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Original Research Paper

Accuracy Investigation of Linear Dynamic Analysis for Estimating Local Deformation Demands of Regular MDOF Systems Using SDOF Inelastic Displacement Ratio

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Abstract

The displacement coefficient method and the inelastic displacement ratio have been the topic of several investigations over the last two decades. Although the vast majority of the previous investigations are related to the single degree of freedom (SDOF) systems, some seismic design and retrofit codes have generalized the results of these investigations for estimating the local responses of structures via the linear elastic dynamic analyses. The question arises whether the use of SDOF inelastic displacement ratios is sufficient for estimating the local responses of multi-degrees of freedom (MDOF) systems? The objectives of this paper are: (i) to review previous investigations on the inelastic displacement ratio for identifying the important factors that affecting the inelastic displacement ratio, and (ii) to investigate the accuracy of linear dynamic analysis for estimating local deformation demands of regular MDOF systems using SDOF inelastic displacement ratio. Results indicate that although the inelastic displacement ratio obtained from SDOF systems provides an acceptable estimation of the global response of MDOF systems, it is not suitable for estimating the local responses of the MDOF systems.

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INTRODUCTION

Estimating seismic deformation demands of structures has acquired renewed importance as a result of the tendency of the profession to move toward performance-based seismic design. Although the nonlinear dynamic analysis is the most accurate method for estimating the seismic deformation demands of a structure, it is not practical for day-to-day design due to the high computational intensity and the difficulty of interpreting its results. To avoid these difficulties, several approximate methods have been developed by researchers for estimating seismic deformation demands. One of the simplest approximate methods is to use the linear dynamic analysis results that are magnified by a displacement modification factor. In the other word, the maximum deformation of an inelastic system is approximated as a product of the maximum deformation of an elastic system with the same lateral stiffness and the same damping coefficient as the inelastic system times a displacement modification factor. This approach which is accepted by ASCE/SEI 41-13 (ASCE, 2014), FEMA 356 (ASCE, 2000), FEMA 440 (ATC, 2005) and many other building codes has been referred to as the coefficient method. The displacement modification factor which is defined as the ratio of the maximum inelastic to the maximum elastic displacement of a single degree of freedom (SDOF) system has been referred to as inelastic displacement ratio.

Several investigations have been conducted to develop the relationships between the peak deformations of inelastic and corresponding linear elastic systems and the influences of many parameters such as period of vibration, level of ductility demand, strength ratio, post-yield stiffness, site conditions, earthquake magnitude, and distance to source have been evaluated and discussed (Veletsos and Newmark, 1960; Veletsos, Newmark and Chelapati, 1965; Newmark and Hall, 1982; Miranda, 2000, 2001; Chopra and Chintanapakdee, 2001, 2004; Riddell, Garcia and Garces, 2002; Miranda and Ruiz-García, 2002; Ruiz-García and Miranda, 2003, 2004, 2006, 2007; Akkar and Miranda, 2005; Chenouda and Ayoub, 2008; Mollaioli and Bruno, 2008; Hatzigeorgiou and Beskos, 2009; Ruiz-García, 2011; Durucan and Dicleli, 2015; Durucan and Durucan, 2016). The vast majority of these investigations are related to the SDOF systems. This is due to the fact that the main goal of most of these investigations was to develop a relationship for estimating the target displacement (roof displacement demand) of structures which is used in the nonlinear equivalent static analysis procedures. In the other word, the coefficient method has been only used to estimate the global response (roof displacement) of the structures and the local responses such as inter-story drift and plastic hinge rotations have been estimated from the nonlinear equivalent static analysis. However, some seismic design and retrofit codes (ASCE, 2000, 2014) have generalized these relationships for estimating the local responses of structures via the linear elastic dynamic analyses (response spectrum or response history). The question arises whether the use of SDOF inelastic displacement ratios is sufficient for estimating the local responses of multi-degrees of freedom (MDOF) systems?

The above question arises from two issues. First, although the contribution of higher modes to the roof displacement is usually weak, their contribution to the local responses could be very important. Secondly, SDOF systems are statistically determinate structures while MDOF systems are statistically indeterminate structures whose post-yield behavior is accompanied by the force re-distribution between their members. Thus, even if the inelastic displacement ratios obtained from SDOF systems provide a good estimation of the global response of MDOF systems, their use to estimate the local responses of the MDOF systems is questionable and should be investigated carefully. The main goal of this paper is to answer the above-mentioned question and this is a distinguishing feature of this research in comparison with the previous researchers. Another objective of this paper is to review previous investigations for categorizing their results based on the factors that may affect the inelastic displacement ratio.

Literature Review

The inelastic displacement ratio has been the topic of several investigations over the last two decades. The vast majority of these investigations are related to the SDOF systems. In the following, the conducted literature review on factors that may affect the inelastic displacement ratio, C, is described.

Spectral regions and characteristic period

A response spectrum is the peak response of a series of simple oscillators of different natural periods, T, when subjected to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variation of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping. The response spectrum is generally divided into three regions so-called acceleration-, velocity- and displacement-sensitive region. Characteristic period, T_c, divides the acceleration-sensitive spectral region from the velocity-sensitive region. The basis of the coefficient method returns to the investigations conducted by Veletsos and Newmark (Veletsos and Newmark, 1960) and Veletsos *et al.* (Veletsos, Newmark and Chelapati, 1965) in 1960s. Using SDOF systems subjected to simple pulses and to three earthquake ground motions, they observed that in the short and moderate period range, the inelastic displacements were significantly higher than their elastic counterparts while in the long period region (low frequency range) the maximum deformation of the inelastic and elastic systems was approximately the same. This observation gave rise to the well-known equal displacement rule for long period structures, which is the basis for estimating maximum deformations in specific spectral regions in most building codes. These investigations provided the basis for the well-known Newmark and Hall (Newmark and Hall, 1982) method to estimate inelastic response spectra from the elastic one. This method provides some relationships for C in different spectral regions. For velocity-sensitive and displacement-sensitive spectral regions (periods longer than T_c) the strength ratio, R, is approximately equal to the demand ductility, μ, which leads to $C \cong 1$ that corresponds to the equal displacement rule, which states that in this period range the maximum displacement of an inelastic system is equal to the maximum displacement of an elastic system with the same lateral stiffness and the same damping coefficient as the inelastic system. For acceleration sensitive regions, the absorbed energy is the same in the inelastic and the corresponding elastic systems at maximum deformation which referred to as equal energy Rule. But For very short periods, the strength ratio is equal to one, which leads to an inelastic displacement ratio equal to demand ductility and the whole base acceleration will be transmitted to the system mass (equal acceleration rule). Similar rules have been observed by many other researchers (Miranda, 2000; Chopra and Chintanapakdee, 2001, 2004; Riddell, Garcia and Garces, 2002; Ruiz-García and Miranda, 2003; Mollaioli and Bruno, 2008). Thus, proper recognizing of spectral regions is the important factor. Inelastic displacement ratios for different site class and ground motions (far-fault and near-fault) are similar over all spectral regions if the period scale is normalized relative to the T_c value (Chopra and Chintanapakdee, 2001, 2004; Ruiz-García and Miranda, 2003). Chopra and Chintanapakdee (Chopra and Chintanapakdee, 2001) concluded that If the design equations for C explicitly recognize the spectral regions (such as Newmark and Hall equation) then the same equations may be applicable to various classes of ground motions (far-fault and near-fault, firm soil and soft soil, smaller magnitude and larger magnitude earthquakes) as long as the appropriate divisions for spectral regions are used.

Velocity spectrum predominant period of the ground motion

Velocity spectrum predominant period of the ground motion, T_g, is defined as the period corresponding to the maximum ordinate in the relative velocity spectrum computed for an elastic SDOF system having 5% damping ratio. Response data for 118 ground motion records on soft soils demonstrated that T_g is an important factor and normalizing periods of vibration by T_g results in a better characterization (smaller dispersion) of deformation demands in structures built on soft soil (Ruiz-García and Miranda, 2006). For systems with periods of vibration smaller than about 0.75 T_g, inelastic displacement ratios are larger than unity and increase linearly with increase in displacement ductility ratio. However, for systems with periods of vibration close to T_g, inelastic displacement ratios are, on average, significantly smaller than unity. This means that, in this spectral region, the well-known equal displacement rule will significantly overestimate lateral displacement demands of inelastic systems practically for any ground motion recorded on very soft soils. For systems with periods of vibration that are more than 1.5 times the T_g, the inelastic displacement ratios are, on average, close to one. With the exception of periods close to T_g, levels of dispersion of inelastic displacement ratios of soft soil sites are smaller than those of firm sites (Ruiz-García and Miranda, 2004, 2006).

Near-fault ground motions and pulse period

Horizontal ground motion components oriented normal to the fault strike recorded within the near-fault region of an earthquake at stations located toward the direction of the fault rupture are typically, but not always, characterized for having a noticeable large velocity pulse. This large velocity pulse is a result of forward-directivity effects that occur when the earthquake rupture moves towards the site at a velocity slightly less than the velocity of the shear waves and the direction of the fault slip is aligned with the site (Ruiz-García, 2011). The pulse period, T_p, is the period associated to the main pulse in the ground velocity time history. T_p is the most important near-fault ground motion characteristic that influences the shape and amplitude of the inelastic displacement ratio, which is particularly true for systems with T shorter than T_g. An investigation based on 40 forward-directivity near-fault ground motions showed that for systems with T smaller than about $0.85T_p$, inelastic displacement ratios are, on average, larger than one and its ordinates increases nonlinearly with increasing R. For systems with T between 0.85 and 2.0 times T_p, inelastic displacement ratios are, on average, significantly smaller than one. For systems with T that are more than $2.0T_p$, inelastic displacement ratios are, on average, close to unity. Moreover, forward-directivity near-fault ground motions with T_g shorter than 1.0 s leads to a local amplification for systems with T near $0.5T_p$ (Ruiz-García, 2011).

From the review of the literature (Bray and Rodriguez-Marek, 2004; Ruiz-García, 2011), it can be found that there is a good correlation between T_p and T_g from a statistical point of view. In general, it was found that the scatter of inelastic displacement ratios for forward-directivity near-fault ground motions is smaller when the period of vibration is normalized with respect to T_g instead of T_p (Ruiz-García, 2011). Although the two components of most far-fault records are quite similar in their demands, the fault-normal component of near-fault ground motions usually imposes much larger deformation and strength demands compared to the fault-parallel component over a wide range of vibration periods. The velocity-sensitive spectral region for the fault-normal component of near-fault records is much narrower, and their acceleration-sensitive and displacement-sensitive regions are much wider, compared to far-fault motions. The narrower velocity-sensitive region of near-fault records is shifted to longer periods (Chopra and Chintanapakdee, 2001). In the acceleration-sensitive spectral region, the average C versus T plots for near-fault ground motions are systematically different than far-fault ground motions. However, if the period scale is normalized relative to the T_c value, they become very similar in all spectral regions (Chopra and Chintanapakdee, 2004).

Peak ground acceleration to peak ground velocity ratio

The ratio of peak ground acceleration to peak ground velocity, A_p/V_p, of ground motions have a significant effect on inelastic displacement ratio, particularly for systems with high ductility levels (Zhai et al., 2007; Yaghmaei-Sabegh, 2012; Durucan and Dicleli, 2015). This ratio is a function of the earthquake magnitude, distance to fault, faulting mechanism and site class. A more recent investigation based on 98 near-fault pulse-type and 306 far-fault ground motion records showed that for earthquakes with small A_p/V_p ratios, inelastic displacement ratios obtained using ground motions recorded on the same NEHRP site are significantly scattered for periods smaller than 2.0 s and for large strength ratio R. Moreover, for smaller A_p/V_p ratios, the inelastic displacement ratios were observed to dramatically increase, particularly for periods smaller than 1.0 s, while for periods larger than 1.5 s, the effect of the A_p/V_p diminishes and inelastic displacement ratio approaches unity (Durucan and Dicleli, 2015). It should be noted that the smaller values for A_p/V_p are related to stronger ground motions.

Faulting mechanism, earthquake magnitude and distance to rupture

In summary, the fault type mechanism is observed to affect the variation of inelastic displacement ratio in the short period range (Durucan and Dicleli, 2015). The earthquake magnitude is found to affect the value of C for periods smaller than 1.0 s and for larger R values (Ruiz-García and Miranda, 2003; Durucan and Dicleli, 2015).

For periods of vibration longer than 1.0 s changes in earthquake magnitude do not affect inelastic displacement ratios (Miranda, 2000; Chopra and Chintanapakdee, 2001, 2004; Ruiz-García and Miranda, 2003, 2004, 2006). With the exception of very near-field sites that may be influenced by forward directivity effects, inelastic displacement ratios are not significantly affected by changes in the epicentral distance or the closest distance to the horizontal projection of the rupture (Miranda, 2000; Chopra and Chintanapakdee, 2001, 2004; Ruiz-García and Miranda, 2003, 2004, 2006; Ruiz-García, 2011). However, the effect of earthquake magnitude on the inelastic displacement ratio is more than that of the site to source distance (Akkar and Küçükdoğan, 2008). In general, it can be said that the effects of faulting mechanism, earthquake magnitude and distance to rupture on inelastic displacement ratio are implicitly taken into account when the effects of the other important factors (i.e. T_c, T_g and A_p/V_p) are considered.

Soil condition and site classes

The effects of soil conditions on the inelastic displacement ratio have been studied by many researchers (Miranda, 2000; Chopra and Chintanapakdee, 2001, 2004; Riddell, Garcia and Garces, 2002; Ruiz-García and Miranda, 2003, 2004, 2006; Mollaioli and Bruno, 2008; Durucan and Dicleli, 2015). From the review of these investigations, soil conditions can be categorized into firm soil (NEHRP site classes B, C, and D) and soft soil (NEHRP site classes E and F). For the firm sites, inelastic displacement ratios were not significantly affected by local site conditions (NEHRP site classes B, C, and D), especially for long periods and when the period scale is normalized relative to the T_c value (Miranda, 2000; Chopra and Chintanapakdee, 2001, 2004; Ruiz-García and Miranda, 2003). However, for soft soils, the predominant period of the ground motion, T_g, is important. Dispersion of C is not constant over the whole normalized period range (T/T_g), tending to increase as T/T_g decreases. In general, the record-to-record variability of C is smaller for ground motions recorded on soft soil than for ground motions recorded on rock or firm soil sites (Ruiz-García and Miranda, 2004, 2006).

Response data for 216 ground motions recorded on NEHRP site classes B, C, and D demonstrated that neglecting the effect of site classes for structures with periods smaller than 1.5 s built on firm sites will typically result in errors less than 20% in the estimation of mean inelastic displacement ratios, whereas for periods longer than 1.5 s the errors are smaller than 10%. Differences are even smaller if $R \leq 3$ (Ruiz-García and Miranda, 2003). In general, it can be said that the effects of soil conditions on inelastic displacement ratio are implicitly taken into account when the effects of the other proper factors (i.e. T_c, T_g and A_p/V_p) are considered.

Hysteretic behavior, post-yield stiffness, and structural degradation

Some researchers have concluded that the inelastic displacement ratio in the acceleration-sensitive spectral region is reduced because of post-yield stiffness(Veletsos, 1969; Xiaoxuan and Moehle, 1991; Chopra and Chintanapakdee, 2004), and increased due to stiffness degradation (Xiaoxuan and Moehle, 1991; Song and Pincheira, 2000; Ruiz-García and Miranda, 2004; Chenouda and Ayoub, 2008; Ruiz-García, 2011) and pinching (Gupta and Krawinkler, 2000; Song and Pincheira, 2000) of the hysteresis loop. On the other hand, at longer periods, the influence of post-yield stiffness ratio, α, on the inelastic displacement ratio is not significant (Chopra and Chintanapakdee, 2004; Ruiz-García and Miranda, 2006; Mollaioli and Bruno, 2008; Ruiz-García, 2011) and the mean responses of constant-ductility systems can be conservatively estimated using the elastoplastic model (Riddell, Garcia and Garces, 2002; Ruiz-García and Miranda, 2003, 2004; Ruiz-García, 2011). Chopra and Chintanapakdee (Chopra and Chintanapakdee, 2004) concluded that ignoring post-yield stiffness in estimating deformation is too conservative for seismic evaluation of existing structures with known strength ratio in the acceleration-sensitive region.

An investigation based on 118 ground motion records on soft soils demonstrated that strength and (or) stiffness degradation can result in considerable increments in deformation demands for systems with periods of vibration that are smaller than $0.5T_g$ of the ground motion. However, for systems with T longer than T_g, maximum inelastic displacement demands of degrading systems tend to be smaller than those of non-degrading systems (Ruiz-García and Miranda, 2006). The effects of stiffness degradation are more important on structures built on soft soil than for structures on rock or firm soil sites (Ruiz-García and Miranda, 2004). Form comparison of the results obtained based on 40 forward-directivity near-fault ground motions (Ruiz-García, 2011) with those obtained from a total 216 ordinary far-field ground motions(Ruiz-García and Miranda, 2003), it can be concluded that the effect of post-yielding stiffness in limiting maximum inelastic displacements demands is less beneficial for SDOF systems exposed to forward directivity near-fault ground motions than for systems subjected to far-field ground motions.

Response data for 80 ground motion records (Chenouda and Ayoub, 2008) demonstrated that for short period SDOF systems the inelastic displacement of the degrading systems were substantially larger than the corresponding displacements of non-degraded systems and collapse is typically observed for very short period systems, even for systems with low strength reduction factors (R). However, for long period degrading systems, collapse is not expected, even for systems with large strength ratios and the well-known equal displacement rule is preserved even for these systems. Moreover, since the behavior of peak-oriented models is dominated by accelerated degradation, which strongly increases the inelastic displacements, the effect of degradation on the maximum inelastic displacements is lower for bilinear models than for modified Clough models. Furthermore, bilinear models have a faster collapse rate than peak-oriented models for short period structures. This is due to the fact that bilinear models dissipate the largest hysteretic energy and, hence, reach their capacity earlier (Chenouda and Ayoub, 2008).

Ductility demand and strength ratio

The available relationships for inelastic displacement ratios in the literature can be categorized into two groups. First, the so-called constant-ductility inelastic displacement ratio relationships expressed as a function of elastic vibration period, T, and ductility demand factor, μ, which is very useful in the preliminary design of new or rehabilitated structures where an estimate of the global displacement ductility capacity is known. Second, the so-called constant-strength inelastic displacement ratio relationships expressed as a function of T and strength ratio, R, which can be used to determine the inelastic deformation of an existing structure with known strength. Thus, these two parameters (R and μ) are the important factors that affect the inelastic displacement ratios. It should be noted that the use of constant-ductility inelastic displacement ratios underestimates the expected value of the maximum deformations in systems with known strength ratio (Miranda, 2001; Ruiz-García and Miranda, 2003).

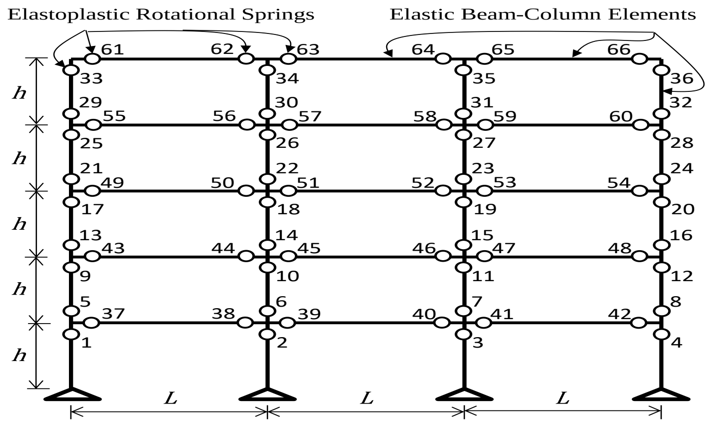
The average values of inelastic displacement ratio greater than one in the acceleration-sensitive spectral region, and increases as the level of ductility demand or strength ratio increases; approximately equal to one in the velocity- and displacement-sensitive regions, essentially independent of μ and R; except for the period range that they fall below unity, decreasing for increasing μ and R (Chopra and Chintanapakdee, 2004; Ruiz-García and Miranda, 2004, 2006). For very short-period systems, inelastic displacement ratio is very sensitive to the yield strength and can be very large even if the strength of the system is only slightly smaller than that required for it to remain elastic (Chopra and Chintanapakdee, 2004).

An Investigation based on 116 ground motion records on soft soils showed that the dispersion on inelastic displacements ratios increases as the level of ductility demand increases (Ruiz-García and Miranda, 2004). Response data for 216 ground motions (Ruiz-García and Miranda, 2003) concluded that dispersion of C is relatively large for R higher than 4 and T smaller than 1.5 s. Limiting periods dividing regions where the equal displacement rule is applicable from those where this rule is not applicable depend primarily on R value and the level of μ. These limiting periods increase with increasing μ and R (Miranda, 2000; Ruiz-García and Miranda, 2003).

A more recent investigation based on 98 near-fault pulse-type and 306 far-fault ground motion records (Durucan and Dicleli, 2015) showed that for strong earthquakes ($A_p/V_p < 10$) the strength ratio significantly affects the variation of inelastic displacement ratios. However, for weak ($A_p/V_p > 20$) and moderate ($10 < A_p/V_p < 20$) earthquakes, the effect of the strength ratio on the variation of C is small and moderate, respectively. The strength ratio has a great influence on the collapse potential of degrading structures (Chenouda and Ayoub, 2008) and the effect of sequential earthquake loading is more pronounced for the systems with larger R values (Durucan and Durucan, 2016).

MDOF systems considered in this study

To investigate the accuracy of linear dynamic analysis for estimating local inelastic deformation of MDOF System using SDOF inelastic displacement ratio, a total of 8 regular MDOF systems having different natural period of vibrations were selected. These MDOF systems were assembled based on regular two-dimensional moment resisting frame structures. In the other words, the geometry, degree of indeterminacy (or redundancy), and deformation of the MDOF systems were considered to be in accordance with the characteristics of two-dimensional moment resisting frames. Since the vibration period (T) and the strength ratio (R) were the main considered variables in this study, some idealizations were made to prevent the effects of other parameters (i.e. hysteresis behavior, plastic hinge length and so on) on the results. Thus, each MDOF system was assembled from elastoplastic rotational springs and elastic beam-column elements as shown in Fig. 1. In such a system it is possible to directly compare the local deformations (spring rotations) obtained from linear analysis with those obtained from the nonlinear analysis. Each frame had 5 stories with the height of 3.2 m and 3 bays with the width of 5 m. The distance of each rotational spring from its adjacent joint was equal to 5% of the bay length (or story height). All the elements except rotational springs were linear elastic. The elastoplastic (elastic-perfectly plastic) model was used to present the hysteresis behavior of the springs. Since the force distribution between members of a system depends on relative stiffness of each member (and the force redistribution depends on relative plastic strength of each member), the stiffness and plastic strength of the springs for each MDOF system were obtained based on a regular steel moment resisting frame structure designed according to usual design codes. These values are shown in Fig. 1. The mass was concentrated at story levels as a line mass along the story beams. The value of the line mass was calculated to achieve the desired value for the natural period. These MDOF systems were different in the natural period of vibration as shown in Fig. 1. As described in the next section, in this investigation, strength ratio (R) was controlled via the earthquake intensity.



$L = 5.0\ m$
$h = 3.2\ m$

Spring	K_θ $(kN.m)$	M_p $(kN.m)$
1 ~ 4	487200	416
5 ~ 12	239164	240
13 ~ 28	124688	155
29 ~ 36	86284	104
37 ~ 42	388584	314
43 ~ 48	273336	245
49 ~ 54	197736	193
55 ~ 60	140381	151
51 ~ 66	97272	116

MDOF Model Name:	F-1	F-2	F-3	F-4	F-5	F-6	F-7	F-8
Line Mass ($kN.S^2/m/m$):	0.285	0.641	1.139	1.779	2.561	3.486	4.553	5.762
Natural Period (S):	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25

Fig 1. Configuration and details of the MDOF systems

Table 1: Main properties of the considered ground motions.

