrate that both linear and polynomial curve suitable and acceptable for this data dispersion and the results were observed in Table 3.36 which indicates that there is almost 2 % increase while using polynomial curves instead of using a linear plate for this data correlation which is negligible. The R-square values for linear and polynomial correlation curves are 0.7907 and 0.8090 respectively.

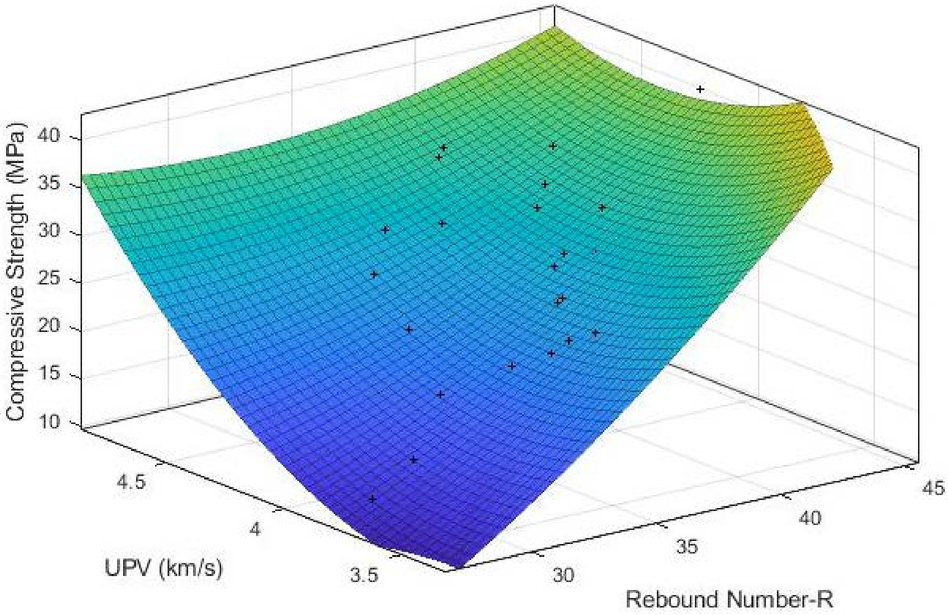


Figure 3. 145: Combine correlation (SonReb method): Rebound R vs. UPV vs. Compressive Strength of 4-story set (All).

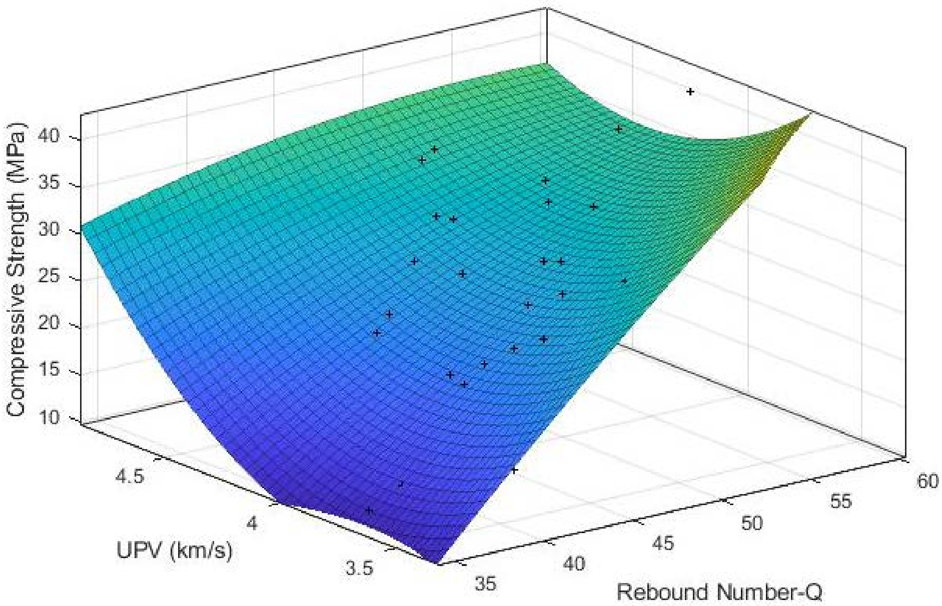


Figure 3. 146: Combine correlation (SonReb method): Rebound Q vs. UPV vs. Compressive Strength of 4-story set (All).