Earthquake Name	Year	Station	M	Mechanism	Rjb (km)	Rrup (km)	V_{s30} (m/s)	PEER Seq. #
Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	Strike-slip	18.2	18.2	192.05	721
Imperial Valley-06	1979	Delta	6.53	Strike-slip	22.03	22.03	242.05	169
Kobe, Japan	1995	Shin-Osaka	6.9	Strike-slip	19.14	19.15	256	1116
Kocaeli, Turkey	1999	Duzce	7.51	Strike-slip	13.6	15.37	281.86	1158
Loma Prieta	1989	Capitola	6.93	Reverse Oblique	8.65	15.23	288.62	752
Duzce, Turkey	1999	Bolu	7.14	Strike-slip	12.02	12.04	293.57	1602
Northridge-01	1994	LA - Saturn St	6.69	Reverse	21.17	27.01	308.71	1003
San Fernando	1971	LA - Hollywood Stor FF	6.61	Reverse	22.77	22.77	316.46	68
Superstition Hills-02	1987	Poe Road (Temp)	6.54	Strike-slip	11.16	11.16	316.64	725
Landers	1992	Joshua Tree	7.28	Strike-slip	11.03	11.03	379.32	864
Chi-Chi, Taiwan	1999	TCU095	7.62	Reverse Oblique	45.15	45.18	446.63	1524
Friuli, Italy-01	1976	Tolmezzo	6.5	Reverse	14.97	15.82	505.23	125
Northridge-01	1994	Beverly Hills - 12520	6.69	Reverse	12.39	18.36	545.66	952
Manjil, Iran	1990	Abbar	7.37	Strike-slip	12.55	12.55	723.95	1633
Hector Mine	1999	Hector	7.13	Strike-slip	10.35	11.66	726	1787

Rjb: Joyner-Boore distance to rupture plane
Rrup: Closest distance to rupture plane

Earthquake ground motions

The set of 15 ground motion records used in this investigation are listed in Table 1. These far-field records were selected from the strong ground motion database of the Pacific Earthquake Engineering Research (PEER) Centre (http://ngawest2.berkeley.edu/site). These records had been also used by FEMA p695 (ATC-63 Project) (ATC, 2009).

To ensure that each MDOF system responds into different inelastic range (nearly elastic, medium and high strength ratio) when subjected to ground motions, each record was scaled to three PGA for the MDOF system. Records with smaller PGA (L-PGA) were used to produce low demand ductility (nearly elastic - $R \cong 2$) in the system; Records with intermediate PGA (M-PGA) were used to produce medium demand ductility in the system ($R \cong 3.5$), while records with greater PGA (H-PGA) were used to produce high demand ductility in the system ($R \cong 5$). It should be mentioned that for each earthquake record, the L-PGA, M-PGA and H-PGA vary for different MDOF systems.

Accuracy evaluation procedure

In this investigation, the roof displacement was considered as the global deformation while the rotations of the springs were considered as the local deformations. Approximate roof displacement for each MDOF system subjected to each ground motion record was calculated as the product of the maximum roof displacement obtained from the linear dynamic analysis times the inelastic displacement ratio obtained from an equivalent SDOF system subjected to the ground motion record. The period and the strength ratio of the equivalent SDOF system were the same as those of the MDOF system. However, for each spring of the MDOF system, two approximate rotations were calculated. The first one ($\theta_{ap.i}$) was calculated based on the inelastic displacement ratio obtained for the roof displacement of the MDOF system. The second one ($\theta^*_{ap.i}$) was computed based on the inelastic displacement ratio obtained from a new SDOF system with the strength ratio equal to the strength ratio of the spring and with the period equal to the period of the MDOF system.

In summary, the accuracy of linear dynamic analysis for estimating global and local inelastic deformations of MDOF Systems using SDOF inelastic displacement ratios was evaluated using the following steps:

1- Perform a nonlinear static analysis (pushover) for each MDOF system to generate the capacity carve of the system and to calculate the capacity base shear of the system (V_y).

2- Perform a linear time history analysis (LTHA) for the MDOF system subjected to each ground motion record to calculate the L-PGA, M-PGA, and H-PGA of the ground motion record for the MDOF system as the following sub-steps:

a. Using the maximum elastic base shear (V_E) obtained from the LTHA and V_y, compute the initial strength ratio as $R_0 = V_E/V_y$,

b. For the desired strength ratio values corresponding to the Low-, Medium- and the high-strength ratio (i.e. R_1, R_2 and R_3, respectively), calculate the corresponding ground motion scale factors as $SF_i = R_i/R_0$ ($i = 1, 2$ and 3).

3- Compute the elastic global deformation (roof displacement), Δ_E, and the elastic local deformations (spring rotations), θ_{Ei}, of the MDOF system subjected to the ground motion record with different intensities (L-PGA, M-PGA, and H-PGA). These deformations can be calculated by multiplying the deformations obtained from LTHA of Step 2 by the corresponding SF_i calculated from Step 2-a.

4- For each spring of the MDOF system subjected to the ground motion record with the specific intensity (L-PGA, M-PGA or H-PGA) calculate the local strength ratios as $R_L = M_E/M_y$, in which M_E and M_y are the maximum earthquake-induced bending moment obtained from LTHA (by considering SF_i) and the bending capacity of the spring, respectively.

5- For each spring of the MDOF system subjected to the ground motion with the specific intensity, if $R_L \leq 1$ then the corresponding SDOF inelastic displacement ratio $C_L = 1$, else (i.e. if $R_L > 1$) compute C_L as the following sub-steps:

a. Generate an SDOF system with the period of vibration equal to the period of vibration of the MDOF system.

b. Perform LTHA for the SDOF system subjected to the ground motion record to obtain the elastic displacement (δ_E) and the elastic force (f_E).

c. Calculate the plastic strength of the SDOF system for strength ratio equal to R_L as $f_y = f_E/R_L$.

d. Perform a nonlinear time history analysis (NTHA) for the SDOF system subjected to the ground motion record to obtain the inelastic displacement (δ_{in}).

e. Compute the inelastic displacement ratio as $C_L = \delta_{in}/\delta_E$.

6- For each spring of the MDOF system subjected to the ground motion with the specific intensity compute the approximate inelastic rotation of the spring as $\theta^*_{ap.i} = C_L\theta_{Ei}$.

7- For the MDOF system subjected to the ground motion with the specific intensity, compute the inelastic displacement ratio (C) using a SDOF system with the period of vibration equal to the period of vibration of the MDOF system and the strength ratio equal to the corresponding R_i (R_1, R_2 or R_3). The sub-steps are similar to the Step 5-sub-steps.

8- Calculate the approximate inelastic roof displacement of the MDOF system as $\Delta_{ap} = C\Delta_E$.

9- Calculate another approximate inelastic rotation for each spring as $\theta_{ap.i} = C\theta_{Ei}$.

10- Perform NTHA for the MDOF system subjected to the ground motion record with the specific intensity to obtain the exact inelastic roof displacement (Δ_{ex}) and the exact inelastic rotation of the springs ($\theta_{ex.i}$).

11- Compute the error indices as defined in the next section for the local (spring rotations) and global (roof displacement) deformations. These indices were computed for all combinations of the ground motions, the period of vibrations, and the strength ratio levels.

12- For each period of vibration and each level of strength ratio, calculate median, average and cumulative percentage of the error indices for statistical interpretation and discussion.

13- Compare the error index values for local and global deformations.

Correlation factor and error indices

Correlation analysis is one of the practical methods which can be used for estimating the accuracy of an analysis method. In this research, the Pearson product-moment correlation coefficient, ρ, is used. The coefficient is computed as follows:

$$\rho = \frac{\sum_{i=1}^{m}\left(Q_i^N - \overline{Q^N}\right)\left(Q_i^L - \overline{Q^L}\right)}{\sqrt{\sum_{i=1}^{m}\left(Q_i^N - \overline{Q^N}\right)^2} \times \sqrt{\sum_{i=1}^{m}\left(Q_i^L - \overline{Q^L}\right)}} \quad (1)$$

Where m is the total number of data. Q_i^N is the NTHA response (such as roof displacement and rotation of springs) for the i^{th} ground motion and Q_i^L is the corresponding estimated response from the approximate LTHA for the i^{th} ground motion. $\overline{Q^N}$ is the average of m NTHA results, and $\overline{Q^L}$ is the average of m approximate LTHA results. This coefficient is the measurement of correlation and ranges between $+1$ and -1. $\rho = 0$ indicates no relationship between the two

measures, $\rho = +1$ indicates the strongest positive correlation possible, and $\rho = -1$ indicates the strongest negative correlation possible.
The well-known relative error index is also used in this research which is calculated as follows:

$$Err_i(\%) = \frac{Q_i^L - Q_i^N}{Q_i^N} \times 100 \quad (2)$$

If the relative error index values are positive, the approximate LTHA procedure overestimates response and vice versa. Another practical measure for estimating the accuracy of the approximate LTHA is the root mean square error, which can be calculated by the following equation:

$$Err_{RMS}(\%) = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{Q_i^L - Q_i^N}{Q_i^N}\right)^2} \times 100 \quad (3)$$

This error index represents the sample standard deviation of the differences between predicted values and actual values.

Statistical results for global responses

The conservatism and accuracy of the LTHA for estimating roof displacement can be presented by scatter plotting the roof displacements estimated by the LTHA versus the roof displacements resulted from the NTHA as shown in Fig. 2.

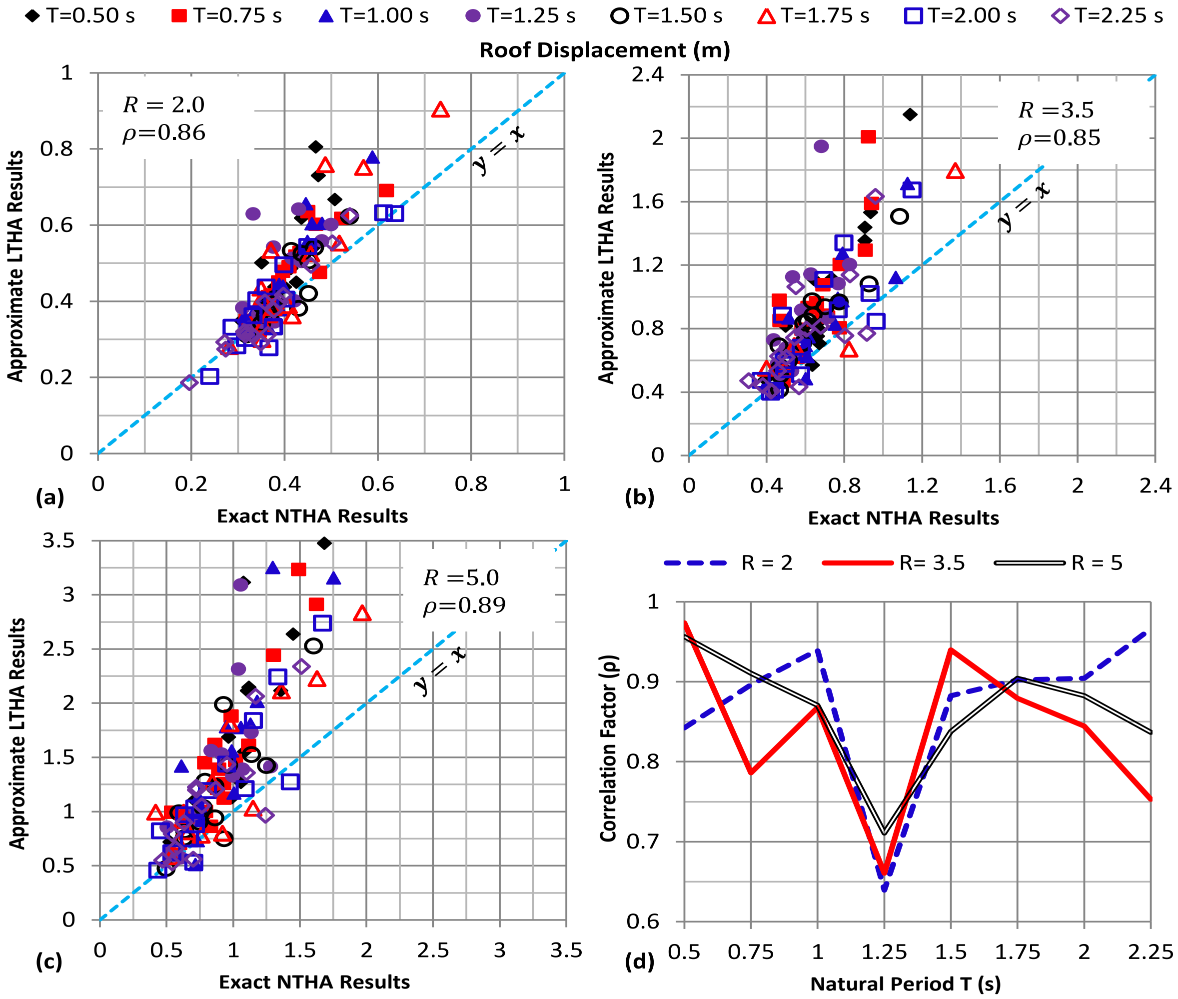


Fig 2. Scatter plots of the roof displacements estimated by the LTHA versus those resulted from NTHA

Each graph of Fig. 2a to Fig. 2c has been plotted for $m = 8 \times 15 = 120$ data points. In these graphs, if the data points are located above the line $y = x$, indicating that the LTHA overestimates roof displacements and vice versa. It can be seen that the tendency of the LTHA to overestimate roof displacement increases with the decrease of the natural period of vibration or with the increase of ductility demand of structures. In general, the LTHA overestimated the roof displacement for about 82% of the cases. For all data points, the correlation factor is 0.92 showing good correlation between the estimated roof displacements and those obtained from the nonlinear time history analysis (individual correlation factor for each MDOF system and each strength ratio is presented in Fig. 2d).

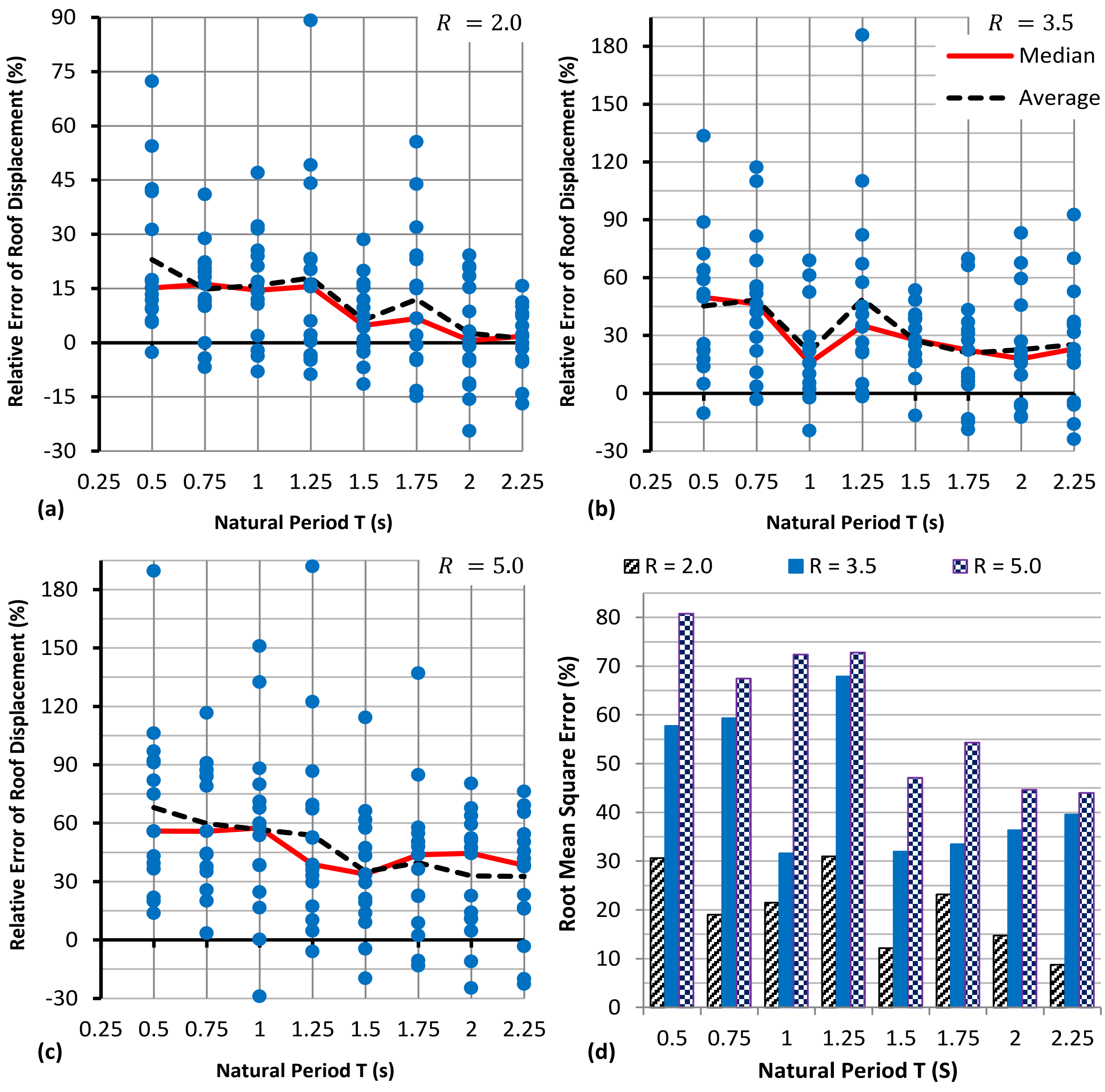


Fig 3. Relative and root mean square errors of the roof displacements estimated by the LTHA Procedure

The relative error distribution of the estimated roof displacement for MDOF systems with different natural period and different strength ratio are shown in Fig. 3a through Fig. 3c. In these graphs, each point corresponds to an MDOF system subjected to a specific earthquake record. The average of the data is shown by the solid line while the dashed line is used to represent the median of the data. It can be seen that the relative error decreases as the natural period of vibration increases. However, by increasing strength ratio the relative error also increases. It can be said that the relative error value for estimating roof displacement via LTHA is on average about 30% on the safe side. Fig. 3d illustrates the root mean square errors of the estimated maximum roof displacements for MDOF systems with different natural period and different strength ratio.

Statistical results for local responses

Fig. 4 illustrates the scatter plots of the spring rotations estimated by different linear dynamic analysis procedure versus spring rotations obtained from the nonlinear time history analyses.

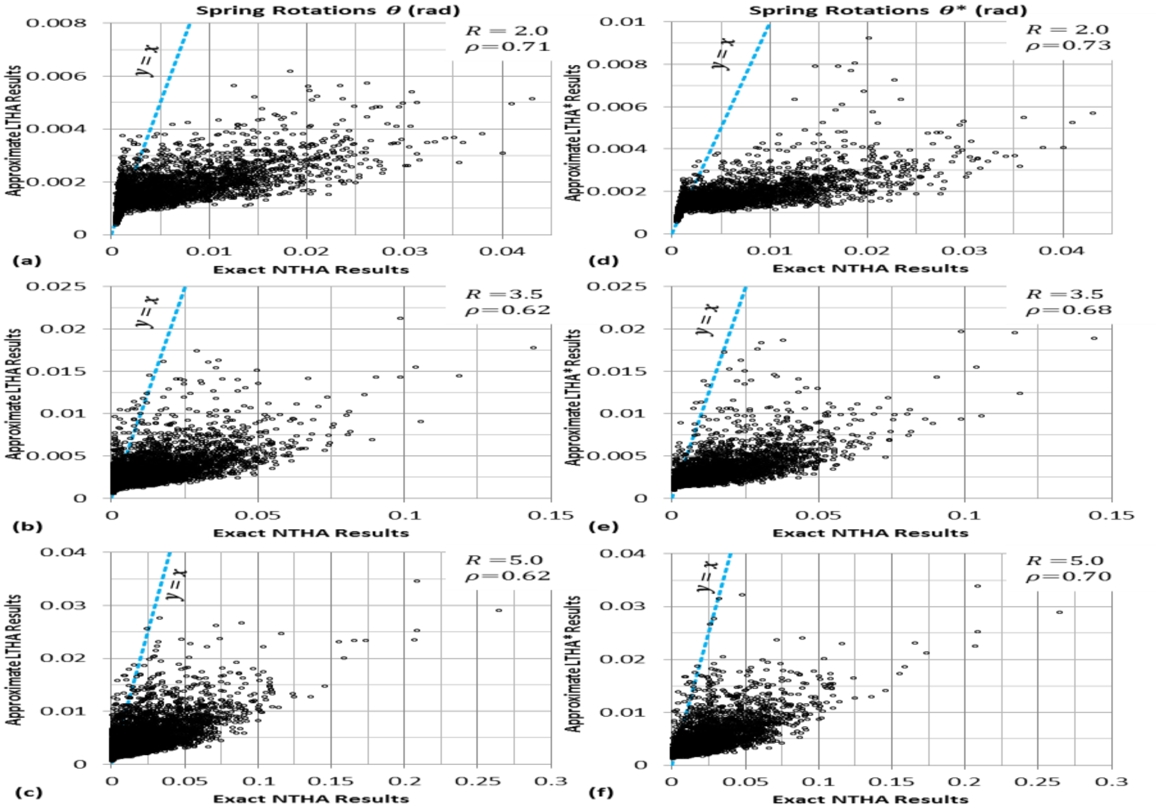


Fig 4. Scatter plots of the spring rotations estimated by the LTHA versus those resulted from NTHA.

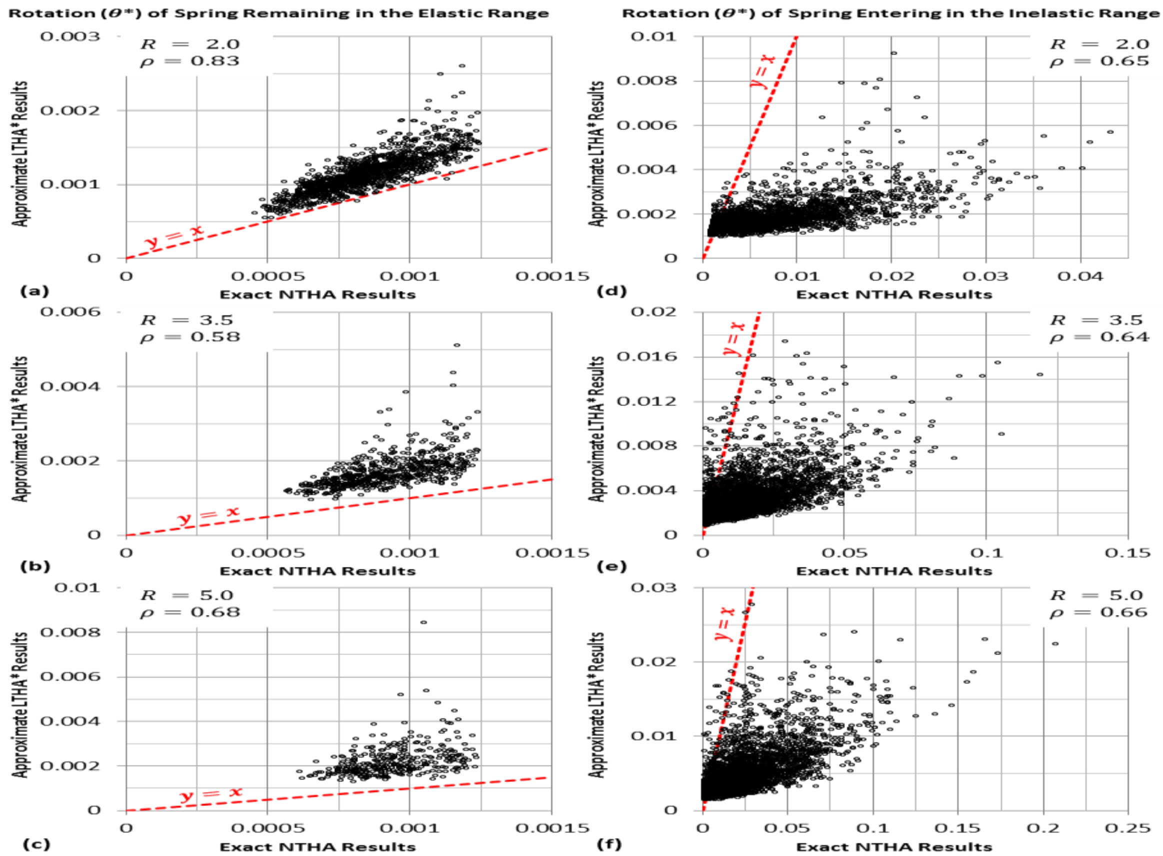


Fig 5. Scatter plots of the spring rotations estimated by the LTHA versus those resulted from NTHA: (a), (b) and (c) for springs remaining in the elastic range, (d), (e) and (f) for springs entering in the inelastic range

One of the approximate procedures used the inelastic displacement ratio obtained for the roof displacement of the MDOF system (Fig. 4a through Fig. 4c); while the second one used the inelastic displacement ratio obtained from a new SDOF system with the strength ratio equal to the strength ratio of the spring and with the period equal to the period of the MDOF system (Fig. 4d through Fig. 4f). Each graph of Fig. 4 has been plotted for $m = 8 \times 15 \times 66 = 7920$ data points. It is clear from these graphs that both approximate procedures tend to underestimate the spring rotations for many cases. In general, the LTHA procedures underestimated the spring rotations for about 75% of the cases. For all data points, the correlation factors for the first and the second LTHA procedures are 0.70 and 0.74, respectively (individual correlation factor for each strength ratio is presented in Fig. 4). It is important to note that the LTHA procedures overestimate the rotation of springs which remain in the elastic range and tend to underestimate the rotation of springs that entering the inelastic range. This issue is shown in Fig. 5 in which the scatter plots are drawn individually for the springs which remained in the elastic range and the springs that entered in the inelastic range.

The relative error distribution of the spring rotations for MDOF systems with different natural period and different strength ratio are shown in Fig. 6. In this figure, the left graphs are related to the LTHA procedure which used the inelastic displacement ratio obtained for the roof displacement of the MDOF system while the right graphs are related to the LTHA procedure that used the inelastic displacement ratio obtained from a new SDOF system with the strength ratio equal to the strength ratio of the spring and with the period equal to the period of the MDOF system. In these graphs, each point corresponds to a spring of an MDOF system subjected to a specific earthquake record. The average of the data is shown by the solid line while the dashed line is used to represent the median of the data. It can be seen that the relative errors for spring rotation obtained from the second LTHA procedure (θ^*) are less than those obtained from the first LTHA procedure (θ). However, by increasing strength ratio the relative error increases. It can be said that the relative error value for estimating spring rotation via LTHA is on average about 35% on the unsafe side. Nevertheless, it is important to realize that dispersion of the relative errors in some cases is substantial, particularly for large levels of inelastic behavior. Thus, when applied to individual ground motion records; the LTHA methods could lead to significant errors in the estimation of local deformation. Fig. 7 illustrates the root mean square errors of the estimated spring rotations for MDOF systems with different natural period and different strength ratio.

The dispersion of the relative errors of spring rotations for two LTHA procedures is explained in Fig. 8. In this figure, the vertical axis of each graph represents the percentage of the springs whose relative errors are higher than those values shown on the horizontal axis of the graph. For each strength ratio (R), two curves are provided. The first curve is presented for the relative error percentage on the safe side and the second curve is developed for the relative error percentage on the unsafe side. For example, in Fig. 8b, it can be observed that, for $R = 3.5$, the spring rotations are underestimated at least by 20% for about 75% of springs and are overestimated at least by 60% for about 15% of springs. This means that for about 10% of the potential plastic hinges, the relative errors of the spring rotations are between -20% and +60%.

Comparison of local and global responses

From the presented results in the previous sections, it is clearly evident that the accuracy of the approximate linear dynamic analysis procedures for estimating local deformations is less than the accuracy of these methods for estimating global deformations. By comparing Fig. 2 and Fig. 4, it can be seen that there is a good correlation between the estimated global deformation and those obtained from the nonlinear time history analysis while for the local responses the correlation is not well. The relative error values for global responses vary between -30% to +180% while these values for local responses vary between -100% to 1200% or between -100% to 750% for the first and second LTHA procedures, respectively. And most importantly, on average, the LTHA overestimates global deformations while this approximate method underestimates local deformations. Dispersion is relatively very high for local responses. Summary of the results is presented in Table 2.

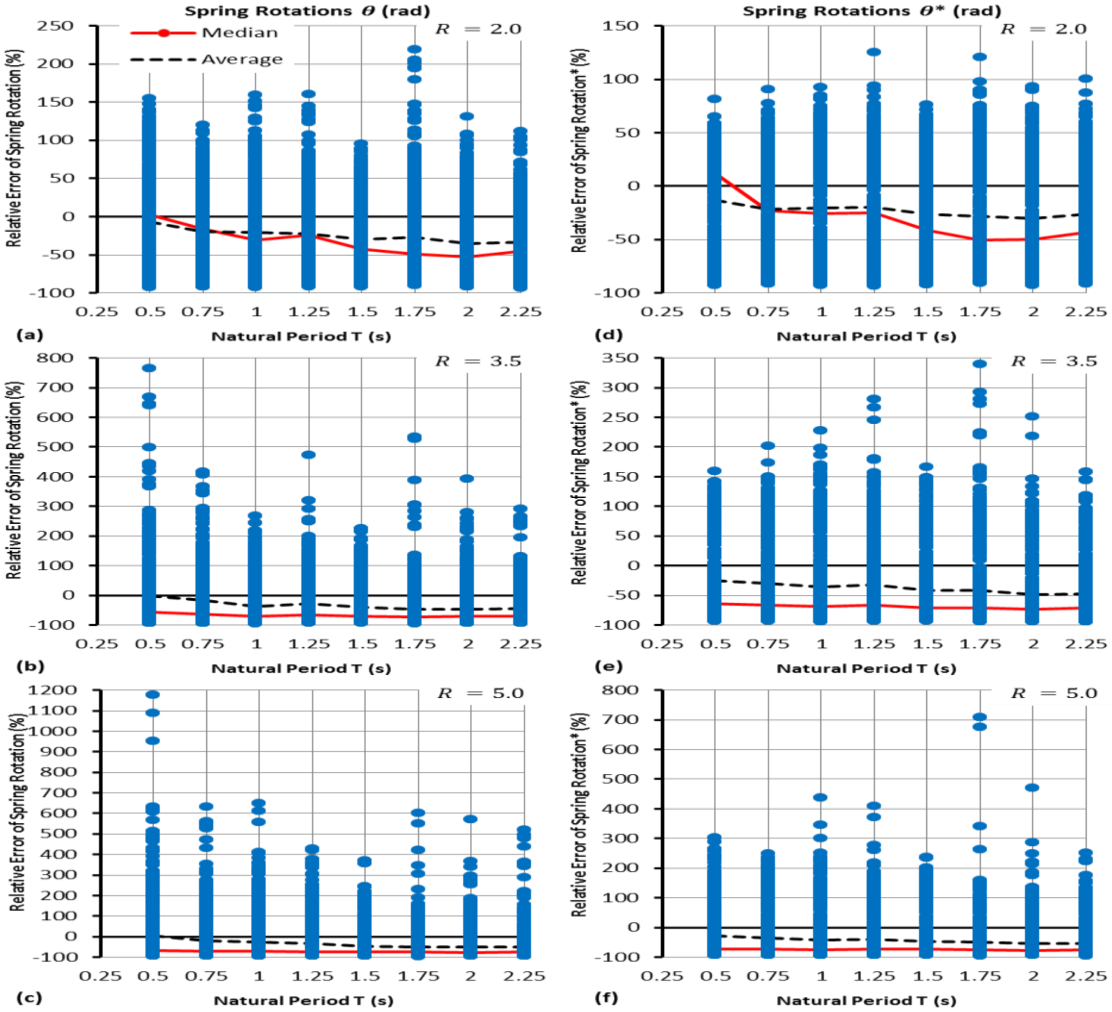


Fig 6. Relative errors of the spring rotations estimated by the LTHA Procedures

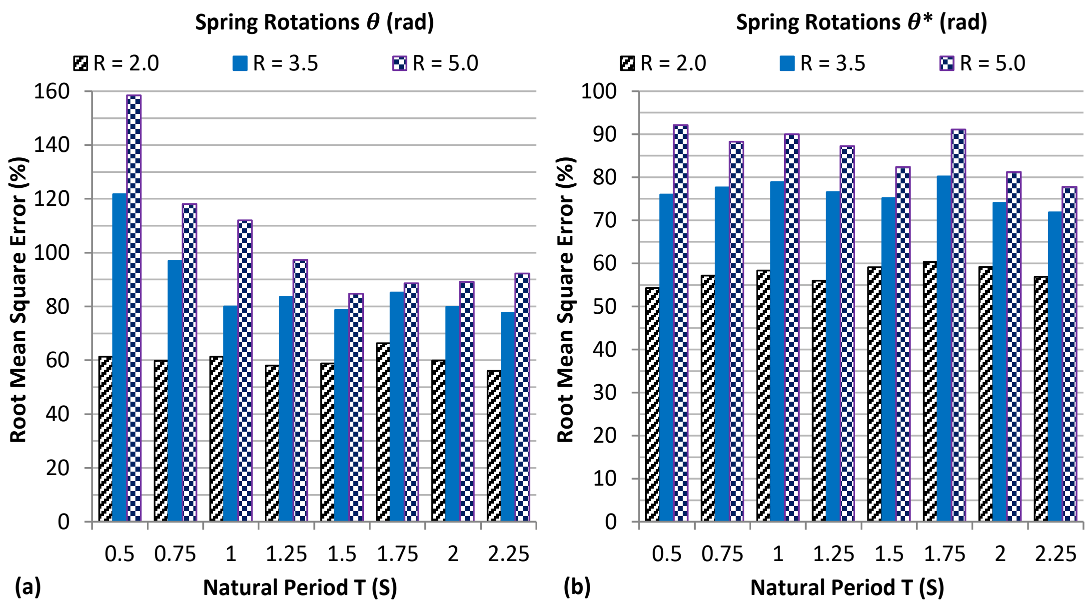


Fig 7. Root mean square errors of the spring rotations estimated by the LTHA Procedures.

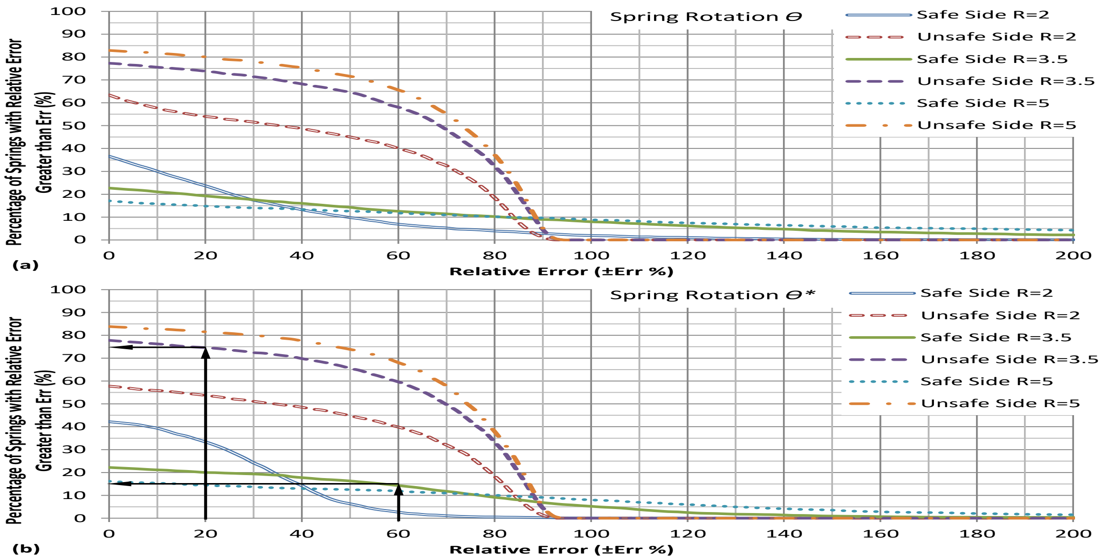


Fig 8. Dispersion of the relative errors of spring rotations

Table 2: Summary of the results obtained for global and local responses.

	Global Deformations					
	$R = 2$		$R = 3.5$		$R = 5$	
Correlation factor (ρ)	0.86		0.85		0.89	
Variation of median of Err	0.6 ~ 16.2		15.8 ~ 49.8		33.8~57.6	
Median of Err for all data	10.03		26.00		44.23	
Variation of RMS errors	8.8 ~ 31.1		31.6 ~ 67.9		44.1 ~ 80.8	
RMS error for all data	21.56		46.75		61.98	
	Local Deformations (θ and θ^*)					
	$R = 2$		$R = 3.5$		$R = 5$	
Correlation factor (ρ)	0.71	0.73*	0.62	0.68*	0.62	0.67*
Variation of median of Err	-53 ~ 2	-50 ~ 12*	-73 ~ -57	-73 ~ -64*	-76 ~ -67	-76 ~ -73*
Median of Err for all data	-35.47	-34.37*	-68.71	-69.72*	73.30	-74.47*
Variation of RMS errors	56 ~ 66	54 ~ 60*	78 ~ 122	72 ~ 80*	85 ~ 159	78 ~ 92*
RMS error for all data	60.32	57.70*	89.06	76.34*	107.59	86.42*

Summary and conclusions

The displacement coefficient method is widely used by the profession to estimate seismic deformation demands of structures. Although this method has been the topic of several investigations over the last two decades the vast majority of these investigations are related to the estimation of roof inelastic displacement demands (global deformations) of structures; and there is a lack of evidence about the ability of the method to estimate local deformations of structures. This paper investigated the accuracy of linear dynamic analysis for estimating local deformations of regular MDOF systems using SDOF inelastic displacement ratio. To attain this objective, 8 regular MDOF systems with different natural period of vibration subjected to 15 ground motion records were selected. To ensure that each MDOF system responds into different inelastic range when subjected to ground motions, each record was scaled to three PGA for the MDOF system. For each spring of the MDOF systems, two approximate rotations were calculated. The first one ($\theta_{ap.i}$) was calculated based on the inelastic displacement ratio obtained for the roof displacement of the MDOF system. The second one ($\theta^*_{ap.i}$) was computed based on the inelastic displacement ratio obtained from a new SDOF system with the strength ratio equal to the strength ratio of the spring and with the period equal to the period of the MDOF system. This investigation has led to the following conclusions:

1- There is a good correlation between the global deformations obtained from the approximate linear dynamic analysis and those obtained from the nonlinear time history analysis. However, the correlation between the local deformations obtained from the approximate linear dynamic analysis procedures and those obtained from the nonlinear time history analysis is not suitable.
2- In general, the relative errors for estimating local deformations are very larger than those for estimating global deformations. The dispersion is also relatively very high for local responses.
3- Based on the median values, the approximate linear dynamic analysis procedure overestimates global deformations while this approximate method underestimates local deformations.
4- It should be noted that the approximate linear dynamic analysis procedures overestimate the local deformations which remain in the elastic range and tend to underestimate the local deformations that entering in the inelastic range.
5- The results presented in this study indicate that although the inelastic displacement ratio obtained from SDOF systems provides an acceptable estimation of the global response of MDOF systems, it is not suitable for estimating the local responses of the MDOF systems.

Abbreviations

ATC	Applied Technology Council
FEMA	Federal Emergency Management Agency
LTHA	Linear Time History Analysis
MDOF	Multi Degree of Freedom
NTHA	Nonlinear Time History Analysis
PEER	Pacific Earthquake Engineering Research
PGA	Peak Ground Acceleration
SDOF	Single Degree of Freedom

Nomenclature

A_p	Peak ground acceleration
C	Inelastic displacement ratio
C_L	Inelastic displacement ratio for local deformation
Err_i	Relative error index
Err_{RMS}	Root mean square error
f_E	Elastic force of the SDOF system obtained from LTHA
f_y	Plastic strength of the SDOF system
M_E	Maximum earthquake-induced bending moment obtained from LTHA
M_y	Bending capacity (plastic moment) of the spring
Q_i^L	Estimated response from the approximate linear dynamic analysis for the i^{th} ground motion
$\overline{Q^L}$	Average of the estimated linear dynamic analysis results
Q_i^N	Nonlinear time history response for the i^{th} ground motion
$\overline{Q^N}$	Average of the nonlinear time history results
R	Strength ratio, defined as the strength required to maintain the system elastic divided by the yield strength
R_i	$i = 0, 1, 2$ and 3 are the initial, low, medium and high strength ratios, respectively
R_L	Local strength ratio, defined as the strength required to maintain the member elastic divided by the capacity strength of the member
SF_i	$i = 1, 2$ and 3 are the ground motion scale factors corresponding to L-, M- and H-PGA, respectively
T	Natural period of vibration of the system
T_c	Characteristic period or corner period, divides the constant acceleration spectral region from the constant velocity spectral region
T_g	Predominant period of the ground motion, defined as the period corresponding to the maximum ordinate in the relative velocity spectrum computed for an elastic SDOF system having 5% damping ratio
T_p	Pulse period of the ground motion, defined as the period associated to the main pulse in the ground velocity time history
V_E	Maximum elastic base shear obtained from the LTHA
V_p	Peak ground velocity
V_y	Capacity base shear obtained from the pushover analysis
α	Post-yield stiffness ratio
Δ_{ap}	Approximate inelastic roof displacement of the MDOF system
Δ_E	Elastic roof displacement of the MDOF system obtained from LTHA
Δ_{ex}	Exact inelastic roof displacement of the MDOF system obtained from NTHA
δ_E	Elastic displacement of the SDOF system obtained from LTHA
δ_{in}	Inelastic displacement of the SDOF system obtained from NTHA
$\theta_{ap.i}$	Approximate inelastic rotation of the ith spring of the MDOF system (based on C)
$\theta^*_{ap.i}$	Approximate inelastic rotation of the ith spring of the MDOF system (based on C_L)
θ_{Ei}	Elastic rotation of the ith spring of the MDOF system obtained from LTHA
$\theta_{ex.i}$	Exact inelastic rotation of the ith spring of the MDOF system obtained from NTHA

μ Demand ductility of the system

ρ Pearson product-moment correlation coefficient

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Original Research Paper

Influence of Waste Rubber Powder on the Physical and Mechanical Behavior of Clay Soils

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Abstract

transportation networks. One major challenge is the presence of weak soils. Clayey soils, due to their high plasticity and deformability, are considered problematic, and improving their geotechnical properties remains a key issue in civil engineering. Recently, the use of waste materials, especially waste rubber powder, as sustainable soil stabilizers has gained attention.This study examines the influence of different contents (5%, 10%, and 15%) and particle sizes (0.5, 1.3, and 3.5 mm) of waste rubber powder on the strength and mechanical behavior of clayey soils. Untreated clay was used as a control, and standard laboratory tests—including Atterberg limits, compaction, consolidated drained direct shear, and unconfined compressive strength—were conducted according to ASTM standards.The results show that adding rubber powder lowers the liquid limit, plastic limit, optimum moisture content, and maximum dry density. Higher rubber content reduced unconfined compressive strength, while the internal friction angle increased and cohesion decreased.Overall, incorporating waste rubber powder offers a sustainable approach to improving the engineering performance of clayey soils while reducing the environmental burden of rubber waste.

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INTRODUCTION

The role and significance of transportation in the social, economic, and political dimensions of modern societies are undeniable. Transportation networks are closely intertwined with key components, such as economic growth, national security, and social equity. With the increasing global population, the demand for suitable soils in infrastructure and road construction has become more pressing. Enhancing the geotechnical properties of soils has therefore emerged as a critical issue in civil engineering.

Clayey soils, from a geotechnical perspective, are considered problematic due to their high plasticity and substantial deformation potential. The strength and stability of such soils are often insufficient for structural applications, making soil stabilization or modification essential. Soil improvement through stabilization is a widely adopted method in design practice, and the addition of specific materials has proven effective in enhancing behavioral parameters such as strength, stress–strain response, and permeability. Traditionally, stabilizers such as lime, cement, and bitumen have been employed for this purpose.

One of the key requirements in large-scale geotechnical projects, especially in infrastructures like highways, dams, and airports, is cost reduction. To address this, the reuse of waste tire products, in shredded or powdered form, has been proposed as a low-cost soil additive. While traditional stabilizers like cement, lime, and bitumen are effective, their relatively high cost has encouraged the search for more economical alternatives. Consequently, the use of industrial waste materials as alternative stabilizers has gained attention in recent years. Recycling rubber waste not only helps mitigate environmental pollution but also offers economic and technical benefits in geotechnical and pavement engineering applications.

For decades, engineers around the world have conducted numerous studies to evaluate the effects of various materials on soil stabilization, aiming to identify viable solutions for improving soil performance. One such material is waste rubber, particularly in the form of shredded or powdered rubber, which has received considerable attention. With the growing population and decreasing availability of suitable construction land, the competition among different ground improvement techniques has intensified. Additionally, the increase in solid waste generation has prompted researchers to explore new approaches for reusing these materials in construction.

The transportation and road construction sectors, which constitute a significant portion of national infrastructure development, are directly linked to the tire industry. In light of increasing environmental concerns and the growing number of waste tires in countries like Iran, addressing this issue has become particularly important. Waste tires decompose very slowly in natural environments. Therefore, in recent years, various methods have been proposed for recycling and reusing waste tires. One promising solution involves incorporating rubber waste into construction materials. Due to the favorable geotechnical properties of waste rubber, its use as a soil additive has the potential to significantly improve the mechanical behavior of clayey soils.

The application of rubber waste in geotechnical engineering, particularly in combination with soil, has gained significant attention in recent decades as a method for mitigating environmental impacts and enhancing certain mechanical properties of soils. One of the main drivers of this approach is the massive volume of scrap tires, which are non-biodegradable and pose major challenges for waste disposal. For instance, approximately 279 million used tires are generated annually in the United States (Massey, 2020), and the numbers in the United Kingdom are estimated at around 25 million passenger car tires and 3 million truck tires per year (Bridgwater & Mumford, 1979). The accumulation of such waste presents serious public health concerns (Jastrzębska, 2019).

Various geotechnical applications have been proposed for shredded rubber, including the reinforcement of soft subgrades in road construction, erosion control, slope stabilization, backfill for retaining structures, embankment materials, asphalt additives, and frost depth mitigation (Nightingale & Green, 1997; Poh & Broms, 1995; O'Shaughnessy & Garga, 2000; Lee et al., 1999; Foose et al., 1996; Tuncan et al., 1998).

Numerous laboratory investigations have indicated that rubber inclusions can improve the mechanical behavior of soils, although the degree of improvement depends on soil type and the amount of rubber added. Yoon et al. (2004) in South Korea showed that using rubber mats in layered systems increased bearing capacity and reduced settlement, with the first layer having the most significant effect. However, the influence decreased as the soil density increased.

In contrast, other studies have reported limited benefits of rubber inclusion. Ghazavi (2004), through consolidated direct shear tests on sand–rubber mixtures, found no significant effect on internal friction angle and emphasized the environmental benefits over mechanical performance. Ayothiraman & Meena (2011) highlighted the advantages of shredded rubber in generating low horizontal stress and high compressibility, which help reduce lateral pressure on retaining walls. However, their results also showed that increasing the rubber content led to a decrease in internal friction angle.

Regarding cohesive soils, the findings have been more inconsistent. Carraro et al. (2013), in a series of triaxial tests on expansive soils, reported a reduction in stiffness modulus and a slight increase in Poisson's ratio. Similarly, Ramirez et al. (2015), in consolidated drained (CD) triaxial tests on clay, observed an increase in shear strength up to a certain level of confining pressure, followed by a decrease at higher pressures.