The shape of the plate is so close to the Rebound-R combined SonReb correlation (Fig. 3.144); however, there is high rise at final parts of both sides in the plate which shows the difference in data dispersion between the Rebound-Q combined SonReb correlation and the previous one (see Fig. 3.146). In addition, polynomial correlation is also the proper option for the intended data because there is 7 % increase compared linear one; however, if the simplicity of equations and curves was considered, using linear correlation is more reliable because the difference between linear and polynomial correlations`s R-square values is not such a great amount and could be neglected easily considering the simplicity of the linear plate.

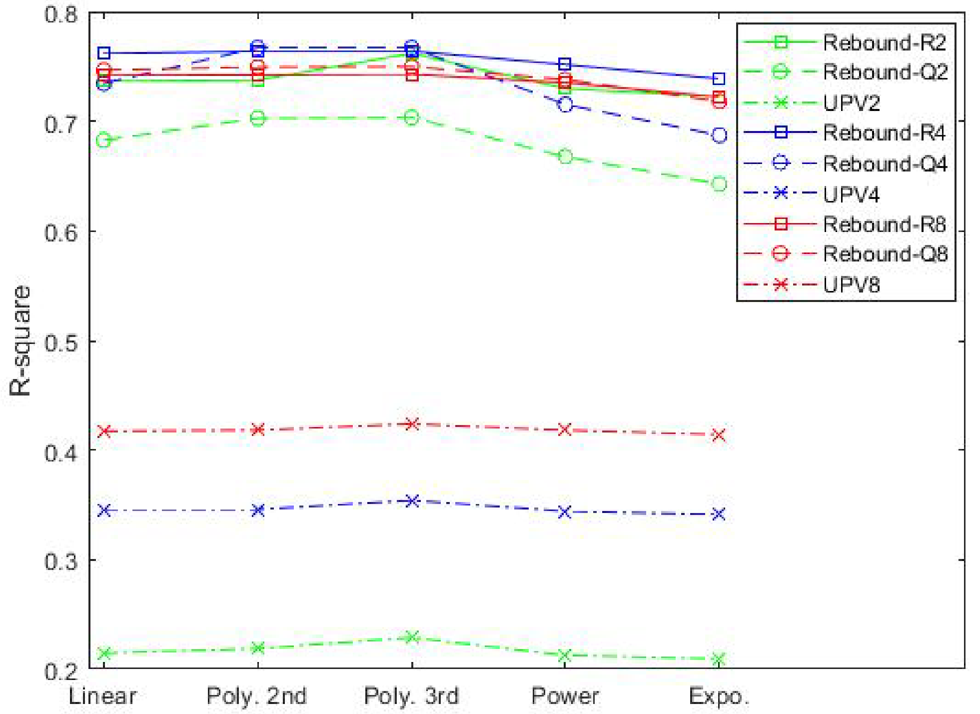


Figure 3. 147: R-square values for different equations, methods, and sets of story based analysis (All).

There is a logical increase from linear to Poly. 2nd degree and then a low slope increase to the Poly. 3rd degree correlation`s R-square values. Then, there is a decrease from Poly. 3rd to Power and then straight continue with an almost equal amount to exponential correlation's R-square value. The R-square values were illustrated in Fig. 3.147 for all four different sets and three NDT methods and the changes of R-square values was observed in the above mentioned figure. However, all of the sets illustrates little changes with low frequencies.

The slope of change between Rebound-R to Rebound-Q and Rebound-Q to UPV for all sets are approximately the same. Furthermore, the standard deviation for Rebound-Q of All8 set in this building reach the highest amount among the sets and other buildings same set and method (see Fig. 3.148) which indicates the reason that why the R-square values are not much greater than Rebound-R, R-square values and the effect of Rebound-Q is less than Rebound-R in SonReb method.

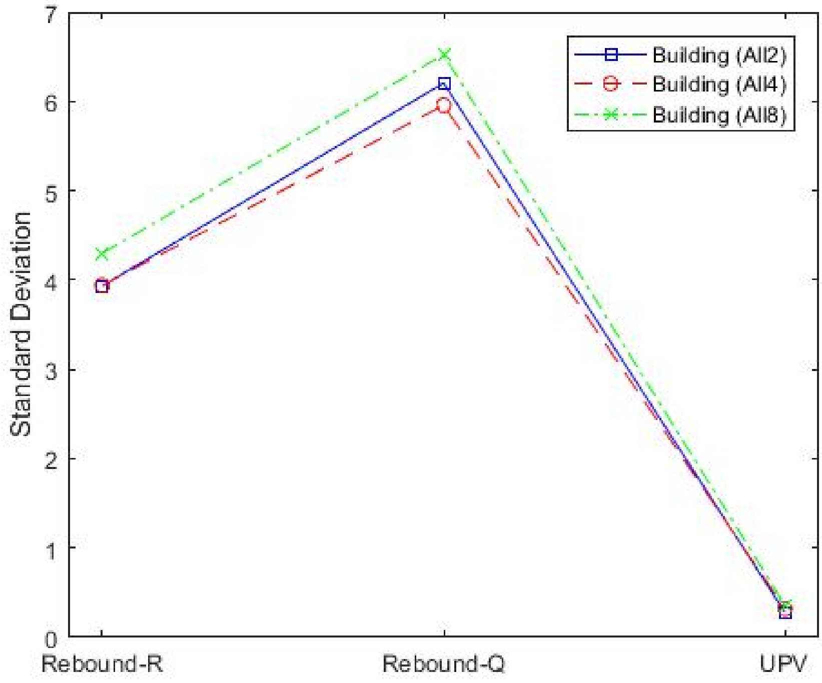


Figure 3. 148: Standard deviation of different sets of couple cores (All).

3.2.4.6 Data analysis

The analysis of all evaluation and comparison of obtained values based on each set of five different data was assessed and discussed in this section based on equation and method which was used for each set.

The correlation results (R-square values) was observed in Fig 3.149 for all different story based sets in all four buildings and considering all together as one case called All for the four different sets in each case. The R-square values illustrate that the behavior of results changes from set to set and building to building; however, considering the overall view in Fig. 3.149 it could be concluded that in the sets that include few numbers of cores the results are abnormal comparing other results in the previous scenarios. In addition, considering the simplicity factor in implementing the NDT methods, using either Rebound-R or Rebound-Q seems more logical due to the results which were obtained during this section analysis and based on the R-square results. Moreover, considering 4-story sets was suggested based o the results which was shown in this figure due to lower frequencies in R-square results.