Cetin et al. (2006) observed that adding up to 40% shredded rubber increased cohesion, but beyond that threshold, cohesion began to decline. Balasooriya et al. (2012) also reported a nonlinear trend in internal friction angle, where cohesion initially decreased and then increased with higher rubber content.

In another laboratory investigation, Hataf & Rahimi (2006) studied the effect of randomly distributed rubber particles in sandy soils. They found that the bearing capacity ratio (BCR) increased up to 3.9 when rubber content reached 40% and the aspect ratio of 4:1 was used. However, exceeding this threshold led to a decrease in BCR.

In a separate study, Moghaddas Tafreshi et al. (2019) examined the behavior of foundations over layered rubber–soil mixtures (RSM) using plate load tests. Results showed that incorporating RSM layers enhanced the bearing capacity and reduced settlement. Numerical analyses further demonstrated that rubber layers improved subgrade resistance by distributing the stress more effectively.

Boushehrian & Hataf (2008) investigated the enhancement of clayey soil bearing capacity using reinforcing materials such as geosynthetics. Their research analyzed the effects of parameters like depth, number, and stiffness of geogrid layers on the bearing capacity of ring footings, which provides a basis for comparing this performance with rubber-reinforced clays. In another study focused on reducing long-term settlements in cyclically loaded footings, Boushehrian et al. (2011) used geosynthetics and grid anchors. Experimental and numerical results on square footings over reinforced sand showed significant reductions in settlement, offering a benchmark for evaluating rubber waste as an alternative reinforcement strategy.

A review of existing literature reveals that most research has focused on non-cohesive soils and primarily used strip-type rubber particles. The majority of studies have targeted strength parameters such as internal friction angle, cohesion, and stiffness modulus. However, the present study specifically investigates the effects of adding waste rubber powder to clayey soils, a combination that has received less attention in past research. This approach not only aims to enhance geotechnical behavior but also offers a sustainable solution for reducing tire waste.

In this study, the effects of various percentages of rubber powder on Atterberg limits, maximum dry unit weight, elastic modulus, internal friction angle, cohesion, and unconfined compressive strength of clayey soils will be evaluated. It is hypothesized that the addition of rubber powder can enhance the unconfined compressive strength of clay and improve its shear strength parameters, including cohesion and internal friction angle.

Research Methodology

Materials and Methods

The objective of this study is to evaluate the effects of incorporating recycled rubber powder into clayey soil on its strength-related properties, including shear strength and unconfined compressive strength. To achieve this goal, a series of standard geotechnical laboratory tests were conducted, including direct shear, unconfined compressive strength (UCS), Atterberg limits, and compaction tests.

Properties of the Materials Used

The soil used in this study is a clayey soil, the particle size distribution of which is presented in Table 1. According to the Unified Soil Classification System (USCS), the soil is classified as CL (inorganic clay of low to medium plasticity).

Table 1: Composition of the soil used in the study

Component	Percentage (%)
Sand	1.20
Gravel	18.10
Fine Courses	80.70

To evaluate the plasticity characteristics of the soil, Atterberg limits tests were conducted. The results showed a liquid limit (LL) of approximately 36.86% (based on 25 blows) and a plastic limit (PL) of approximately 31.22%, indicating moderate plasticity behavior.

The maximum wet unit weight of the untreated soil was approximately 20.3 g/cm³, which decreased to around 18.3 g/cm³ upon the addition of rubber powder. In all specimens, the matrix unit weight (i.e., the unit weight of the soil excluding the rubber volume) was kept constant to ensure both accurate control of rubber content and consistency in total sample unit weight.

The optimum moisture content of the natural soil was determined to be 19.5%.

Recycled Rubber Powder

The recycled rubber powder used in this study was obtained from waste passenger vehicle tires. The powder was classified into three particle size ranges:

1. 0 to 0.5 mm
2. 1 to 3 mm
3. 3 to 5 mm

Figures 1 and 2 illustrate the produced rubber powder derived from the waste tires.

Fig 1. Image of the produced rubber powder.

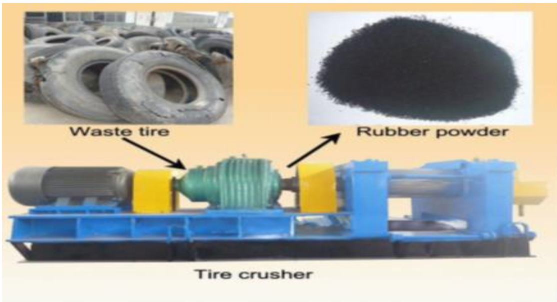

Fig 2. Image of the rubber powder production process.

Sample Preparation

Soil specimens were prepared by mixing the clayey soil with varying weight percentages of rubber powder: 0%, 5%, 10%, and 15%. These percentages were selected based on prior studies and preliminary laboratory test results. Previous research has reported the use of rubber content up to 25% in similar applications.

Table 2 summarizes the specifications of the tested soil–rubber mixtures.

Table 2: Specifications of the Tested Samples

Sample No.	Rubber Particle Size (mm)	Rubber Content (%)	Initial Moisture Content (%)
1	0 (Control)	0	3 – 5
2	0 – 0.5	5	3 – 5
3	1 – 3	5	3 – 5
4	3 – 5	5	3 – 5
5	0 – 0.5	10	3 – 5
6	1 – 3	10	3 – 5
7	3 – 5	10	3 – 5
8	0 – 0.5	15	3 – 5
9	1 – 3	15	3 – 5
10	3 – 5	15	3 – 5

Research findings

Effect of Rubber Powder Content on Atterberg Limits

Liquid Limit (LL)

To perform the liquid limit test, the selected clayey soil was first passed through a No. 40 sieve and washed with water to remove impurities. The oven-dried soil samples were then mixed with different percentages of water and tested using the Casagrande apparatus under standard impact procedures. After recording the number of blows, the corresponding moisture content was calculated for each specimen. This procedure was repeated for both untreated soil and mixtures containing 5%, 10%, and 15% rubber powder, with three different particle sizes.

The test results indicate that the addition of rubber powder generally reduces the liquid limit of clay soil. The most significant reduction was observed in mixtures containing 10% rubber content.

For 0.5 mm particles, the LL decreased by 2% at 10% rubber content, but then increased by 1.1% at 15% rubber. For 1–3 mm particles, a 0.25% decrease was observed at 10% content, followed by an increase of 1.4% at 15%. For 3–5 mm particles, the LL decreased up to 4.5% at 5% rubber and decreased by 1% at 15%.

In general, adding up to 10% rubber powder improves (reduces) the liquid limit. Additionally, increasing particle size tends to increase the final LL values. This may be attributed to a higher void ratio and reduced cohesion between soil particles as rubber size and content increase.

Rubber powder contains non-polar and hydrophobic particles and does not tend to absorb water like clay. By replacing part of the clay particles (which are hydrophilic), the amount of water required to reach a fluid state is reduced.

Plastic Limit (PL)

To determine the plastic limit, approximately 20 grams of soil were taken from previously prepared samples and manually rolled into a thread until it reached a diameter of 3 mm, at which point cracking was observed. The corresponding moisture content was then measured. The results of these measurements are summarized in Table 3.

Table 3 presents the plastic limit (PL) values for untreated clay and mixtures containing varying percentages and sizes of rubber powder.

Table 3. Plastic Limit Values for Pure Clay and Rubber-Soil Mixtures with Different Rubber Sizes and Contents

Rubber Particle Size (mm)	Rubber Content (%)	Plastic Limit (PL %)
(Pure clay)	0	31.22
0 – 0.5	5	29.88
0 – 0.5	10	29.10
0 – 0.5	15	29.10
1 – 3	5	28.89
1 – 3	10	28.14
1 – 3	15	28.00
3 – 5	5	28.01
3 – 5	10	26.94
3 – 5	15	25.05

The results indicate that the addition of rubber powder in various sizes generally leads to a reduction in the plastic limit (PL) of clay soil, although the degree of reduction depends on both the rubber content and particle size.

Rubber powder reduces the cohesion between clay particles, causing the soil to crack at lower moisture levels and reduces its plastic Limit.

Effect of Rubber Powder Content on Compaction Parameters

As expected the optimum moisture content of clay (OMC) decreased with the addition of rubber powder. The maximum reduction was approximately 2.5%. Both the wet unit weight and dry unit weight of the clayey soil consistently decreased with increasing rubber content. Specifically, the wet unit weight dropped from 20.3 g/cm³ to 18.3 g/cm³ as the rubber content increased. These results are summarized in Table 4.

Table 4. Effect of Rubber Content onOptimum Moisture Content and Soil Unit Weight

Rubber Content (%)	Optimum Moisture Content (%)	Wet Unit Weight (g/cm^3)	Dry Unit Weight (g/cm^3)
0	19.5	20.3	17.0
5	18.5	19.5	16.5
10	18.0	18.8	15.9
15	17.0	18.3	15.64

The compaction test results revealed that increasing the percentage of rubber powder led to a reduction in both the optimum moisture content (OMC) and the maximum dry unit weight. This reduction can be attributed to the lower specific gravity of rubber particles and the increase in soil porosity caused by the presence of these lightweight additives. They also have elastic properties and, under pressure, limits the compaction of the soil. In the other hand, since rubber powder is waterproof, achieving proper compaction requires less water to reach the maxim dry density.

Specifically, the optimum moisture content decreased from 19.5% (for pure clay) to approximately 17%, while the wet unit weight dropped from 20.3 g/cm^3 to 18.3 g/cm^3 with increasing rubber content. At higher percentages of rubber powder (usually more than 10-15%), the reduction in density becomes more noticeable.

Effect of Rubber Powder on Shear Strength Parameters

Clay samples containing 0%, 5%, 10% and 15% of rubber powder and granules were prepared at their optimum moisture content and compacted in three layers, with 25 blows per layer using a standard Proctor hammer. The target dry unit weight of all specimens was maintained at 1.8 g/cm^3.

Following 18 hours of saturation under vertical stress, the direct shear tests were performed at a displacement rate of 0.048 mm/min, and under vertical (normal) stresses of 0.5, 1.0 and 1.5 kg/cm^2. These stress levels were used to calculate the internal friction angle (ϕ) and cohesion (C) of each mix.

Table 5 summarizes the shear stress values obtained from direct shear tests for both the untreated clay and rubber-treated samples with various rubber sizes and contents.

Table 5. Shear Stress (τ) Results Under Three Normal Stresses for Rubber-Clay Mixtures

Rubber Content (%)	Rubber Size (mm)	=0.5 $kg/cm^2\sigma$	=1.0 $kg/cm^2\sigma$	=1.5 $kg/cm^2\sigma$
0	—	0.58	0.73	0.95
5	0–0.5	0.53	0.74	0.91
5	1–3	0.54	0.81	1.02
5	3–5	0.56	0.92	1.09
10	0–0.5	0.59	0.85	1.03
10	1–3	0.53	0.84	1.07
10	3–5	0.57	0.93	1.21
15	0–0.5	0.53	0.72	0.97
15	1–3	0.58	0.84	1.15
15	3–5	0.54	0.81	1.14

The direct shear test results indicate that adding rubber powder influences shear strength behavior in a nonlinear manner, depending on both particle size and rubber content.

The corresponding Mohr–Coulomb parameters (ϕ and C) were calculated using the linear fit of shear stress vs. normal stress data, and are presented and discussed.

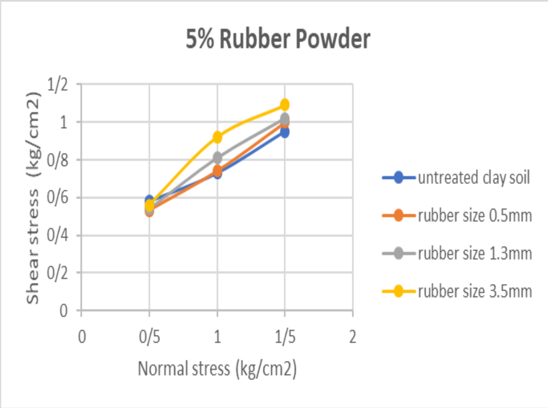

Fig 3. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 5% rubber powder at different particle sizes

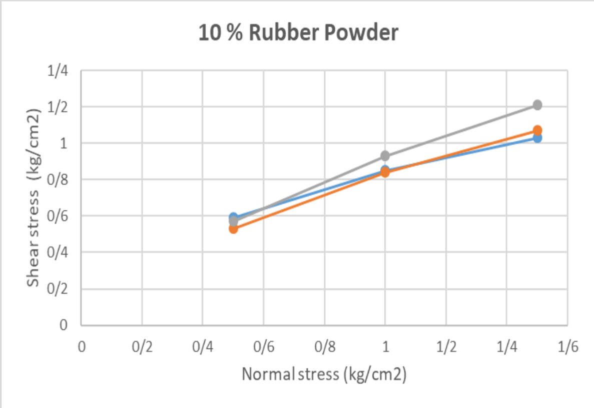

Fig 4. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 10% rubber powder at different particle sizes

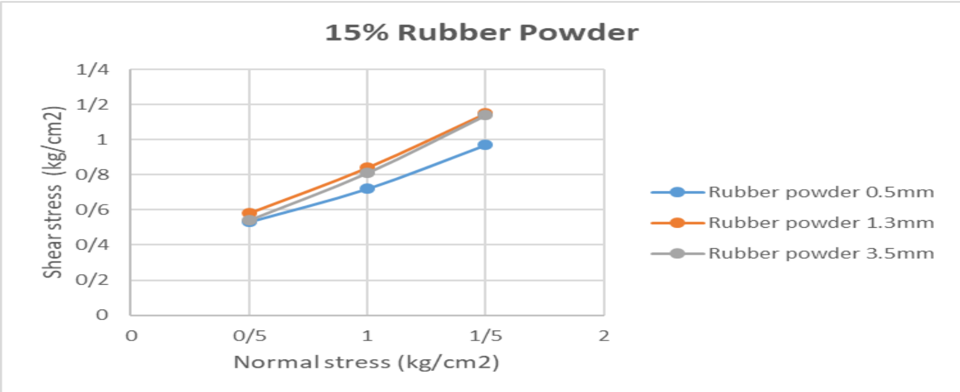

Figure 5. Shear stress–strain curves obtained from direct shear tests on clay samples mixed with 15% rubber powder at different particle sizes

Mohr–Coulomb Parameters (C and ϕ): The cohesion (C) and internal friction angle (ϕ) values derived from the shear strength envelopes are presented in Table 6.

Table 6. Values of Cohesion (C) and Internal Friction Angle (ϕ) for Various Rubber Contents and Particle Sizes

Rubber Content (%)	Rubber Size (mm)	Cohesion, C (kg/cm²)	Friction Angle, ϕ (°)
0	—	0.39	20
5	0–0.5	0.34	21
5	1–3	0.30	26
5	3–5	0.31	29
10	0–0.5	0.38	23
10	1–3	0.28	29
10	3–5	0.25	33
15	0–0.5	0.28	24
15	1–3	0.28	30
15	3–5	0.22	31

The internal friction angle (ϕ) increased with the addition of rubber, particularly at 10% rubber content and with larger particle sizes (3–5 mm). The highest ϕ value of 33° was recorded under these conditions.
This improvement is mainly due to the interlocking effect between coarse rubber particles and the surrounding soil matrix, which enhances resistance to sliding and increases particle-to-particle friction.
In contrast, cohesion (C) values decreased as rubber content increased—especially for larger rubber sizes.This reduction in C can be attributed to the disruption of clay particle bonds caused by the presence of rubber particles, which do not contribute to

electrochemical attraction or capillary forces that normally bind clay particles together.At low contents (5%), the behavior remains balanced, with a modest increase in ϕ and only slight loss in C, suggesting minimal interference in the soil fabric.

At 15% content, although ϕ remained high, the drop in cohesion became more pronounced, likely due to the dilution of the clay matrix and increased presence of voids, which weaken intergranular contact.

10% rubber powder with 3–5 mm particle size yields an optimal improvement in shear strength. It maximizes internal friction without critically compromising cohesion, making it a favorable choice for clay soil stabilization from both mechanical and environmental perspectives.

Rubber powder weakens the bonding between clay particles. It increases internal friction angle of soil due to enhanced internal friction angle.

Effect on Unconfined Compressive Strength (UCS)

To evaluate the mechanical behavior of clay mixed with varying percentages of waste rubber powder, unconfined compressive strength (UCS) and the strain at failure were measured under controlled laboratory conditions. The samples were compacted under standard procedures and subjected to axial loading at a constant strain rate.The main objective of this study is to investigate how the rubber content and particle size influence both the compressive strength and the ductility of the clay. The results provide a clear comparison across the different rubber mixtures and allow interpretation of how rubber addition affects load-displacement behavior of clay.The unconfined compressive strength (qu) and corresponding axial strain at failure (ε) for clay samples mixed with 5% rubber powder of various particle sizes are presented in Table 7. The results are compared with those of pure clay under identical test conditions.

Table 7. UCS and Axial Strain for 5% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
5	0–0.5	6.80	0.36
5	1–3	6.80	0.33
5	3–5	6.80	0.297

The results indicate that adding 5% rubber powder—regardless of particle size—did not significantly alter the peak compressive strength compared to pure clay. The UCS remained nearly constant at around 6.8–6.9 kg/cm². However, an important change was observed in the strain behavior:The rubber-modified samples exhibited a more gradual and uniform strain progression, indicating increased ductility and a more stable failure pattern.The stress–strain curves of these samples showed smoother gradients, which reflect a less brittle failure mode than the sharp peak typically observed in pure clay.Small variations in UCS values, as seen in the table, are considered to be within the acceptable range of experimental error, rather than a direct result of material behavior. This is further supported by observed failure surfaces, which showed more even deformation in the rubber-treated samples.While 5% rubber powder did not enhance compressive strength, it modified the deformation behavior toward a more ductile response. This could be beneficial in geotechnical applications where strain accommodation and post-peak load redistribution are important.For clay samples containing 10% rubber powder of various particle sizes are summarized in Table 8.

Table 8. UCS and Axial Strain for 10% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
10	0–0.5	6.90	0.35
10	1–3	6.70	0.264
10	3–5	6.00	0.231

The results indicate that the addition of 10% rubber powder led to slight variations in UCS compared to the pure clay sample:

- Both Small particles (0–0.5 mm) and larger particles (1–3 mm and 3–5 mm) did not improve the strength or even slightly reduced it.
- The axial strain at failure decreased with increasing particle size—dropping from 0.35 to 0.231. This implies a reduction in ductility at higher rubber particle sizes.
- Although the peak compressive strength remained relatively stable, the behavior of the samples under load changed noticeably:
- The observed reduction in strain at failure in samples with coarser rubber particles indicates increased stiffness and a transition to brittle behavior at lower strains.
- Visual examination of the failure mechanisms revealed that specimens incorporating coarser rubber particles demonstrated significantly constrained deformation propagation and more distinctly defined failure planes.

At 10% rubber content, fine rubber particles may slightly enhance compressive strength and maintain deformability, but coarser rubber sizes tend to reduce strain capacity, which could be critical in applications requiring post-yield deformation.

Table 9 presents the unconfined compressive strength (qu) and corresponding axial strain at failure (ε) for clay samples mixed with 15% rubber powder of various particle sizes.

Table 9. UCS and Axial Strain for 15% Rubber-Modified Samples

Rubber Content (%)	Rubber Size (mm)	UCS, qu (kg/cm²)	Axial Strain, ε
0	—	6.90	0.34
15	0–0.5	6.30	0.231
15	1–3	5.00	0.165
15	3–5	4.20	0.132

The data reveal a clear trend in the variation of UCS and axial strain with increasing rubber powder content:

- Increasing the rubber powder content beyond 5% generally does not improve the unconfined compressive strength and in some cases, especially at 15%, causes a reduction in UCS.
- Samples with 5% rubber powder showed UCS values close to that of pure clay, with only slight improvement in strain at failure, although minor fluctuations likely due to experimental error were observed, consistent with the failure patterns.
- At 10% rubber powder content, the UCS remained comparable to pure clay; however, the axial strain at failure decreased, indicating reduced ductility.
- The most pronounced effects were observed at 15% rubber powder, where the UCS was nearly halved compared to pure clay, and the axial strain at failure also dropped by approximately 50%. This indicates a significant reduction in both strength and deformability.
- These results suggest that increasing rubber powder content and particle size beyond optimal limits leads to diminished mechanical performance, likely due to decreased effective cohesion between rubber and soil particles and the high elasticity of rubber particles, which hinders effective stress transfer within the sample.

Rubber powder, due to its elastic and flexible structure, does not tolerate compressive loads effectively. At higher mixing percentages (typically above 10-15%), the reduction in uniaxial strength becomes more noticeable.

While adding rubber powder at higher percentages and larger particle sizes tend to reduce both the strength and ductility of clay soils. This trade-off highlights the importance of optimizing rubber powder content and particle size for geotechnical applications, especially in critical infrastructure projects requiring enhanced soil performance. In this study, the best balance of ultimate strength and corresponding strain was observed for the 10% rubber powder with 0–0.5 mm particle size mixture.

Results

After conducting numerous tests on various rubber powder mixtures with different gradations, the following results can be summarized as the general conclusion.Rubber powder contains non-polar and hydrophobic particles and does not tend to absorb water like clay.As a result, the soil mixed with rubber powder, reaches a liquid state from a plastic state faster (i.e., it requires less water to achieve a liquid consistency).Rubber powder reduces the cohesion between clay particles, causing the soil to crack at lower moisture levels and lose its plastic Limit.Rubber particles have lower density than clay particles. They also have elastic properties and, under pressure, limits the compaction of the soil. At higher percentages of rubber powder (usually more than 10-15%), the reduction in density becomes more noticeable. In the other hand, since rubber powder is waterproof, achieving proper compaction requires additional water to help bond the soil and rubber particles.The incorporation of rubber powder adversely affects clay particle cohesion while exhibiting a non-linear relationship with internal friction angle. At low concentrations, the rubber particles may marginally enhance the internal friction angle through particle interlocking. However, beyond a critical threshold, the material's frictional resistance deteriorates due to dominant rubber-to-rubber interactions.Rubber particles, due to its elastic and flexible structure, does not tolerate compressive loads effectively. At higher mixing percentages (typically above 10-15%), the reduction in uniaxial strength becomes more noticeable.

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Shiraz Branch

Original Research Paper

Assessment of The Effective Factors on The Adoption of Modern Technologies in Industrial Construction in Order to Improve the Quality of Construction By Sustainable Development Perspective.(Case Study: Constructional Companies Providing Modern Technologies)

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Abstract

Population growth and the increasing demand for housing require a shift from traditional construction methods to industrialized approaches aligned with sustainable development. Using modern materials and technologies can lower costs, shorten construction time, and improve quality.This study reviewed literature and consulted experts to identify factors influencing the adoption of industrialized construction methods. A researcher-designed questionnaire was completed by 92 construction professionals, and factors were grouped into four main indicators. The Analytical Hierarchy Process (AHP) was applied to prioritize them.Findings showed that the urban management index, with a weight of 0.454, was the most influential factor. This index highlights environmental responsibilities and managerial commitments within the urban system. Its proper implementation can significantly reduce energy consumption and promote sustainable practices. Within this index, strict legislation, effective monitoring, and proper resource allocation (weight 0.15) were identified as critical sub-factors.The results stress the importance of urban governance in facilitating sustainable construction. By focusing on management and policy, decision-makers and construction firms can better integrate innovative technologies into housing projects. This study provides practical guidance for aligning industrialized construction with sustainability goals, improving efficiency, and reducing environmental impacts while meeting growing housing needs.

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INTRODUCTION

Today, industrialization has played a role as one of the important factors in creating sustainability in the design and use of new construction techniques. Among these factors, reducing energy consumption, speeding up construction time, and reducing economic costs have attracted more attention from residents. In Iran, the need for safe, cheap, and long-lasting housing in construction has become important. Given the importance of technology in the engineering industry in the present era and its growing and evolving trend, understanding these technologies in mass volume and their increasing production and development can be one of the valuable things in this field. In the last few decades, the issue of sustainable development has received public attention. So much so that a global movement has been launched to pay attention and importance to it. Sustainable development indicators can create balance and harmony between the built environment and construction processes, and in architecture and urban planning, create environments and spaces that are healthy, interactive, and develop economic indicators. Sustainable development is not just about the environment, but also includes balancing the economic, social and environmental goals of society as the three dimensions of sustainable development and integrating them whenever possible, through policies and methods that are compatible with each other. In our country, the role of sustainable development has also been paid attention to for several years. Among these laws, we can mention the laws that have been considered for development projects. One of these laws is the resolution of the Supreme Council for the Environment regarding plans and projects subject to environmental assessment, approved on 29/03/1390.

Modern construction technologies in the world today are based on compatibility with nature, and the technologies used in construction and building technologies are such that energy consumption is saved and renewable fuels, solar panels, wind generators, etc. are used to protect the environment. In the current situation of the country, the most important necessity of using these technologies is due to its important role in sustainable development.

Iran has also made plans for this in line with its short and long-term strategies. The current economic downturn in the country has prompted planners and politicians to take steps to address issues related to quality, sustainability, and standardization in the construction industry to meet the country's construction needs. Despite these efforts, studies and evidence show that the construction industry in the country is still far from sustainable. Industrialization and development of new technologies in the implementation of building components and systems is the first research axis in the country's fourth five-year development plan in the field of construction, which is also a research priority of the Road, Housing, and Urban Development Research Center. The status of regulations has improved compared to previous years, but little has been done to study the conditions of different regions of the country due to climate and weather issues in order to correctly select new technology, and given the great potential of this field, attracting investors to enter this sector has also been low. On the other hand, the construction industry is one of the main industries in the country, with many dependent industries, each of which can play a serious role in sustainable development.

Given that different new technologies are being developed and expanded in the world, and every day we see more attention to these technologies in the construction industry, and given the increasing development of these technologies, we must pay attention to their effects from the perspective of sustainable development. Considering the above, the main goal is to determine the factors affecting the acceptance of new construction technologies and determine priorities from the perspective of sustainable development in construction companies and suppliers of new technologies, and to rank and prioritize them.

Literature Review

Waqar et al. (2024) addressed sustainable leadership practices in building construction, barriers and challenges to industrializing sustainable building in Pakistan. The statistical population of this study included 86 male and 8 female construction project managers and university professors. The findings highlight the importance of using renewable energy, green building certification and standards, infrastructure monitoring and development, and incorporating sustainable technologies in construction, creating a balance between economic development, environmental monitoring, and social equity (Waqar et al., 2024).

Shirish Jain et al. (2024) in their paper A Statistical Approach to Assess the Impact of Barriers on Green Building Development in North East India examined the challenges and barriers to the adoption of new technologies in the Indian construction industry. The study meticulously reviewed the available data and identified 18 potential barriers to green building construction. The results showed that green building development depends on various factors including advanced technology, environmentally friendly materials, suitable locations, scientific planning and design, and sustainable construction processes. However, green engineering management is an often overlooked yet pivotal element. As the green building movement gains momentum, owners and contractors are responsible for driving this forward (Jain et al., 2024).

Hafez et al. (2023) in their article Energy Efficiency in Sustainable Buildings: A Systematic Review with Classification, Challenges, Motivations, Methodological Aspects, Recommendations, and Directions for Future Research, reviewed 134 selected articles from 2014 to 2021 on the energy efficiency of sustainable buildings and conference and research papers related to environmental, social, and economic impacts. The findings showed that the need for sustainable buildings can be achieved by adopting measures such as the use of renewable energy sources, purchasing energy-efficient systems, using materials and equipment to reduce greenhouse gas emissions, and using software to design buildings to achieve higher energy efficiency. Adopting policies and regulations for the public to promote sustainable buildings, adaptive techniques such as energy-saving techniques to improve sustainable energy performance by reducing the building's energy demand for better overall performance, and using modern construction technologies (Hafez et al., 2023).

Table 1. Summary of research conducted

Author's name and year of publication	Article title	Description of results
Jane et al. (2024)	A statistical approach to assess the impact of barriers on green building development in Northeastern India.	The development of green buildings depends on various factors, including advanced technology, environmentally friendly materials, suitable locations, scientific planning and design, and sustainable construction processes
Waqar et al. (2024)	Sustainable leadership practices in construction: Building a resilient community.	The importance of using renewable energy, green building certification and standards, monitoring and developing infrastructure, and incorporating sustainable technologies into construction
Fernandez et al. (2023)	performance in public buildings supported by daylighting technology	Proper lighting design reduces energy consumption, toxic substances, and light pollution, and protects cultural and public buildings.
Chan et al. (2017)	Strategies for Promoting Green Building Technologies Adoption in the Construction Industry-An International Study, Management Strategies and Innovations for Sustainable Construction	The impact of accurate cost information and green construction on the acceptance of this type of construction
Boardeau et al. (2017)	Development and the Future of Construction	The importance of developed countries to sustainable development factors
Shan et al. (2017)	A Global Review of Sustainable Construction Project Financing	The importance of sustainable development in the construction industry
Al-Hatim et al. (2014)	Sustainable construction implementation requirements	Lack of full understanding of the implementation requirements of sustainable construction and lack of sustainable technologies are fundamental challenges for sustainable construction.
Samari et al. (2013)	Problems in the development and adoption of green construction technology	The essential role of the government in the development of green construction technology
Suliman et al. (2010)	Sustainable development and the construction industry in Malaysia	Compliance with sustainable development components by construction companies in works and contracts

Author's name and year of publication	Article title	Description of results
Abedin et al. (2010)	Perception in sustainable construction	Managers' favorable understanding of sustainable development and poor performance in its adoption and use
Crowley et al. (1999)	Challenges of implementing sustainable construction	Emphasizes the importance of green specifications as a critical factor in the success of sustainable construction projects

Research Methodology

The research method depends on the purpose and nature of the research study and its implementation facilities. Therefore, considering the nature of the subject of the present study, which is to evaluate the factors affecting the adoption of new technologies in the industrialization of construction in order to improve the quality of construction from the perspective of sustainable development, the research method is descriptive-analytical and is applied in terms of research purpose. In this study, a questionnaire has been prepared to collect the opinions of experts using library studies and discussions with experts. The process of achieving the research goal is presented in the diagram below.

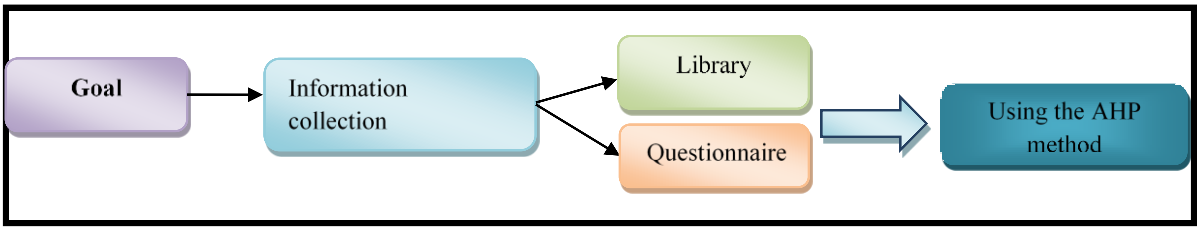


Fig 1. The process of achieving the desired goal in the present study

In the researcher-made questionnaire in this study, 42 indicators were introduced based on sustainable development parameters for approval, evaluation, and prioritization. These rankings were categorized into four main indicators or criteria as follows:

1- Ecological Design Management Index (8 sub-criteria)

2- Construction and Operation Management Index (7 sub-criteria)

3- Urban Management Index (16 sub-criteria)

4- Indoor Environment Management Index (11 sub-criteria)

The validity and reliability of the questionnaires were confirmed using the opinions of professors and Cronbach's alpha. Considering the purpose and subject of the present study, the statistical population of this study includes some managers, executives, employees and executive specialists in mass housing projects as well as a number of major suppliers in this field related to Fars province. A total of 110 questionnaires were distributed among the above individuals, of which 90 responded to the questions. Considering the number of parameters and respondents, Cronbach's alpha was determined to be 0.867, which indicates the desirable reliability of the research tool.

Research findings

Descriptive statistics

When a mass of data is collected for research, it is essential to first organize and summarize it in a way that is meaningfully understandable and relatable. Descriptive statistical methods are used for this purpose. Often the most useful and at the same time the first step in organizing data is to arrange the data according to a logical criterion, and then extract indicators of central tendency and dispersion, and if necessary, calculate the correlation between the two sets of data, and use more advanced analyses such as regression and prediction.

Gender distribution

Typically, the construction industry requires full-time work for architects and civil engineers. In case of problems or deadlines for completing some projects, they may need to work outside of normal hours. On the other hand, working on a project site is subject to varying weather conditions and usually involves business trips. For this reason, women engineers (especially in the civil engineering field) are usually employed in consulting or technical offices due to the above conditions, and few of these women engage in construction activities. Therefore, it is natural that the majority of those who completed the questionnaire were men.

Table 2. Gender distribution

Gender	Abundance	Percentage
Number of men	74	82%
Number of women	16	18%
Total	90	100%

The results obtained from the research sample show that 82 percent of the people are men and 18 percent are women, which is due to the greater presence of men and easier access to them at the construction site level.

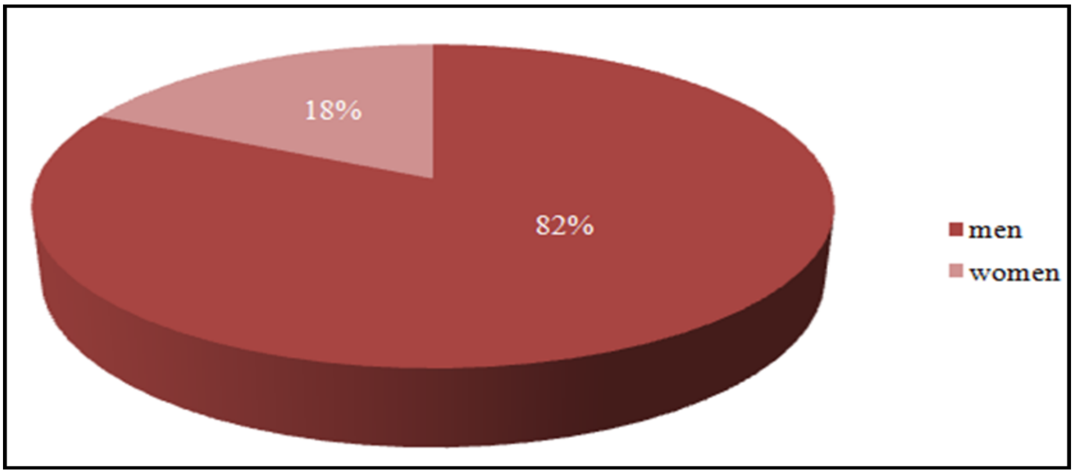


Fig 2. Gender distribution

Distribution of education levels

Training and developing the knowledge and skills of engineers is one of the most important parameters for empowering the construction industry. Up-to-date education and knowledge in the field of construction and familiarity with new materials and up-to-date laws in this field can help the construction industry to optimally use new materials and construction methods.

Table 3. Distribution of educational attainment

Level of education	Abundance	Cumulative frequency	Percentage
Associate degree	8	8	8.89%
Bachelor	45	53	50%
Master	32	85	35.56%
PhD and above	5	90	5.55%
Total	90	-	100

The results obtained from the research sample show that about 50% of the people have a bachelor's degree and on the other hand, most of the age distribution is in the 25 to 35 age range. These two indicate that relatively young experts and executive managers with appropriate academic knowledge are present in construction projects.

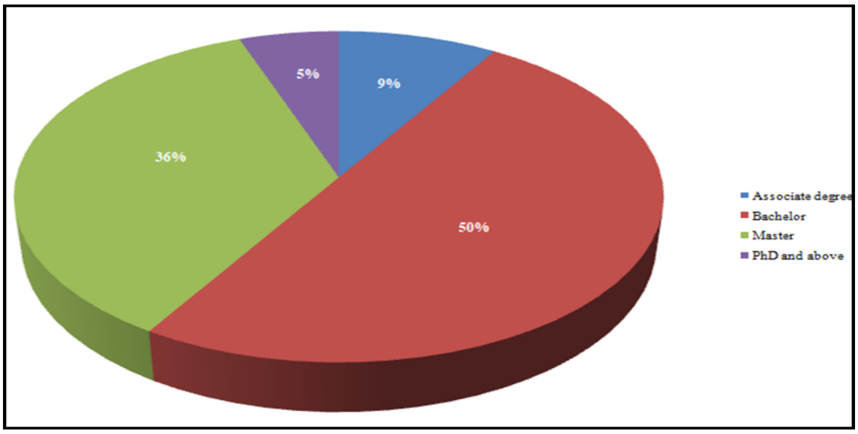


Fig 3. Distribution of education

Distribution of activity history

Activity in the field of construction in addition to the knowledge of the day requires experience in this field. In general, people in the building industry have a better understanding of the conditions and how to use modern materials and the rules and regulations around the industry, and the choice of these people to answer the questions can double the validity and value of the questionnaire reviewed.

Table 4. Distribution of activity history

Distribution of education	Abundance	Cumulative frequency	Percentage
Less than 3 years	18	16	20%
3 to 5 years	24	41	26.67%
5 to 10years	33	75	36.67%
More than 10 years	15	90	16.66%
Total	90	____	100%

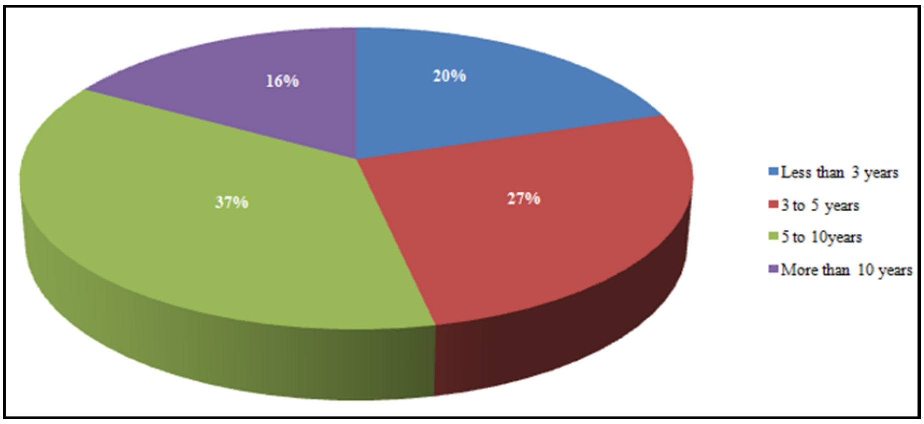


Fig 4. Distribution of a history of activity

The results of the sample individuals show that 37% of people have a more than 5 years of work experience. As a result, the comments and responses provided by them will have a good empirical and practical support.

Inferential Statistics

As mentioned at the beginning of the study, the main purpose of the research is to "rank new technologies in building industrialization based on sustainable development parameters", so the Kolmogorov-Smirnov test is used for normal data distribution.

H_0: There is no difference between observed and expected abundance (there is normal distribution).

H_1: There is a difference between observed and expected abundance (not normal distribution).

Table 5. Data normalization test

Variable	The type of distribution used	Significant level	The amount of error	Confirmation of the hypothesis	result
New building technology	Normal	0.001	0.05	H_0	It is normal
Sustainable development goals	Normal	0.001	0.05	H_0	It is normal

Given the amount of Kolmogorov-Smirnov statistics, it can be deduced that the expected distribution is not significant for all variables and therefore the distribution of these variables is normal. Therefore, parameter statistics should be used to test hypotheses.

Determining the factors affecting the adoption of new construction technologies from the perspective of sustainable development

In this study, 42 rankings are based on sustainable development parameters for approval, evaluation and prioritization, which are categorized into four main management indicators, after completing the questionnaire and using the marshes for each index parameters, first extracting the weight of each opportunity, and then the priority. Finally, using the couple comparison of the main indicators to the goal, we extract the weight of each index and identify one index as the superior option. According to research, various factors and parameters are influenced by the use of modern technologies and green materials in the construction industry. Each of these factors has been analyzed and concluded in previous articles, to what extent each of them is effective in achieving sustainable development goals. Therefore, by studying these articles and determining the factors affecting the admission of new technologies, 42 parameters of the most important questionnaire were prepared and provided to experts. The four main indicators and the following criteria are as follows:

1) Ecological Design Management Index

The parameters related to this index relate to the proper design of buildings based on sustainable development indicators and environmental protection and evaluate their impact on building industrialization in line with sustainable development. Eight parameters for this section are as follows:

ECO1- Building architecture based on sustainable and environmental development indicators

ECO2- Design of buildings to avoid or reduce the consumption of toxic substances and produce them

ECO3- How to design the building to reuse and recycle materials

ECO4- Long Life of buildings or improve their quality

ECO5- Consider climatic issues and use native materials

ECO6- Building architecture based on optimization and reduction of energy consumption

ECO7- Proper project location in terms of environmental protection and preventing it from being destroyed

ECO8- Maximum utilization of climatic conditions to reduce energy consumption

2) The Management Management Index of Implementation and Construction

The parameters listed in this index mostly evaluate the new methods and practices of project implementation operations to reduce energy consumption. Seven parameters for this section are as follows:

OP1- Requires rules and criteria for reducing energy consumption in the process of implementation

OP2- Requires rules and criteria for accuracy in the use of materials and materials

OP3- Using new technologies

OP4- Analytical review of all construction operations in terms of resource and energy saving

OP5- Introduction to Structural Systems, Members or Modern Connections in Structures

OP6- Use Lightweight Methods in Today's Buildings

OP7- Applying lightweight concrete as a type of modern building material

3) Urban Management Index

The options related to this index mostly reflect the duties and management of the environmental and the commitment of managers in the urban system, which will allow for a significant reduction in energy consumption in construction projects if implemented at the level of companies active in construction. Sixteen parameters are introduced and numbered in this section as follows:

UM1- Teaching engineers to reduce the harmful effects of construction on the environment

UM2- Existing structures of engineering, municipal and related institutions for creativity and innovation in the design and implementation of buildings

UM3- The existence of innovative and committed to the country's ecosystem

UM4- The seriousness of legislation, implementation, supervision and accuracy of opinion and control and supply of general resources in the field of executive

UM5- Updating the National Building Regulations and its implementation as the main foundation of construction rules

UM6- Culture in the use of modern materials

UM7- Ranking buildings and monitoring structures

UM8- Transfer and Development of Technology in Modern Building Materials

UM9- Introducing lightweight and thermal insulation materials to reduce the risks of earthquake and reduce energy consumption

UM10- Scientific planning and management of courses and seminars related to materials and products.

UM11- Quality control of building materials in the form of technical certification of products and products

UM12- Building and ranking building in terms of compliance with national building regulations

UM13- Encouraging and providing facilities to executives for buildings that adhere to the state-of-the-art standard

UM14- Engineers and executives' awareness of the green building problem

UM15- Support factories with new and green technologies by purchasing their products

UM16- How much do our current construction fits in to the stable standards

4) Index of internal environment management

The parameters related to this index mostly represent the tasks and commitment of corporate executives, which, if implemented at the level of mass companies, will be able to use new quality materials and create new construction systems in construction projects. The ten parameters in this section are as follows:

IEM1- Existence of energy or ecosystem on the materials and materials to the workshop

IEM2- Introduction to Sustainable Development Goals in Building Industrialization

IEM3- Introduction to the concept and application of building industrialization

IEM4- High quality of materials and use of green and environmentally friendly materials

IEM5- New Methods in Building Industrialization

IEM6- Nanotechnology and Nanotechnology Place in Building to improve the quality of building materials

IEM7- Earn Environmental Certificate

IEM8- Construction workers' skills in the field of industrialization

IEM9- Introduction to Building Ranking System by Standard LEED

IEM10- Research on the production and application of lightweight materials in the building industry

IEM11- Housing quality produced, and its resistance to natural disasters

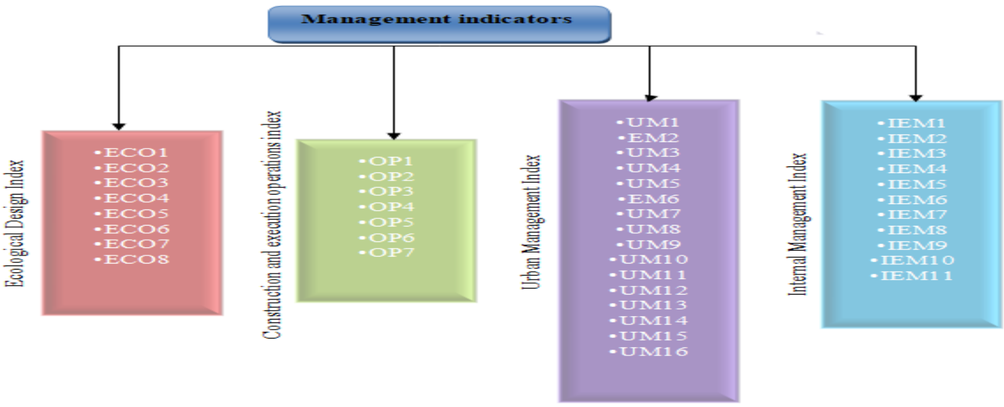


Fig 5. Management indicators and sub-criteria

Pairwise comparison of the main indicators against the target and selection of the superior indicator for factors affecting industrialization towards sustainable development were carried out using Expert Choice software.

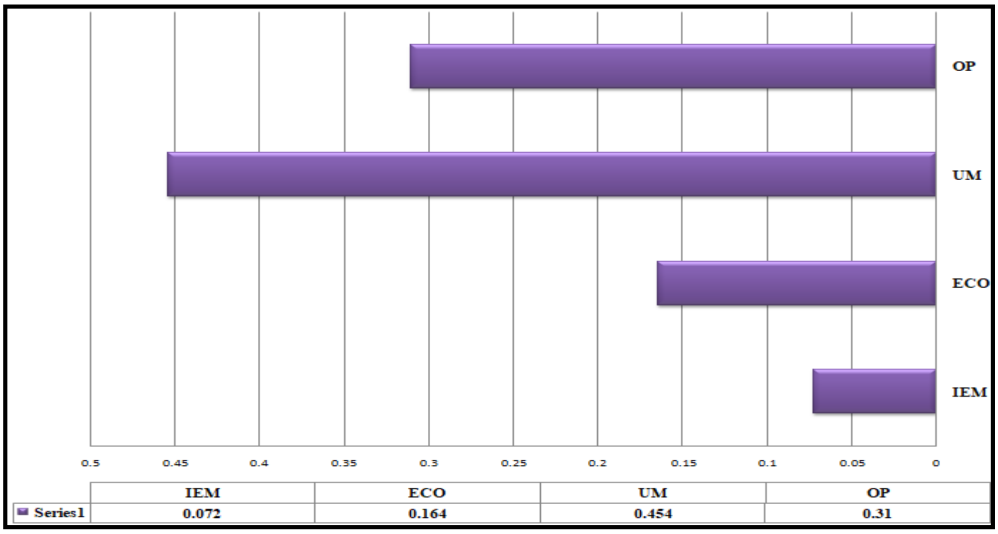


Fig 6. Weight of main indicators

According to the results of data analysis, the urban management index with a weight of 0.454 was determined as the superior index. In the following, we will discuss the pairwise comparisons under the criteria of the main indicators and present three parameters of each main indicator.