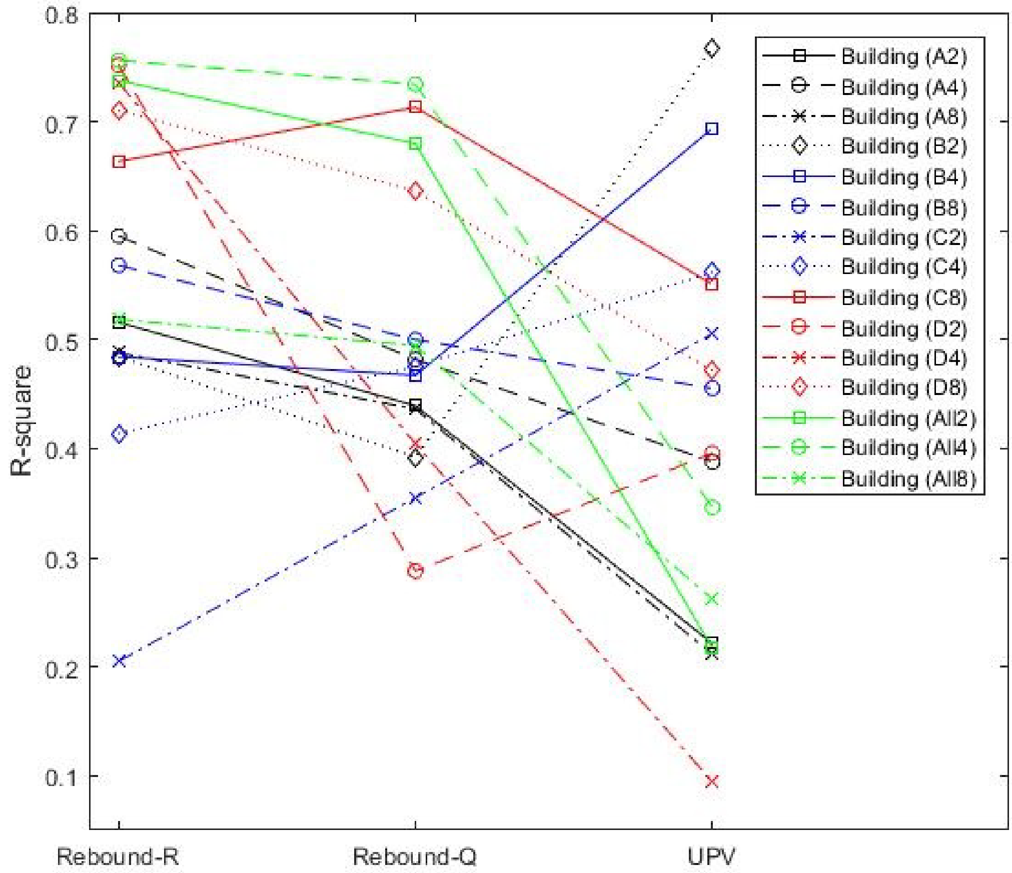


Figure 3. 149: R-square values for different sets based on methods of story based analysis.

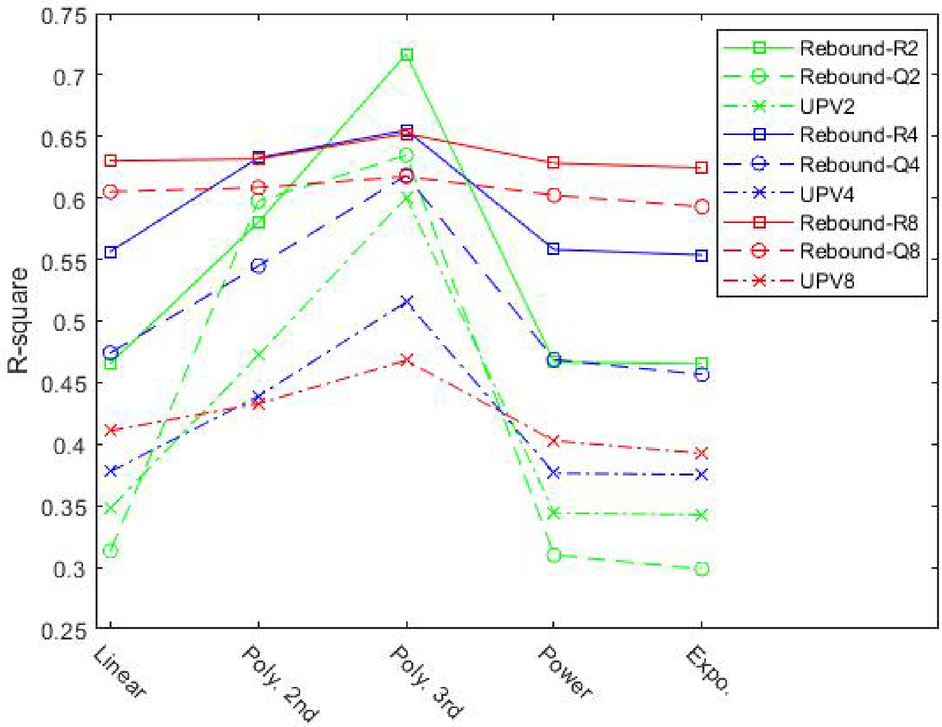


Figure 3. 150: R-square values for different sets based on equations of story based analysis.

The R-square values changes was illustrated in Fig. 3.150 for all three various sets in three NDT methods based on five different equation types. It could be strongly concluded that considering only R-square values, except for the sets with a few numbers of data (core) there are a few increases from linear correlation to the Poly. 2nd degree correlation then, a great increase with high rate toward Poly. 3rd degree correlation; after this point, it was observed that there is a sudden reduction to the power correlation and then a few decreases to the Exponential correlation R-square value. Thus, if the simplicity of equation was neglected during a process it is strongly suggested to use Poly. 3rd degree correlation, but if the simplicity is an important factor in one project Poly. 2nd degree is suitable. However, in some cases such as Rebound-R4 and Rebound-Q4 using linear correlation was suggested due to high reliability.