Table 6. Top parameters under the main indicators criteria

Ecological Design Management Indicators(ECO)	Operations Management Index (OP)	Urban Management Index(UM)	Internal environment management index (IEM)
Paying attention to climate issues and using local materials	Using modern manufacturing technologies	Seriousness in the field of legislation, implementation, and supervision, and careful consideration, control, and provision of general resources in the executive field.	Introduction to the building rating system based on the LEED standard
How to design a building to reuse and recycle materials	Requirement of rules and criteria for accuracy in the use of materials and supplies	Training engineers to reduce the harmful effects of construction on the environment	Necessary skills of construction workers in the field of industrialization
Building architecture based on energy consumption optimization and reduction indicators	Using lightening methods in modern buildings	Building a culture of using new materials	High quality materials and use of green and environmentally friendly materials

In order to determine the superior sub-criteria in each main indicator, the three sub-criteria in Table (6) are analyzed by pairwise comparisons and the superior sub-criteria in each indicator is determined. The results of pairwise comparisons in Table (7) show that attention to climate issues and the use of local materials, the use of modern construction technologies, familiarity with the building rating system based on the LEED standard, and seriousness in the field of legislation, implementation and supervision, and carefulness and control and provision of general resources in the executive field constitute the most important parameters of the management index.

Table 7. Ranking under the main indicators criteria

Management indicators	Number of parameters	The most important parameter	Weight of criteria
internal environment	11	Introduction to the building rating system based on the LEED standard	0.215
Urban	16	Seriousness in the field of legislation, implementation, and supervision, and careful consideration, control, and provision of general resources in the executive field.	0.150
Construction and implementation operations	7	Using new manufacturing technologies	0.304
Ecological design	8	Paying attention to climate issues and using local materials	0.330

Results

The purpose of this research is to rank new building industrialization technologies based on sustainable development goals. According to the results of data analysis, the urban management index with a weight of 0.454 was determined as the superior index. Therefore, urban management will have a significant contribution to reducing energy consumption towards sustainable development goals in the construction and operation stages.

In the ranking section, the following criteria for each parameter index were determined as the most important parameters of the management index, attention to climate issues and the use of local materials, the use of modern construction technologies, familiarity with the building rating system based on the LEED standard, and seriousness in the field of legislation, implementation and supervision, and thoroughness, control, and provision of general resources in the executive field, with weights of 0.330, 0.304, 0.215, and 0.15, respectively.

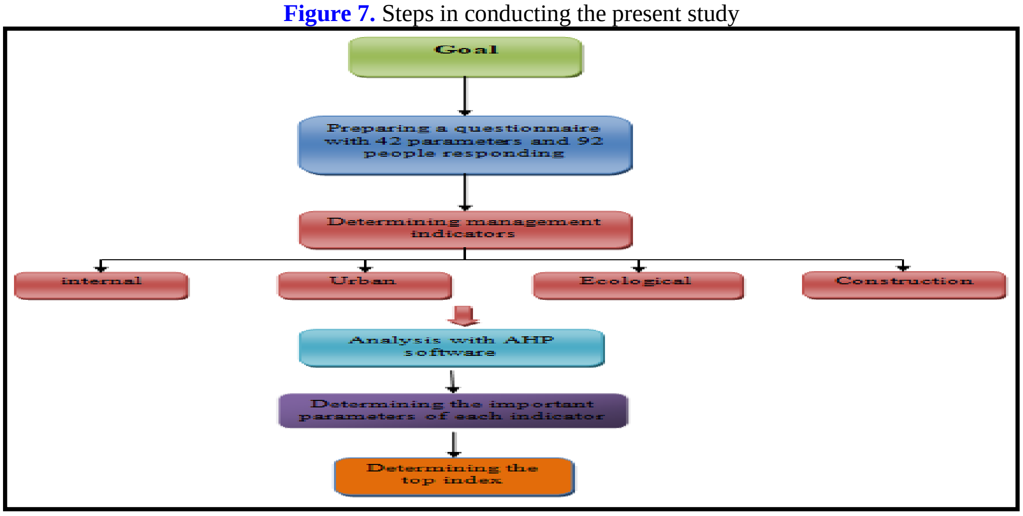
One of the most important differences between indigenous materials and new materials is in the production stage. The production of new materials is associated with high energy consumption and pollution, while most indigenous materials only require a simple initial processing. Many indigenous materials are obtained from renewable resources. Also, by changing traditional construction methods and utilizing new technologies and new construction materials to increase the speed of implementation, increase the useful life, reduce construction costs, and as a result, improve the quality and quantity of housing construction, effective steps can be taken to solve the problem of waste and excessive consumption of energy and, as a result, achieve sustainable development goals in the field of housing construction and operation. So far, no written plan has been prepared to achieve sustainable development in the energy production sector and in the construction sector. In the National Building Regulations, which are the basis of the technical regulations for construction, basic attention has not been paid to climate issues and the conditions and criteria for using different types of energy and the type of design in accordance with the climate and the protection of energy resources, which are the principles of sustainable development. These regulations are not in line with technology and current issues in the world in this field, and perhaps the only law related to sustainable development; The Consumption Pattern Reform Law, in Article 18 of which, explicitly refers to the construction of green buildings, which is a sub-branch of sustainable development, but unfortunately, it has not been implemented in the country so far.

In general, the formula for achieving sustainable development at the national level is the construction of green buildings in accordance with the regional climate, the prerequisite of which is compliance with the national building regulations and the law on reforming the energy consumption pattern, and for these cases to be implemented, the need for building branding in accordance with the principles of green architecture and sustainable development is needed. Providing green building certificates, which are the completed structure of the building energy label and the main basis of which is compliance with the 22 topics of the national building regulations and the executive regulations of Article 18, as well as the building energy label standards, can transform the current construction into a quality, branded, environmentally friendly, comfortable and safe construction, in which case the result will be a win-win for everyone, including the government, the manufacturer, the community, the operator and all stakeholders.

Summary

This research aimed to rank new technologies in building industrialization in order to achieve sustainable development goals. A summary of the research process is presented in Figure 7.

Figure 7. Steps in conducting the present study



Finally, it should be noted that the government, as one of the most powerful executive organs of the country, can contribute significantly to advancing these goals by providing incentive and support tools, including reducing licensing costs, tax exemptions or exemptions, fees, congestion, licensing, or providing appropriate traffic access to green complexes, providing facilities for passing through green neighborhoods (such as walking or cycling facilities), partnering with the banking system in providing free or very low-interest loans, providing comprehensive support to material recycling plants, cooperating with the Engineering System Organization to reduce the costs of design, supervision, and relevant builders, reducing energy consumption tariffs for green buildings, and other such things.

The results of this study can send a clear message to officials of companies and organizations, especially construction companies, so that they can make better plans to give importance to the issue of sustainable development. This includes solutions to make the construction industry more environmentally friendly, as well as providing the necessary training to students as the future builders of society, and familiarizing construction engineers with the latest developments in the construction industry in the direction of sustainable development

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Original Research Paper

A Data-Driven Framework for Operational Management of Pumping Stations Using Statistical Methods in Water Transmission Infrastructure

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Abstract

This research presents a data-driven framework that integrates spatial modeling techniques and nonlinear methods to analyze the performance of pumping stations in water transmission infrastructure. The study highlights the importance of considering spatial and temporal factors to enhance operational reliability and optimize resource allocation.Modeling the number of failures against electrical energy consumption in pumping stations enables better maintenance planning. By analyzing the relationship between energy use and failures, patterns can be identified to predict potential breakdowns and schedule preventive maintenance more effectively. This approach helps reduce unexpected downtime, lower costs, and improve system efficiency and equipment lifespan.By combining advanced statistical methods, such as spatial regression and generalized additive model, the study develops a comprehensive tool for predicting pumping station performance. A case study at the Pumping Station in Iran demonstrates how these techniques can help analyze the of pumping stations in water transmission.

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INTRODUCTION

The effective operation of pumping stations is crucial for ensuring the efficient and reliable functioning of water distribution networks. These stations are vital for maintaining the continuous movement of water across extensive distances, yet they face various operational challenges, including failures and variations in energy usage. Successfully predicting and managing these challenges is key to enhancing system efficiency, reducing downtime, and lowering operational expenses (Dadar *et al.*, 2021)

Pumping stations are often equipped with complex machinery and control systems that, when exposed to wear and tear, may lead to unexpected failures. Additionally, fluctuations in energy consumption due to changes in demand and operational conditions can further increase operational costs and reduce efficiency in water transmission systems (Luna et al., 2019).

These challenges not only impact the performance and reliability of the infrastructure but also result in higher operational costs and diminished service quality (Ikramov et al., 2020). Effective management of pumping stations requires continuous monitoring and predictive maintenance strategies to avoid costly breakdowns and extend the lifespan of equipment. To address these challenges, there is an increasing demand for data-driven approaches that can monitor, predict, and optimize the performance of these stations in real time (Yates et al., 2001). Spatial statistics and spatio-temporal modeling provide powerful tools for analyzing the complex relationships between various operational factors, such as equipment failure rates, energy consumption patterns, and environmental influences. These techniques have been widely applied in infrastructure management to enhance decision-making processes and improve system reliability (Blokus-Dziula et al., 2023). By integrating these advanced techniques, predictive models can be developed to identify potential issues before they arise, optimize energy usage, and ultimately improve the overall operational efficiency of pumping stations.

There is a notable correlation between the frequency of mechanical failures in pumping stations and their energy usage. Failures such as impeller wear, bearing degradation, and shaft misalignment tend to reduce hydraulic efficiency by increasing internal resistance. As a result, more electrical energy is required to maintain the same level of output, which leads to higher operational expenses and accelerated equipment aging.

A case study conducted at the Gigiri Pumping Station in Kenya highlighted how different operational configurations impact overall efficiency. The study showed that operating a single pump (Pump No. 4) yielded a significantly higher efficiency of 74%, compared to just 34% when Pumps 1 and 2 were run together. These differences were attributed to variations in maintenance status and mechanical condition (Tiony, 2013).

These findings underscore the importance of preventive maintenance, precise equipment selection, and real-time monitoring in minimizing breakdowns and optimizing energy consumption. Utilizing smart diagnostics and predictive tools allows for early detection of faults, which helps ensure reliable performance while minimizing unnecessary power usage.

Recent advancements in data analytics and spatio-temporal modeling have opened up new possibilities for improving the management of infrastructure systems. However, many conventional approaches still fail to account for the intricate spatial and temporal relationships that influence the performance of these systems. To bridge this gap, combining spatial clustering, spatial regression, and spatio-temporal modeling offers a promising strategy to improve the management and forecasting of pumping station operations (Kofinas et al, 2020) .

This research aims to develop and implement a data-driven analytical framework that integrates these techniques to analyze and predict the performance of pumping stations within a water transmission infrastructure. The study particularly focuses on exploring the connection between energy consumption and failure frequency at these stations, employing spatial regression to forecast future performance trends.

The key contributions of this paper include:

1. Presenting a new method that integrates spatial clustering, regression, and

generalized additive modeling to enhance the management of pumping stations.
2. Demonstrating how data-driven methods can be leveraged to gain a deeper understanding of the spatial and temporal behavior of system performance.
3. Offering a case study based on the water transmission pipeline, providing insights into the practical application of the proposed framework .

Through the integration of these advanced analytical techniques, this study aims to deliver a more precise and holistic understanding of the operational dynamics of pumping stations, ultimately aiding in more informed decision-making and improving infrastructure management.

Literature Review

The efficient management of pumping stations, which are vital components of water transmission infrastructure, has been a subject of significant research in the field of infrastructure management. Various studies have focused on understanding and improving the operational performance of pumping stations by employing advanced analytical and statistical techniques. This literature review explores the key methodologies used in analyzing infrastructure performance, with a specific focus on spatial regression, nonlinear modeling, and data-driven methods**.**

Spatial modelling in Infrastructure Management

Spatial regression techniques have been widely applied to model and analyze spatial dependencies in infrastructure systems. Anselin (1988) introduced the concept of spatial econometrics, emphasizing the importance of spatial autocorrelation in model specification. Later, researchers such as Getis and Ord (1992) extended these concepts by applying spatial regression models to infrastructure systems to account for spatial dependencies in variables like system failures, maintenance costs, and energy consumption. These models are particularly useful in identifying spatial patterns and correlations that may not be evident using traditional regression methods**.**

For instance, Bao & Chen (2017) used spatial econometrics to model water distribution systems and found significant spatial dependencies in the failure rates of different components **.**

As infrastructure systems are influenced by both spatial and temporal factors, spatio-temporal modelling has become an essential tool for analyzing dynamic performance over time. Cressie (2015) laid the foundation for spatio-temporal statistics by developing models that simultaneously account for both spatial and temporal correlations in environmental data. Du et al. (2023) further advanced these models by applying Gaussian Processes (GP) to infrastructure performance, showing that spatio-temporal models can significantly improve the prediction accuracy of system failures and energy consumption**.**

In the context of pumping stations, Qiu et al. (2024) demonstrated the application of Gaussian Process Regression (GPR) for predicting the energy consumption of pumping stations by integrating both spatial and temporal variables. This approach has shown considerable promise in enhancing the predictive capabilities of infrastructure management systems by accounting for the intricate relationships between time, location, and system performance**.**

Clustering Techniques in Infrastructure Analysis

Clustering methods, particularly K-means clustering, have been widely used to group infrastructure units based on their operational characteristics. Jain (2010) discussed the importance of clustering in identifying patterns in large datasets, which can aid in segmenting infrastructure systems into more manageable units for optimization purposes. In the context of pumping stations, clustering has been used to group stations with similar failure rates or energy consumption patterns, thereby facilitating targeted management strategies**.**

For example, Alyu et al. (2023) used clustering algorithms to identify groups of pumping stations with similar failure characteristics, enabling better resource allocation and maintenance scheduling. Similarly, Huo et al. (2020) applied clustering to water distribution networks to optimize energy usage and reduce operational costs**.**

Applications in Water Transmission Systems

The application of spatial and spatio-temporal analysis methods in water transmission systems has gained traction in recent years. Christodoulou et al. (2012) applied spatial analysis to optimize the maintenance schedules of water pumps in a large distribution system, showing that spatially aware models can lead to more efficient operations. Mutambik (2024) employed spatio-temporal models to predict pipe failure rates in a water supply system, providing a framework for proactive maintenance and resource management.

Baerton et al. (2020) investigated the environmental factors influencing pipe failure in clean water networks using Generalized Additive Models (GAMs). GAMs were applied to model and analyze the effects of variables such as temperature, pressure, humidity, and soil quality on pipe failures. The study emphasized the importance of considering environmental impacts in the design and maintenance of water distribution systems, offering valuable insights for predicting future failures and improving the management of water systems.

Gaps and Contribution of This Study

While previous research has explored individual aspects of infrastructure performance using spatial regression, clustering, and nonlinear modelling (GAMs), few studies have integrated these methods into a unified framework for managing multiple performance indicators, such as failure count and energy consumption, across the same infrastructure system. This study aims to fill this gap by providing a data-driven analytical framework that integrates spatial clustering, spatial regression, and generalized additive model to predict and manage the performance of pumping stations in a water transmission system. By doing so, this study seeks to enhance the predictive accuracy and operational efficiency of pumping stations, contributing to more effective infrastructure management practices.

Research Methodology

This section describes the analytical methods used to investigate the relationship between electricity consumption and system failures in pumping stations. A combination of spatial analysis, time-series visualization, and nonlinear modeling techniques was employed to capture the complex interdependencies across both space and time.

Moran’s I Test for Spatial Autocorrelation

To confirm the existence of spatial autocorrelation in the data, Moran’s I statistic was calculated. This global spatial autocorrelation measure was applied separately to the variables of electricity consumption and failure count, using the same spatial weight matrix W as in the regression models.

Moran’s I values closer to +1 indicate positive spatial autocorrelation (similar values cluster together), while values closer to –1 suggest negative spatial autocorrelation (dissimilar values are adjacent). The test helped determine whether the observed data exhibit significant spatial patterns, justifying the application of spatial regression (Moran, 1950; Cliff & Ord, 1981).

Cumulative Time-Series Analysis

For temporal trend analysis, cumulative plots of both electricity consumption and failure counts were generated for each pumping station over the course of March 2024 to March 2025. These visualizations enabled identification of long-term patterns, seasonal effects, and sudden surges in failures or electricity use.

Additionally, peak analysis was conducted to isolate time intervals with unusually high values, which may correspond to periods of stress or inefficiency in system operations (Chatfield, 2004).

Clustering of Pumping Stations

To identify groups of stations with similar operational characteristics, unsupervised clustering techniques were applied. In particular, K-means clustering was used to partition the pumping stations into distinct groups based on their electricity consumption and failure counts.

This step aimed to: Discover hidden patterns in station behavior, Facilitate targeted interventions, Improve maintenance strategies and resource allocation.

Spatial mapping of the resulting clusters also revealed potential regional performance trends or infrastructure disparities (Jain, 2010; MacQueen, 1967).

Spatial Regression Analysis

To analyze the spatial dependency between electricity consumption and failure count in pumping stations, spatial regression models were utilized. The primary objective was to assess whether electricity consumption at a station is associated with failure occurrences in the same station or its neighboring stations.

Specifically, the Spatial Lag Model (SLM) was implemented. The SLM incorporates the influence of neighboring units through a spatially lagged dependent variable and is expressed as follows:

$$Y = \rho WY + X\beta + \varepsilon$$

Where:

Y is the dependent variable (failure count)

X is the matrix of explanatory variables (e.g., electricity consumption)

W is the spatial weight matrix representing spatial relationships among stations

ρ is the spatial autoregressive coefficient

ε is the error term.

The inclusion of the term WY allows the model to account for spatial spillover effects, where failures in one station may be influenced by conditions in nearby stations (Anselin, 1988; Elhorst, 2014).

To complement the analysis and correct for potential spatial autocorrelation in the residuals, the Spatial Error Model (SEM) was also applied. The SEM is suitable when unobserved spatial effects influence the dependent variable indirectly through the error term (Elhorst, 2014).

Generalized Additive Model

In the final stage of the analysis, a Generalized Additive Model (GAM) was employed to capture potential non-linear relationships between the number of failures and electricity consumption. The model was fitted using a Poisson distribution with a log link function, suitable for count data. A smooth term was applied to the electricity consumption variable to allow for flexible, data-driven estimation of its effect, while the categorical effects of month and station id were included as parametric terms. This approach allowed the potential nonlinear influence of energy use on failure counts to be identified without imposing a strict functional form. General form of the GAM is expressed as follow :

$$g(E[Y]) = \beta_0 + \sum_{j=1}^{p} f_j(X_j)$$

Where:

Y is the response variable

$E[Y]$ is the expected value of the response

$g(.)$ is the link function

$\beta_0$is the intercept

$f_j(.)$ is Smooth functions estimated from the data (e.g., splines), allowing for nonlinear relationships

P is the number of predictors

One of the advantages of GAM is its ability to model complex, non-linear effects of predictors, such as electricity consumption, while also accounting for other factors like month and station id (Wood, 2017).

A real word case study

This section presents the case study used in the present research, focusing on a water transmission line located in Kerman Province, Iran. The transmission line includes four pumping stations situated in the southeastern region of the province, responsible for the transportation and pumping of water.

A real-world dataset was collected, including the number of failures at each pumping station and the corresponding electricity consumption over a 12-month period. The geographic coordinates (longitude and latitude) of each station were used as spatial axes for geostatistical analysis.

"The data collection period spans from March 2024 to March 2025. All spatial and statistical analyses in this study were conducted using specialized R packages, including sf, ggplot2, sp, spdep, spatialreg and mgcv.

Research findings

Moran’s I statistic was initially employed to detect potential spatial autocorrelation in the distribution of failure counts and electricity usage across stations. The results of the Moran's I test for the failure count and electricity consumption have been presented in Table 1 and Table 2, respectively.

Table 1: Moran's I statistic for failure count

Moran I statistic standard deviate = 5.3308		p-value = 0.7161
Moran I statistic	Expectation	Variance
-0.064384141	-0.021276596	0.005692039

The result of the Moran's I test suggests that there is no significant spatial pattern or clustering in the failure count data, meaning that failures are randomly distributed across the stations and do not exhibit a clear spatial correlation. Since the p-value is greater than 0.05, we fail to reject the null hypothesis, indicating that there is no significant spatial autocorrelation in the failure count data. In other words, the number of failures does not show any significant spatial clustering or pattern.

Table 2: Moran's I statistic for electricity consumption

Moran I statistic standard deviate = -0.57137		p-value = 4.889e-08
Moran I statistic	Expectation	Variance
0.0005835877	-0.021276596	0.005835877

Since the p-value is very small (much smaller than 0.05), we reject the null hypothesis and conclude that there is significant spatial autocorrelation in the electricity consumption data. This means that electricity consumption values exhibit a spatial pattern, suggesting that stations located closer to each other tend to have similar levels of electricity consumption.

A cumulative plot for failure count and electricity consumption over time was generated to investigate the temporal trends of these variables. The plot, shown in Fig 1, displays the cumulative sum of failures and electricity consumption for each station, revealing underlying patterns and trends across the period.

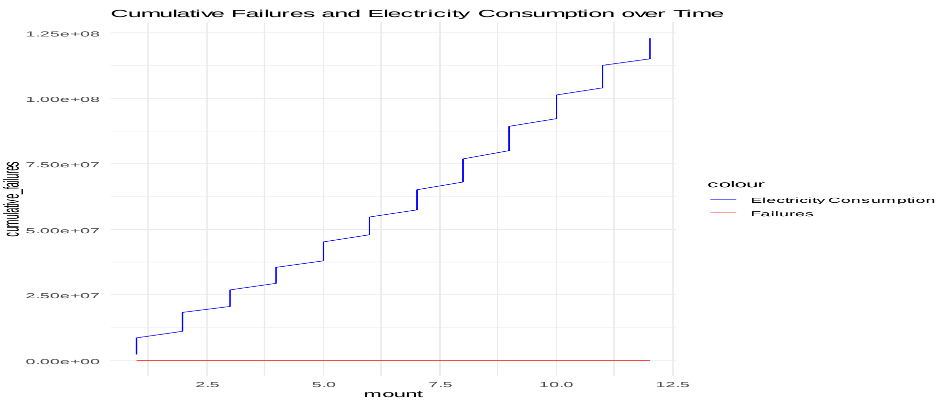

Fig 1: Cumulative failure count and electricity consumption over time

The cumulative plot in Fig 1 shows the temporal trends of failure count and electricity consumption over the period of one year. The horizontal axis represents the months of the year, while the vertical axis shows the cumulative failures. The horizontal line, located at the bottom of the plot, represents the failure count. This line remains relatively constant, showing that failures occur at specific times throughout the year but do not exhibit a rapid increase or decrease over time. The blue stepped line represents electricity consumption. This line increases progressively, showing the cumulative electricity consumption over the months. The stepped nature of the line indicates that electricity consumption increases in increments, reflecting usage over time.

K-means clustering was applied to partition the pumping stations into distinct groups based on their electricity consumption and failure counts. This technique helps to categorize stations that exhibit similar characteristics in terms of energy usage and failure frequency, enabling a better understanding of operational patterns and performance. The result has been shown in Fig 2.

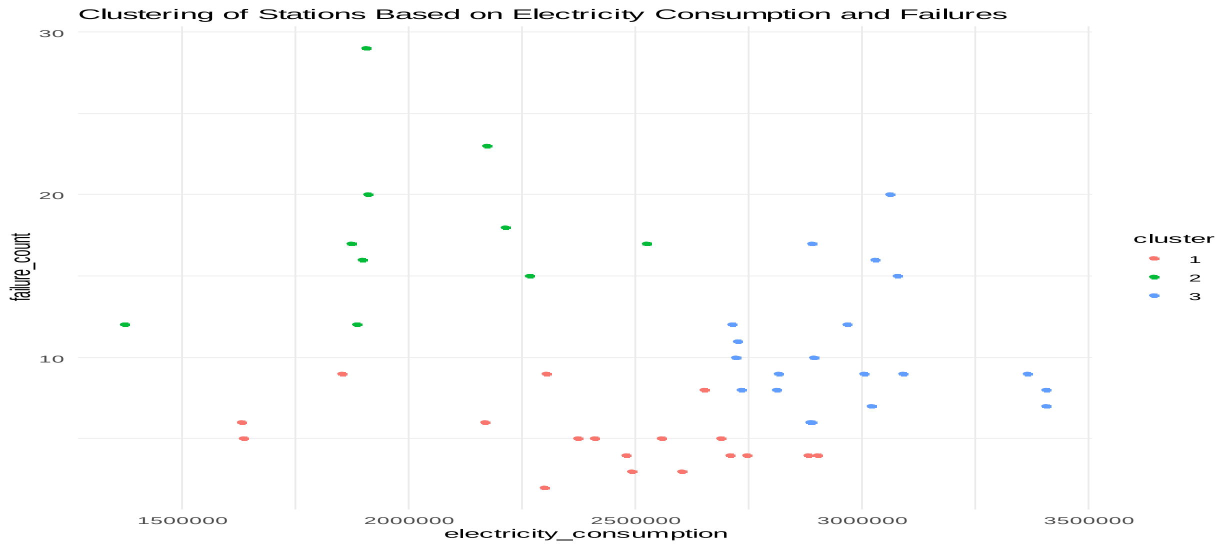

Fig 2: Clustering of stations based on electricity consumption and failure count

The clustering clearly shows that the stations with similar characteristics, in terms of failure count and electricity consumption, are grouped together. The points within each cluster are close to one another, indicating that these stations have similar patterns of performance and energy usage.

- The blue cluster might represent stations with high failure counts and relatively higher electricity consumption.
- The green cluster could indicate stations with moderate failure counts and moderate energy consumption
- The red cluster may correspond to stations with low failure counts and lower electricity consumption

To investigate the relationship between electricity consumption and failure count at the four pumping stations, a simple linear regression model was applied, and the results are presented in Table 3.

Table 3: Simple linear regression analysis

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.674e+01	6.380e+00	2.624	0.0118
electricity_consumption	-2.637e-06	1.978e-06	-1.333	0.1892
station_id	-4.609e-03	8.549e-01	-0.005	0.9957
Multiple R-squared	0.04702	Adjusted R-squared	0.004668	

As observed from the results of the model, the p-value for electricity consumption is greater than 0.05, indicating that the model is not statistically significant. Therefore, changes in electricity consumption does not have a significant impact on the number of failures. Although the model does not show a significant impact of energy consumption on failure count, it is important to consider other factors or use more advanced models to capture potential effects.

Also, for the stations, the p-value is greater than 0.05, indicating that the number of failures is not significantly different between the stations according to the model. In other words, the model does not distinguish significant variations in failure counts based on the station id.

The values of Multiple R-squared and Adjusted R-squared indicate that the model does not effectively captures the variations in the number of failures. These values suggest that the model does not explains a significant portion of the variability in failure counts, reflecting its adequacy in modeling the underlying patterns. The intuitive interpretation of the linear regression model is presented in Fig 3.

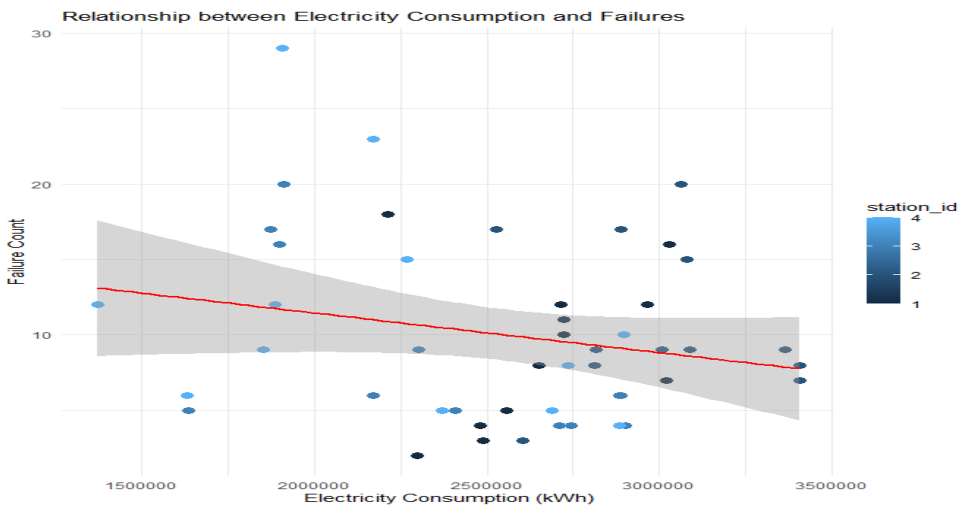

Fig3: Spatial relationship between electricity consumption and failure count

Although the values Multiple R-squared and Adjusted R-squared do not confirm the goodness of fit of the model, the Figure1 suggests that there is an inverse relationship between electricity consumption and the number of failures. Generally, with an increase in electricity consumption, the number of failures decreases. This downward trend is more pronounced at stations 1, 2, and 3, while it is less evident at station 4. In other words, the reduction in failure count with increasing electricity consumption is stronger at stations 1 to 3, while this relationship is less clear at station 4. This could indicate differences in performance or specific characteristics of the stations that should be considered in further analysis.

Due to the inadequacy of the linear regression model in explaining the variations in failure count with respect to electricity consumption, spatial regression has been applied to further investigate the relationship, and the results are presented in Table 4:

Table 4: Spatial Lag model analysis

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	2.1540e+01	4.6631e+00	4.6192	3.852e-06
electricity consumption	-3.7555e-07	1.6707e-06	-0.2248	0.8221431
factor(month)2	-1.0480e+01	3.0181e+00	-3.4723	0.0005161
factor(month)3	-1.2836e+01	3.0121e+00	-4.2616	2.030e-05
factor(month)4	-1.5619e+01	3.0559e+00	-5.1109	3.206e-07
factor(month)5	-1.0977e+01	3.0296e+00	-3.6232	0.0002910
factor(month)6	-6.4960e+00	3.0163e+00	-2.1536	0.0312713
factor(month)7	-8.4140e+00	3.0885e+00	-2.7243	0.0064437
factor(month)8	-1.4270e+01	3.3094e+00	-4.3121	1.617e-05
factor(month)9	-1.1240e+01	3.3698e+00	-3.3355	0.0008515
factor(month)10	-1.3003e+01	3.3445e+00	-3.8878	0.0001012
factor(month)11	-1.3836e+01	3.1951e+00	-4.3303	1.489e-05
factor(month)12	-1.4158e+01	3.0951e+00	-4.5744	4.776e-06
Rho	0.0308	LR test value	0.03283	
z-value	0.13011	p-value	0.89648	

The results of fitting the Spatial Lag Model (SAR) to the data indicate that the spatial lag parameter (ρ = 0.0308, p = 0.896) is not statistically significant. This suggests that incorporating spatial dependence does not substantially improve the model's explanatory power. Furthermore, electricity consumption (p-value= 0.822) does not have a statistically significant effect on failure counts, confirming that changes in energy consumption are not a significant driver of failure events in this context.

To evaluate the adequacy of the model, a scatter plot of residuals versus fitted values has been used, and the results are presented in Fig 4.

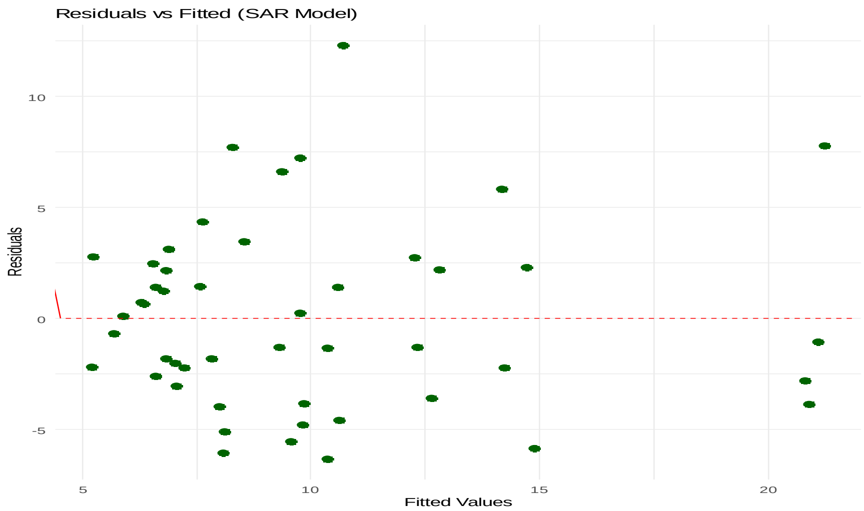

Fig 4: Residuals versus Fitted values

As visually observed in Fig 4, the residuals appear randomly scattered around the fitted values without forming an S-shaped pattern along the diagonal, indicating that the spatial lag model is appropriately fitted to the data."

Despite the adequate fit of the spatial regression model, it failed to reveal a significant relationship between electricity consumption and the number of failures across pumping stations. Therefore, to investigate the effect of electricity consumption on the number of failures, a generalized additive model (GAM) has been applied, and the results are presented in Table 5.

Table 5: Generalized additive model

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	2.949449	0.153235	19.248	< 2e-16
factor(month)2	-0.599345	0.211560	-2.833	0.004612
factor(month)3	-0.876623	0.208450	-4.205	2.61e-05
factor(month)4	-0.440336	0.327143	-1.346	0.178302
factor(month)5	0.000000	0.000000	NaN	NaN
factor(month)6	0.164635	0.269455	0.611	0.541204
factor(month)7	0.719540	0.263956	2.726	0.006411
factor(month)8	0.000000	0.000000	NaN	NaN
factor(month)9	0.301532	0.264218	1.141	0.253777
factor(month)10	0.000000	0.000000	NaN	NaN
factor(month)11	-0.002296	0.298742	-0.008	0.993867
factor(month)12	0.156700	0.292498	0.536	0.592146
factor(station_id)2	-0.627595	0.274741	-2.284	0.022353
factor(station_id)3	-1.143090	0.278886	-4.099	4.15e-05
factor(station_id)4	-1.021784	0.281624	-3.628	0.000285
Electricity consumption	edf	Ref . df	Chi . sq	p-value
	6.756	7.694	24.8	0.00148

To better capture the potential nonlinear relationship between electricity consumption and the number of failures, a Generalized Additive Model (GAM) with a Poisson distribution and a log link function has been applied. In this model, a smooth term was used for electricity consumption, while month and station id were included as categorical covariates.

According to the results, the smooth term (electricity consumption) was found to be statistically significant (p-value = 0.00148), indicating that a nonlinear relationship between electricity consumption and failure count is present. This suggests that a linear model would not have been sufficient to capture this pattern accurately.

Additionally, several levels of the month and station id variables were shown to have significant effects, indicating their influence on failure count. Approximately 67% of the deviance was explained, and the adjusted R-squared was reported as 0.469, suggesting that the model was reasonably well-fitted to the data.

These results imply that nonlinear effects and spatial-temporal variation should be accounted for when modeling failure counts in pump stations.

The non-linear relationship between electricity consumption and failure count has been depicted in Fig 5 based on the smooth term of the GAM:

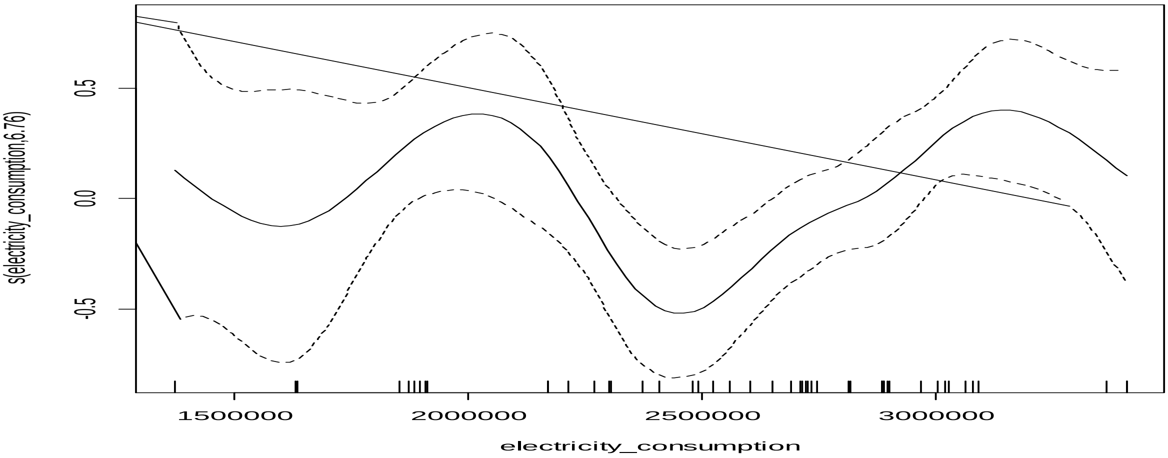

Fig 5: Smooth plot of the GAM

In Fig 5, the smooth term corresponding to electricity consumption has been plotted. The x-axis represents electricity consumption levels, while the y-axis displays the estimated partial effect on failure count. The figure clearly reveals a sinusoidal pattern in the relationship between electricity consumption and failure count.

Results

In conclusion, this research successfully integrates spatial modeling techniques and nonlinear method to analyze the performance of pumping stations in a water transmission infrastructure. The study underscores the importance of considering spatial and temporal factors in infrastructure management to enhance operational reliability and optimize resource allocation. By combining advanced analytical techniques, the study offers a robust framework for improving the management of pumping stations. Further research is needed to refine predictive models and explore the underlying causes of station-specific variations in performance, particularly at stations where performance patterns do not align with general trends.

In summary, this research offers a comprehensive approach to infrastructure management by integrating spatial statistics and predictive modeling techniques. The findings contribute to a deeper understanding of the factors influencing the performance of pumping stations, with the potential to guide future improvements in the management of water transmission systems and beyond.

Lastly, the application of this framework to other types of infrastructure systems beyond water transmission, such as wastewater treatment plants or energy distribution networks, could further validate its versatility and impact. By expanding the scope of analysis to include various systems, researchers and practitioners alike can leverage these advanced analytical techniques to enhance decision-making, optimize system operations, and ensure long-term sustainability.

Future research should aim to uncover these local factors more comprehensively. Additionally, refining the predictive models through machine learning techniques could provide more accurate forecasts and improve the overall predictive power of the framework

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Original Research Paper

Analysis of Human Resource Factors Influencing the Delivery of Construction Projects in Shiraz

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Abstract

Construction delays are a chronic problem in Shiraz, marring schedules, pushing up costs and putting a strain on the regional economy. This report explores the drains on timeliness, focusing on two key players: employers and the workforce. Through 180 major housing projects across the city, the research reveals how poor scheduling, workforce mismanagement and employer decision-making more often stymie progress. filtered out through surveys and site visits the opinions of 60 project supervisors the variety of whom was supposed to accurately reflect the wider landscape and scrutinized their responses to figure out where errors occur.T he findings stung: 43% of the time, delays return to the workforce things like skill gaps or bad coordination and 37% of the time to employers things like delayed approval or budget mistakes. These are not just figures: They represent real-world frustrations for workers, developers and communities left in limbo for homes. By directly addressing these human-centered issues such as enhancing training, simplifying decisions or optimizing resource use the study claims Shiraz can unlock its construction bottlenecks.

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INTRODUCTION

It is a challenge that often delays them from completing large-scale projects on time. Such disruptions refer to any event or action that prevents tasks from being completed within their contracted times (Schumacher, 1995). Such potential setbacks result in wastage of national resources besides questioning the technical and financial viability of initiatives (Ahmadi, 2006). As such, these entities, including government bodies, technical experts, and urban planners are increasingly prioritizing timely execution, as meeting deadlines is a hallmark measure of project management effectiveness and a key metric used to evaluate project outcomes from both practical and analytical perspectives. Reasons for project delays are many and complex, inter-connected, interdependent. According to research, several issues have contributed, primarily up to contractual vagueness, contractors lack of sufficient funds, improper contractor/inadequate personnel, lack of owner's expertise in consultancy, disruption of the supply chain, difficulties in sourcing materials, and unpredictable weather (Schumacher, 1995). The generalization of extended project duration represents an additional worry in areas of the world such as the Middle East where developing countries like Iran remain to be a figurative depiction of this trend. Oversight from employers, contractors and consultants cannot shield them from operational inefficiencies that lead to budget overruns, extended schedules and even project suspensions. Such challenges serve as a reminder of the urgent need for focused approaches to improve efficiency and minimize delays.

Delays have more than just a time consequence, considerably impacting urban development and sustainability activity. Hold-ups in urban initiatives illuminate systemic barriers that hinder the delivery of must-have projects—inhibiting ambitions for urban fabric revitalization and growth (Eshtehardian, 2010). This "civil project crisis," as it is called, highlights the need for new approaches to clear inefficiencies. And constantly re-adjusting project schedules drives up costs, leaving many projects unaffordable when subjected to cost-benefit scrutiny. According to Ansari (2011), the construction projects have between 40 to 50 years of average lifespan where one-fourth of the functional life of the project might be compromised due to delays and this cycling process increases government expenditure as well as divert project life time. It's devastating to projects, economically and socially, not enough to have delays on their construction. Longer timelines generally raise the costs of borrowing as interest rates rise, increase labor costs and send material costs soaring in the midst of inflation, all of which tend to drive project costs well beyond original estimates. Socially, these delays thwart urban planning efforts further aggravating facets of urbanization involving overcrowding, poor living standards and inadequate infrastructure for communities. These cascading effects highlight the importance of proactive measures to minimize delays so that projects better reflect economic constraints and societal needs. In addition to the immediate consequences, delays hinder long-term national development aspirations. Longer delays in the execution of projects can hinder the process of industrial development at a country level, dissuading foreign investment and reducing the competitiveness of a country on a global scale (Kaming et al., 1997), which is especially concerning where infrastructure development is perceived as a key facilitator of economic growth, e.g., in Iran. The fallout also has a wider implications of eroding public trust in government institutions that overseers of these initiatives, and it is citizens that pay the penalty of customer service delays and lack of facilities. Contributing to the improvement of these broader implications hinges on a holistic approach through the link between policy reform, stakeholder collaboration, and technological progress.The environmental cost of delays is another crucial dimension of this question. Longer project durations contribute to longer-time resource utilization, higher amount of wastage generation, and more carbon emission, contradicting the global sustainability goals (Doloi et al., 2012). Idle machines and prolonged site activity, for example, have even greater potential to contribute to environmental degradation, while delayed urban projects can preclude timely delivery of solutions such as green infrastructure or public transit systems. Such delays combined with environmental impact speak to the need to expedite project execution to be consistent with ecological and nation-wide priorities.There's been considerable research into project delays, however, there's still a lack of understanding of the full extent of project delays and replicable solutions that can be applied across projects. While studies have outlined causes and effects (Assaf & Al-Hejji, 2006; Sambasivan & Soon, 2007), less attention has been paid to how site-specific cultural, political and institutional factors shape delay patterns. Moreover, the absence of real-time data integration and predictive modeling in project management hinders the proactive mitigation of delays (Flvbjerg et al., 2003). Future research should investigate assumptions relating to the aforementioned gaps by analysing context-specific dynamics and using emerging technologies such as artificial intelligence to predict and mitigate delays in advance.

Table 1: Key Factors Contributing to Project Delays and Their Impacts

Factor	Impact
Contractual Issues	Miscommunication, legal disputes, and unclear project specifications.
Financial Constraints	Insufficient funding, delayed payments, and budget overruns.
Contractor Expertise	Inadequate skills, poor planning, and inefficient resource management.
Logistical Challenges	Delays in material delivery, transportation issues, and equipment shortages.
Environmental Conditions	Adverse weather, natural disasters, and regulatory compliance delays.

Tackling project delays and understanding it better by summarizing the entire aspects involved — meticulously planned projects, stakeholder deliverables and timely strategic management techniques. It requires collaboration between government and private sector organizations to create well-defined contracting processes, ensure timely release of funds for crisis response and a focus on continuous workforce training and upskilling. Additionally, implementing technologies like Building Information Modeling (BIM) and advanced project management software, tree can greatly increase efficiency tree, simplify workflows, and improve coordination among all participants involved in the projects. Addressing these pressing issues will help minimize delays in the project, optimize project performance, and contribute to the long-term sustainability of urban infrastructure development.There are several possible causes of project delays, which can have widely varying impacts on the schedule and the interests of the stakeholders involved. These factors must be individually and collectively assessed and measured in order to impact project progress. This evaluation aids in measuring the impact of delays and comprehending the implications on other parties involved. Given the complexity and scale of modern construction projects, some aspects of delay are unavoidable. Such issues become very critical in complex projects, as shown by Peter (2016). Design errors can be identified along a few dimensions based on their causes, compensability, and project phase. Understanding these classifications is important in properly analyzing the complexities of project delays and how this can further impact project success and stakeholder engagement. Realizing what lies at the roots of delays and how they influence later phases is a basic step to come up with successful mitigation measures. Understanding and analyzing these factors that contribute to the delay better prepare project managers to implement proactive strategies that will increase their planning, execution efficacy and overall delivery of the project. Actively mitigating project delays involves several methods: improved scheduling methods; better communication channels between stakeholders; and using risk management frameworks to identify and address risks before they lead to problems. According to Jafarzadeh (2004), understanding the delay factors enables the construction industry to develop best practices in project scheduling and allocation of resources. Thus, by encouraging a more strategic and methodical perspective on delay handling, the sector can enhance compliance with timelines, avoid cost and time losses, and raise the satisfaction rates for all parties concerned.

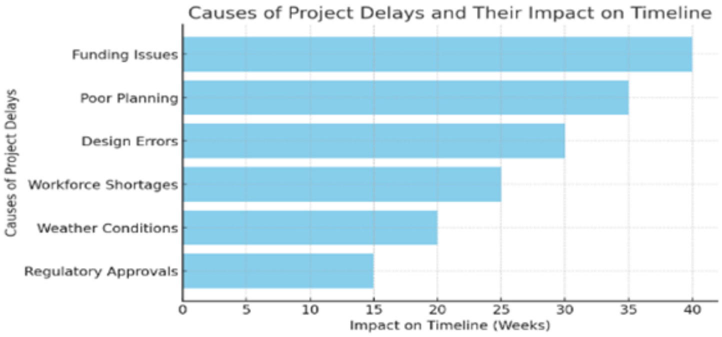

Fig 1: Causes of Project Delays and Their Impact on Timeline (Source: Peter, 2016)

The chart above displays the main causes of construction project delays and the additional allocated weeks to projects in a horizontal bar format. The biggest drivers of this are funding issues and poor planning, both leading to an average delay of 40 weeks and 35 weeks respectively. Design mistakes, workforce shortages, regulatory approvals and weather conditions also have an outsized impact on the timing of projects. By understanding these factors, project managers can identify potential risks and establish mitigation strategies earlier in the planning process.

Fig 2: Mitigation Strategies vs. Reduction in Project Delay (Source: Jafarzadeh, 2004)

Line diagram proving various mitigations are effective in reducing project delays 04 SES-592 Survey: Traffic Advisory for GHL Share 3%06bp Overall, the best forms of intervention that we identified are advanced project management tools (with a 15-week reduction in delays) and improved scheduling (with a 10-week reduction in delays). Such project disruptions can also be minimized through effective stakeholder communication, risk management frameworks and workforce training. By executing these strategies on a systematic level, it can simplify project execution, enhance coordination, and ensure projects are completion within time frames. Identifying the reasons behind the delays and the effective mitigation strategy to implement will go a long way to enhance efficiency and reduce financial losses for the project as well as ensure completion of the project on time.

Root Causes of Delays

Construction delays have vexed the industry for years, and researchers have tried to untangle their complexities. Fahimi (2010), for example, studied five projects to map the pathways through which delays cascade through timelines—finding that progress is frequently undermined by misaligned schedules and poor communication. By polling professionals, Fahimi developed a model that illustrated how backlogs in one phase, such as design mistakes, reverberate to others, such as procurement or execution. Likewise & Molaei (2012) examined urban development projects in Iran and cited employer weakness, contractor inexperience and faulty feasibility studies as prime offenders. The two studies emphasised that land acquisition-related challenges and sped up design phases magnify delays, reflecting patterns seen around the world (Gupta & Patel, 2021).