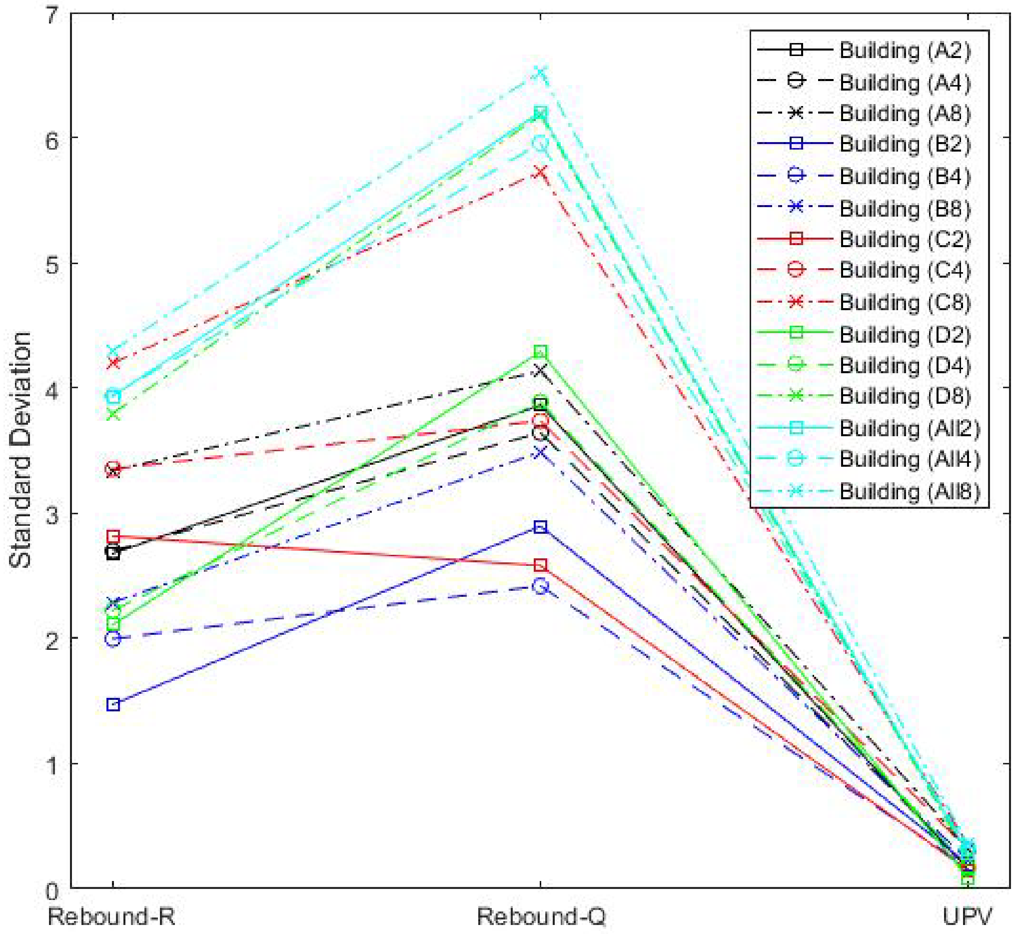


Figure 3. 151: Standard deviation of different sets of couple cores based on method.

Figure 3.151 demonstrates the changes in standard deviation magnitude for all four sets, four buildings and, one All case based on three NDT methods which were used in this project. The behavior and rate of changes observed in previous standard deviation figures and in this figure for all shows that there is a slight increase from Rebound-R to Rebound-Q and then a reduction with high rate from Rebound-Q to UPV standard deviation magnitude; however, in some sets which is mostly the sets with few number of data the amount of increase toward Rebound-Q`s standard deviation is with lower slop and rate which is different with the sets with higher number of data.

4. CONCLUSION AND RECOMMENDATION

This chapter is divided into two sections. In the first section, conclusions, which obtained from different NDT methods, are presented. In the second section, recommendations are presented for further works and correlation that is optimum based on time, results, and simplicity.

The condition assessment of existing RC building is an important issue to reveal the actual condition of the structure and its serviceability. Non Destructive Testing methods could obtain the compressive strength of existing concrete in RC buildings which is an essential factor to assess the condition of existing RC buildings.

NDT methods due to special procedure could significantly increase the speed of process in condition assessment of buildings. Implementing NDT methods associated with coring (which gives the compressive strength of concrete) could increase the speed and decrease the costs of projects which is an important factor in engineering society.

In this real case study four different fifteen-story half-finished specially designed buildings which was produced and left around thirty years ago at Istanbul, Turkey was evaluated using multitude cors and three NDT methods.

In addition, two different hammers used for Rebound numbers, (i) Standard Schmidt (Rebound-R), and (ii) Silver Schmidt (Rebound-Q). The Ultrasonic Pulse Velocity was the other test which was measured for all taken cores. Moreover, compressive tests were implemented in ITU construction material lab using compression machine.
Three cores were taken in each story of four buildings and Rebound-R, Rebound-Q, and UPV measurements was completed at the same place.
The aim of this project is to,

(A) Finding out the optimum core number considering three factors, (i) economy, (ii) accuracy, and (ii) correlation equations simplicity.

(B) Determining the differences between using Rebound-R and Rebound-Q in either correlation with compressive strength or/and in combined SonReb correlations.

The results demonstrate that in similar cases using three cores is the best option; however, it is not economical because it requires lots of energy.

The second scenario which suggested couple cores seem more logical based on the results which was obtained for R-square values comparing other scenarios.

Although, there is some acceptable results in first scenario; however, it is not reliable due to the overall evaluation of results according to the great changes in standard deviations and R-square values.

Finally, based on the results which was demonstrated for the case which all data was gathered in one case and called All for each scenario, it could be strongly concluded that evaluating all cores (considering all building as one case) leads to the best results in standard deviation, R-square values, and data dispersion. Thus, considering some cases together as one case gives more accurate and proper results for compressive strength estimation of RC buildings.

Although, in some sets and cases the R-square values of Rebound-R obtained higher than Rebound-Q but it should be considered that the standard deviation of Rebound Number-Q was much higher than Rebound Number-R in all cases and sets which could negatively affect the results that was find out using Rebound Number-Q in both 2-D correlations using compressive strength and in Combined 3-D SonReb method using compressive strength and UPV measurements.

Furthermore, based on the results which was found in fourth scenario considering both economy and difficulty factors the 4-story sets demonstrates the most proper results and it is suggested for use in correlations in order to compressive strength estimation of whole buildings.

In addition, based on the results which were obtained in this project Rebound-Q seems more accurate and proper equipment and method which could be used for condition assessment of RC building due to better effect in improving the R-square values in combined SonReb correlations when the UPV measurements are too weak.

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APPENDIX

Matlab Codes

The codes which was derived using Matlab Software was shown below for each method type which was used during analysis and assessment of data in this project.

Rebound-R

```
for i=1:n,
    if ‘building name’R (i,1)<24
        ‘building name’REN(i,1)=1.25*‘building
name’R(i,1)-23;
    elseif ‘building name’R(i,1)>=24
        ‘building name’REN(i,1)=1.73*‘building
name’R(i,1)-34.5;
    end
end
a‘building name’R=‘building name’CS-‘building name’REN;
am‘building name’R=mean(a‘building name’R);
deltaf‘building name’R=am‘building name’R-
1.48*(std(a‘building name’R));
c1=@(x) 1.73*x-34.5;
c2=@(x) 1.73*x-34.5+(deltaf‘building name’R);
c3=@(x) ‘Poly. 2nd degree correlation equation’;
hold on
plot(‘building name’R, ‘building name’CS,'k+')
fplot(c1,[25,51],'--','color','k')
fplot(c2,[25,51],'-.','color','k')
fplot(c3,[25,51],'color','k')
box on
xlabel('Rebound Number-R');
ylabel('Compressive Strength (MPa)');
% title('Building (…)');
legend('Data','EN 13791','EN 13791 (shifted )','Poly. 2nd
(r^2 = ‘Value)');
```

Rebound-Q

```
c1=@(x) ‘Poly. 3rd degree correlation equation’;
c2=@(x) ‘Poly. 2nd degree correlation equation’;
hold on
plot(‘building name’Q, ‘building name’CS,'k+')
fplot(c1,[30,65],'--','color','k')
fplot(c2,[30,65],'color','k')
box on
xlabel('Rebound Number-Q');
ylabel('Compressive Strength (MPa)');
% title('Building (…)');
legend('Data','Poly. 3rd (r^2 = 0.511)','Poly. 2nd (r^2 =
Value)');
```

UPV

```
for i=1:n,
    if 4<‘building name’V(i,1) && ‘building
name’V(i,1)<4.8
        ‘building name’VEN(i,1)=62.5*(‘building
name’V(i,1))^2-497.5*‘building name’V(i,1)+990;
    else ‘building name’VEN(i,1)=0;

    end
end
‘building name’vnonz=‘building name’VEN(DVEN==0)=[];
a‘building name’V=‘building name’vnonz-‘building
name’VEN;
am‘building name’V=mean(a‘building name’V);
deltaf‘building name’V=am‘building name’V-
1.48*(std(a‘building name’V));
c1=@(x) 62.5*(x^2)-497.5*x+990;
c2=@(x) 62.5*(x^2)-497.5*x+990+(deltaf‘building name’V);
c3=@(x) ‘Poly. 2nd degree correlation equation’;
hold on
plot(‘building name’V, ‘building name’CS,'k+')
fplot(c1,[4,4.8],'--','color','k')
fplot(c2,[4,4.8],'-.','color','k')
fplot(c3,[3.2,5],'color','k')
box on
xlabel('UPV (km/s)');
ylabel('Compressive Strength (MPa)');
% title('Building (…)');
legend('Data','En 13791','EN 13791 (shifted)','Poly. 2nd
(r^2 = Value)');
```

R-Square value comparison codes:

Equation Based

```
Equtype = {'Linear','Poly. 2nd','Poly.
3rd','Power','Expo.'};
x1 = RsquareR‘building name’;
x2 = RsquareQ‘building name’;
x3 = RsquareV‘building name’;
x4 = RsquareSonRebR‘building name’;
x5 = RsquareSonRebQ‘building name’;
figure
plot(x1,'k-s')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x2,'k--d')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x3,'k:o')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x4,'k-p')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x5,'k--h')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
ylabel('R-square');
% title('R-square of ‘building name’');
legend('Rebound-R','Rebound-Q','UPV','SonReb-R','SonReb-
Q');
```

Method Based

```
RR=[MRSLR;MRSP2R;MRSP3R;MRSPR;MRSER];
RQ=[MRSLQ;MRSP2Q;MRSP3Q;MRSPQ;MRSEQ];
UPV=[MRSLV;MRSP2V;MRSP3V;MRSPV;MRSEV];

Equ = {'Linear','Poly. 2nd','Poly. 3rd','Power','Expo.'};
x1 = RR;
x2 = RQ;
x3 = UPV;

figure
plot(x1,'k-s')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x2,'k--d')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
hold on
plot(x3,'k:o')
set(gca,'XTick',1:5,'XTickLabel',Equtype)
xtickangle(-45);
ylabel('R-square');
% title('R-square of ‘building name’');
legend('Rebound Number-R','Rebound Number-Q','UPV');
```

Standard Deviation codes

```
Method = {'Rebound-R','Rebound-Q','UPV'};
x1 = SD‘building name’;
x2 = SD‘building name’;
x3 = SD‘building name’;
x4 = SD‘building name’;
x5 = SD‘building name’;



figure
plot(x1,'k:h')
set(gca,'XTick',1:3,'XTickLabel',Method)
hold on
plot(x2,'k-->')
set(gca,'XTick',1:3,'XTickLabel',Method)
hold on
plot(x3,'k-.>')
set(gca,'XTick',1:3,'XTickLabel',Method)
hold on
plot(x4,'k--s')
set(gca,'XTick',1:3,'XTickLabel',Method)
hold on
plot(x5,'k-o')
set(gca,'XTick',1:3,'XTickLabel',Method)
ylabel('Standard Deviation');
box on
% title('Standard Deviation of ‘building name’');
legend('Building (A)','Building (B)','Building
(C)','Building (D)','Building (All)');
```

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