Strategies for Improvement

To overcome such delays, Rezazadeh (2005) suggested the Analytical Hierarchy Process (AHP) as a tool to prioritize problems such as gaps in employer budgets, delays of permits or shortage of contractor skills. This technique illuminated that inefficiency in project management strategic planning contributes to longer timelines and prompted companies to use a methodical approach to decision making. Karer (1992) supported this in Jordan, stating that outdated tendering practices and financial instability among contractors and employers have created a culture of "blame game". Their results therefore urge for transparent partnerships and improved risk-sharing frameworks (Lee et al., 2020). On the other hand, Sharifzadeh (2010) found out that both scope changes and client micromanagement are critical triggers and that better contracts and agile project management can prevent these triggers from happening.

Modern Management Innovations

Recent trends focus on the convergence between tech and sustainability. For example, Alavi et al (2022) proved that Building Information Modeling (BIM) enhances the synergy of all stakeholders resulting in reduced rework and miscommunication. Rahman et al (2023) also noted the lack of regulatory delays associated with eco-strategies, and Smith and Johnson (2022) called for resilient supply chains to address shortages in materials. Chen et al (2023) recommended adaptive frameworks for dealing with unexpected disruptions like extreme weather or pandemics. These studies support the argument by Eshtehardian (2010) to modernize metro-area projects using sophisticated time, cost, and risk management systems.

Policies and Training: The Heart of the Matter

But systemic reforms are needed, in addition to technical fixes. Stricter transparency laws and streamlined permit processes could reduce bureaucratic delays (Gupta and Patel 2021). In Jordan, for instance, e-permit platforms reduced approval times by 30% in pilot programs. Martinez and Kim (2023) also emphasized how tax incentives for training programs increased workforce productivity in South Korea, filling skill gaps that often lock projects in a holding pattern. Likewise, O'Connor and Ng (2022) observed that the performance-based contractor selection—emphasizing expertise rather than low bids—yielded better outcomes for Australia's infrastructure projects.

New Trends & Global Takeaways

And the rise of prefabrication and modular construction offers hope. Lee et al. (2020) reported that prefabricated components reduced delays on construction sites by 25 per cent in Singaporean housing projects as weather-related disruptions ear d with reduced time on site. But this calls for an initial capital outlay in factory infrastructure and skilled labor — a tall order for places like Shiraz, where the industrial base is thin. This gap can be filled through cross-border cooperation like partnering with foreign companies that are better equipped to transfer knowledge and technology (Rahman et al., 2023). And finally, the development of a culture of accountability, where employers and contractors are equally accountable for project risks, might help us avoid the blame game that Karer termed decades ago.

Table 2: key findings, and proposed solutions from various studies addressing construction and urban development project delays

Study	Focus Area	Key Findings	Proposed Solutions
Fahimi (2010)	Construction delays	Identified critical delay factors; developed a model for reducing delays.	Categorizing delay factors; prioritizing them; constructing an interaction model.
Molaei (2012)	Urban development delays	Weaknesses in employer, consultant, and contractor performance identified as primary causes of delays.	Enhancing urban planning efforts; addressing land acquisition and design issues.
Rezazadeh (2005)	Construction project duration increases	Financial constraints and design errors as major delay contributors; use of AHP method.	Developing a decision-making framework; systematic prioritization of delay factors.

Study	Focus Area	Key Findings	Proposed Solutions
Karer (1992)	Delays in Jordanian construction projects	Economic challenges, scope changes, and inadequate project management were main delay causes.	Improved project financing; move away from lowest-bid contract awards.
Sharifzadeh (2010)	Construction project delays	Scope changes, client interventions, and poor contractor management identified as major delay factors.	Enhancing contractor selection processes; focusing on contractor experience and management capabilities.
Eshtehardian (2010)	Urban development project delays	Emphasized the need for new management methodologies and project management systems in metropolitan areas.	Incorporating modern management disciplines; promoting sustainable urban development.

This research explores the common risks associated with slowdowns in construction and urban development projects, as well as their potential solutions. To illustrate, in his study, Fahimi (2010) focused on identification and classification of causes responsible for delays in construction projects. He organized his findings into a model for best practices that would help organizations and project managers avoid these problems. In contrast, Molaei (2012) focused on the perspective of the employer, consultants and contractors, and how their interference leads to delays, particularly in urban projects. He said streamlining urban planning processes could help eliminate many of the bottlenecks. On the other hand, Rezazadeh (2005) studied the aspect of financial hardships and design mistakes which most of the time delay the projects. He suggested that the Analytical Hierarchy Process (AHP)—a decision-making tool used to prioritize factors—can be applied to these problems, prioritizing and enabling systematic identification of delay factors.

Likewise, Karer (1992) and Sharifzadeh (2010) also pointed out that economic problems and bad practices of the management of projects can generate delays. This supported the need for better financing strategies and better management of contractors to reduce delays. Eshtehardian (2010) had a broader view and argued that urban development should embrace to modern management techniques. This mesh of projects collar high-level systems to support them, far more than legacy metrics of the system for measurable efficiency, but rather sustainability or the like. Put together these findings allude that delays in construction projects cannot be attributed to just one cause, but instead a myriad of financial, managerial and technical causes. Together, these studies highlight the need for strategic planning, efficient management, and regulatory reform in order to mitigate these barriers. By improving any combination of training programs for workers, writing stronger contracts, or utilizing new project management systems, delays are minimized and projects get delivered on time.

As a follow-up to this conversation, it's worth noting that construction project delays are not just an operational obstacle—they carry serious social and economic consequences, too. Delays result in cost overruns, strained relationships between stakeholders, and public displeasure, especially with road and other urban infrastructure projects. For instance, if a road or public transportation system is delayed, both developers and contractors are affected directly, as well as residents whose daily life depends on these facilities. The wider implications and ripple effects of our interventions should serve as cartographers guiding us to map a multidimensional approach to the landscape of project management. Overcoming delays requires improvements in collaboration from all parties involved, from government agencies to private contractors, to ensure that everyone is on the same page when building toward the project's goal and timeline.

The other big consideration is technology — can it prevent delays? Construction project management has greatly evolved in recent years, thanks to advances in digital tools and software. In recent years, many of the project delays have been caused by factors like inaccuracy of designs — Building Information Modeling (BIM) enables more accurate pre-construction designing that result in fewer chances of a project getting delayed owing to construction errors. Publishing projects on these platforms can aid a large number of both can help track the project on a single platform. By leveraging these technological innovations alongside traditional best practices, a more robust project management framework can be created. Yet, the adoption of such technologies entails an investment in training and infrastructure, which could be more challenging for smaller firms or less-developed regions. So while technology provides bright solutions, it must be implemented carefully, taking into account the individual needs and capacities of each project.

Thirdly, this study will develop the findings of existing studies and focus directly on the reasons leading to the delay of construction projects in Shiraz. The context of the city—straddling rapid urbanization, conflicting interests of stakeholders, and varying degrees of user and workforce expertise—is what makes it an interesting case for multilayer analysis of project delays. This research focuses on the roles of both the employers and the workforce involved in construction while gaining insight into behaviors, trends, and the possibilities of identifying differences between types of companies. The studies reviewed strongly support a more holistic approach that includes the training, development of contracts, and overseeing project management systems. Ultimately, we aim to help construction projects in Shiraz and other cites with similar problems manage and finish successfully and on time. Embracing history and incorporating recent advancements, we will work towards a better, faster and greener future in urbanization.

Research Methodology

In this research, a descriptive-analytical method is used to investigate the reasons for delays in Shiraz construction projects. A total of 60 project managers on construction projects in the city are the subject of the research. Considering the large size of the population, Cochran's formula was applied to achieve a sample of 60 individuals. To make the study practical, a convenience sampling approach was followed for selecting the participants.

A structured questionnaire was used for data collection. The experts assessed its face validity and content validity to confirm the questionnaire validity. The inclusion of these experts helped in reviewing the clarity and precision of the questionnaire items to make sure, it evaluated the tool suitability to the purpose of the study. Moreover, the reliability of the questionnaire was examined through Cronbach's alpha. The software SPSS was used to verify the data obtained from a pilot test on a small group of 5 participants. The reliability of the questionnaire was confirmed through the calculated Cronbach's alpha coefficient, confirming that it is a robust tool for data collection.

It revealed some interesting demographics of participants. 80% of the respondents were men, whereas the remaining were accounted by women (20%). Age-wise males in 30-35 years and above 40 years (both 35.37%) showed the maximum participation respectively. Out of all the respondents, the group with the least amount was between the ages of 25 to 30, with only 11.66% of all respondents being in that age group. In terms of education, undergraduate degrees made up the largest proportion, with participants achieving a 66.67% representation in the overall sample. The marital status data indicated that married participants comprised 76.66% of the sample, with the smallest group being single participants.These data represent some of the first demographic insight into the construction project management data in Shiraz. These characteristics are important to comprehend when finding critical heads to set up strategies to avoid experiencing project handovers. The high participation rate of married individuals and individuals in their 30s and 40s indicates that work-life balance and experience may be essential aspects of the practical components of project management. The academic qualifications of the participants further emphasize the role of academic training in honing their approach to managing construction programs.The results complement wider research into construction projects beyond the study at hand. For example, Alavi et al. ' recent body of work (2022) highlights how demographic factors impact project outcomes, and Rahman et al. (2023) underscore the significance of establishing reliable construction data collection instruments. Smith and Johnson (2022) also emphasize that the construction industry must become more gender-diverse if it wishes to drive innovation and enhance project performance. However, challenges that project managers of Shiraz are facing in order to deliver projects on-time are not properly recognized.

Table 3: Participant Demographics

Demographic Category	Frequency (%)
Gender (Male)	80.00
Gender (Female)	20.00
Age (30-35 years)	35.37
Age (Over 40 years)	35.37
Age (25-30 years)	11.66
Education (Undergraduate)	66.67
Marital Status (Married)	76.66

As for the results I found between time management, study environment, and project delays, the regression analysis also showed results showing a significant relationship. The listings shown in Table 2 show the correlation coefficient (R) of 0.66, the F-value of 24.6 (df = 384, 4) and the p-value of less than 0.01, showing that the human resources can explain 43% of the variance in the project delays with 99% confidence. This is supplemented by the manpower subscale (β = 0.48) at the same confidence level. We then perform a correlation analysis by using dissociative correlation coefficients that reach to the standard correlation coefficients, which we confirm directly and significantly the criterion variable (project delay) is dependent on the predictive variables.

Table 4: Regression Analysis Results

Metric	Value
R (Correlation Coefficient)	0.66
R^2 (Variance Explained)	0.43
F-value	24.6
Significance Level (p)	<0.01
Manpower Subscale (β)	0.48

Research findings

This study also indicates the importance of proper human resource management in delaying the construction projects. Proper labour management is an important aspect of overall project time since it influences the productivity and coordination of the projects. With the right human resources in place, tasks can be completed on time, teams can communicate better with less bottlenecking, and everything in the project goes smoothly. This highlights the need to make workforce management a priority, as one of the ways to address delays in construction.Other variables including time management, study environment, and employer-related factors were also investigated in their study of Shiraz, [Iran]. Results showed significant correlations between these factors and the degree of delays suffered in construction projects. Specifically, poor time management and insufficient study environments were found to worsen delays, while employer-related issues like decision-making and resource allocation were among the most impactful. These findings indicate that, by improving planning, training, and as a consequence of being a better employer, projects can be executed more efficiently.tatistical analysis also confirmed these insights: a high correlation (R = 0.61) between the variables studied. With an F-value of 9.6 and a significance (p) of less than 0.01, the results suggest that factors associated with the employer explain 37% of the variance (99% confidence level) of project delays. The Beta coefficient of 0.50 associated with the employer subscale highlights the significant impact that this factor has on delays. The findings establish a clear and considerable connection between delays in a project and the predictive variables (employer-related and workforce management) in general. Based on this information, they can identify problem areas and the entire supply chain can come up with its own strategies to correct the bottlenecks and make construction projects function more efficiently.

Table 5: Regression Analysis for Employer Impact on Project Delays

Metric	Value
R (Correlation Coefficient)	0.61
R² (Variance Explained)	0.37
F-value	9.6
Significance Level (p)	<0.01
Employer Subscale (Beta)	0.50

Identifying non- financial factors such as employer and manpower issues can be effective in the planning to minimize delay in construction projects for Shiraz through addressing deficiencies in these factors.reports a t-test outcome showing a t-statistic value of 2.947, with a significance of 0.004, below 0.05. It shows a clear gap between the mean values of the examined participants and the mean criterion and emphasizes the necessity to pay attention to the employer and manpower factors to reduce the amount of the project delays.

Table 6: t-Test Results for Employer and Manpower Impact

Metric	Value
t-Statistic	2.947
Significance Level (p)	0.004

Table 6 shows a higher t-statistic value of 6.055, with a significance level of 0.000, further confirming the significant difference between the examined participants and the criterion. This suggests that effective strategies targeting non-financial factors, such as employer and manpower-related issues, could substantially reduce project delays in Shiraz.

Table 7: t-Test Results Confirming Significance

Metric	Value
t-Statistic	6.055
Significance Level (p)	0.000

The study underscores that non-financial factors, particularly those related to employers and manpower, play a crucial role in causing project delays in Shiraz. By implementing targeted strategies to manage these factors, it is possible to minimize delays and improve the overall efficiency of construction projects. The use of visual aids such as bar and pie charts can help stakeholders better understand the impact of these factors and the importance of addressing them to achieve timely project completion.

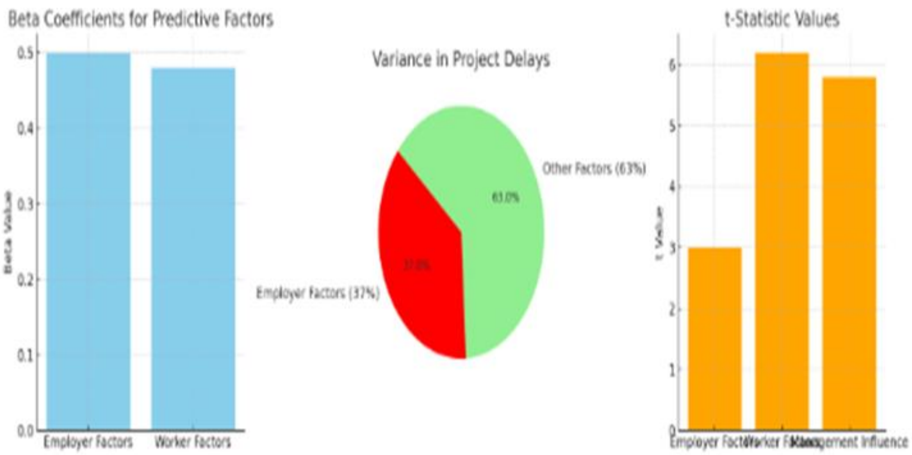

Fig 3: Human Resource Predictive Factors and Their Impact on Project Delays

This bar chart displays the beta values for two key human resource-related predictors: Employer Factors and Worker Factors. Both have high beta values (0.5 and 0.48, respectively), indicating a strong and nearly equal predictive influence on project delays. A higher beta value reflects a stronger contribution of that variable to the delay prediction model. These results emphasize that both employer-related decisions (like planning, funding, or leadership) and worker-related aspects (like skills, productivity, and availability) are significant contributors to delays in construction projects.

Through the bar chart illustrated in our results and the discriminant analysis of our research findings, we can gain a deeper insight into the contributors to construction project delays. The Beta coefficients reveal significant and positive relation of Employer Factors (0.50) and Manpower Factors (0.48) to delays. These findings closely mirror earlier research but also provide new insights into the relative salience of the factors involved. As another example, while both Employer Factors and Manpower Factors were found to significantly add delays, the slightly higher Beta coefficient of Employer Factors indicates that problems related to poor decision making, lack of funds or ineffective project management will adversely affect project duration more than other delays. This finding supports other studies by Fateh (2017) and Koon (2005) who indicated that a factor that impacts on project completion on time is the competence of the manager. When comparing these results to research on delays, it is apparent that most of the time the origin of the delays are inefficiencies for management. A failure of development—a lack of resources or failure to strategically plan—by any of the employers can create bottlenecks where one thing leads to another leading to the next, and eventually cascading through the whole project lifecycle (Molaei, 2005). In line with this, Shakeri (2010) describes poor communication between stakeholders as one of the major contributors to delays, which links up directly to employer related issues. Heumann (2017) and Osmon (2018) explain workforce related issues such as skill gaps, labor shortages, or poor team dynamics are also contributors. The current study, however, adds further nuance to this understanding by quantifying how these factors stack up against each other, suggesting that even if Manpower Factors are marginally less significant than Employer Factors, they are still a highly important area of focus.The study also sheds light on how these factors are interlinked; interestingly. Poor decision-making on employer side for instance can worsen the workforce challenges like low morale or high turnover rate, resulting in further delays. Alternatively, good management of a labor force can counteract some of the harms caused by inefficiencies that are related to employers. This interplay highlights the need for a holistic approach in project management, that is, a simultaneous focus on managerial and workforce-related issues. This can help them build a more resilient and adaptive framework to manage construction projects, ultimately leading to fewer delays and better results.Key Takeaway: External challenges such as bad weather, natural disasters or changes in legislation, have a much smaller overall impact than those coming from managing human resources. This finding contradicts some previous studies, such as Vafaie (2009), which highlighted the importance of external factors as the main cause of delay. Yet the present study suggests a much different perspective, one in which external issues matter but are out of the reach of those leading the initiative. On the contrary, addressing internal factors, such as workforce management, organizational practices, and contractor selection, can provide more concrete and actionable results. The addition that Internal factors offer the most potential for strongly aligns with the research of Francis (1992), who claimed internally-oriented factors were where improvement had the best opportunity.

Results

This research delves into the messy, human reasons why construction projects so frequently trail schedule. It highlights two key offenders: problems related to the employer and problems related to the labor force. Using a technique called discriminant analysis, the study found that managerial hiccups cause 37 percent of the total delays, but that labor-related struggles are responsible for a staggering 43 percent. These aren't just numbers — they're evidence of how profoundly these factors entangle a project's timeline, and the study shows that they are not merely weakly linked, but tightly woven into the problem.What's so compelling about it is the way it builds on what we already know while stripping back new layers. For example, the slightly greater influence of employer-related problems (Beta coefficient of 0.50) than manpower problems (Beta coefficient of 0.48) makes a point: it's often the ones up top—the decision-makers—whose ineffectiveness starts the first spark of delay. Think of it as a domino effect: one manager drops the ball, and suddenly, the entire project feels it. This isn't just a number, it's a wake-up call for project managers to stop following quick fixes and start digging into the root causes.But it isn't all about blaming management. The study tells a larger, more human story. It reflects how employer goof-ups don't just slow progress — they pull down worker productivity as well. Consider a crew stuck by the side of the road waiting on material that didn't arrive on time, or a team fumbling over work because they didn't get trained well enough. These aren't separate problems; they're interdependent. The research lays out practical approaches to breaking this cycle: coaching better to improve skills and performance, sharper decision-making to capture funding and planning, and a comprehensive frame that connects it all up. It's about thinking of the project as a living organism, not a checklist.What I appreciate about this study is its groundedness. It isn't just theory—it also gives you a toolbox. It mentions selecting contractors based on their reputation and expertise, not simply getting the lowest bid the first time out. It emphasizes closely monitoring material quality and procurement, and it calls for training that prepares managers and teams to cope with the chaos of construction. There's even homage to something so basic but so often ignored: writing down what goes bad and learning from it. These aren't out-of-the-blue ideas — they're actions you could picture regular people executing on a muddy job site.At its core, this research isn't just about delays — it's about people. It's a demand to treat working people with dignity, to ensure that leaders are held to accountability standards, and to learn from each misstep. It's challenging the construction world to progress, to embrace more clever, gentle and sustainable ways of working. Miracle to bottom: Imagine an industry without the regularity of delays—where projects hum along because all the way up and down the ladder, people are pulling toward yes. That's what is envisioned here, and it's not a fantasy; it's a plan. This study doesn't merely describe a problem — it illuminates a path forward, one that could cascade across building sites everywhere.

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ORIGINAL RESEARCH PAPER

Performance-Based Analysis of Water-Cement Ratios in Cement Hydration for Hydraulic Applications in Shiraz

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Abstract

There is no denying that concrete is one of the most important building materials in the world, essential for almost every style of structure you can imagine, including bridges, dams, residential buildings, and roads. Its ubiquity has led to ongoing research and innovation on the materials that make it up. Introduction Over so many years, the research work on concrete target components has resulted in identifying some new periphery components that have been used to enhance the quality, durability, and efficiency of the concrete. These advancements have allowed for greater efficiency in the construction of modern infrastructure, leading to sustainable and long-lasting builds. Insights cement It is the major components among concrete. It influences the intensity, durability, and quality of concrete structures. In recent decades, the cement industry in Iran has Flourished and diversified in types and production capacity. But with that growth comes a pressing need for rigorous quality control. Physical and chemical properties of cement must be matched to recognized industry standards in order to ensure the production of strong and predictable concrete. —The city of Shiraz holds great historical value, and its wet environment has resulted in a diverse range of structures with varying architectural styles. We studied the effect of the water-cement ratio and chemical composition of cement on concrete ultimate strength. It was found that an increase in the water–cement ratio will result in the strength of concrete being significantly decreased. That is because excess water causes voids and disrupts the internal structure of the concrete. It also focused on two of the most important cement compounds, C_3S (Tricalcium Silicate) and C_2S (Dicalcium Silicate). This is mainly due to the presence of these compounds in the

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INTRODUCTION

Concrete serves as a foundational material in modern construction, with its performance directly influencing the structural integrity, durability, and longevity of buildings and infrastructure. Its properties depend critically on the quality of constituent materials—cement, aggregates, and water—and their interactions during mixing, hydration, and curing. Cement, as the binding agent, plays a central role in determining concrete's mechanical and durability characteristics, while aggregates and water-cement ratios further refine its behavior at macro- and microstructural levels.
microstructural levels.

Cement Quality and Its Impact

Cement quality governs workability, compressive strength, and long-term durability. Excessive cement content can increase compressive strength initially but may lead to higher drying shrinkage and early-age cracking due to increased heat of hydration. For instance, Wasserman et al (2009) noted that surpassing optimal cement levels reduces workability, necessitating admixtures to mitigate issues like segregation. Finer cement particles also demand more water for hydration, exacerbating thermal stress and porosity in the interfacial transition zone (ITZ). Conversely, high-quality cement with controlled fineness ensures balanced hydration kinetics, minimizing microcracks and enhancing durability.

Aggregates and Structural Uniformity

High-strength aggregates improve load-bearing capacity, while smaller aggregate sizes promote a homogeneous concrete matrix. This uniformity reduces stress concentrations and enhances mechanical efficiency. For example, prefabricated concrete systems in Shanghai utilize optimized aggregate grading to improve batch consistency and reduce material variability, lowering maintenance costs.

Water-Cement Ratio and Density

The water-cement (w/c) ratio is pivotal for compressive strength and porosity. A lower w/c ratio (0.40–0.60) reduces capillary voids, yielding a denser cement paste with higher strength. UltraTech Cement (2024) emphasized that excess water dilutes the cement paste, weakening bonds between particles and increasing permeability. This compromises durability, as aggressive agents like chlorides penetrate more easily, accelerating corrosion.

Hydration and Microstructure Development

Hydration involves exothermic reactions between water and cement compounds (e.g., tricalcium silicate), forming calcium silicate hydrate (C-S-H) gel, which provides strength. Proper curing controls temperature to prevent thermal cracking, ensuring even strength distribution. Inadequate hydration leaves unreacted cement, increasing porosity and reducing long-term durability.

Interfacial Transition Zone (ITZ)

The ITZ, a porous region between aggregates and cement paste, significantly influences mechanical performance. Traditional concrete exhibits weak ITZs with microcracks and high porosity, whereas geopolymer concrete shows denser ITZs, improving fracture resistance. Torrence et al (2022) demonstrated that ITZ properties directly correlate with concrete's effective modulus and yield strength, highlighting the need for optimized mix designs to strengthen this critical zone.

Table 1: Effect of Cement Type and Concrete Age on Relative Compressive Strength

Type of Cement	1 Day	7 Days	28 Days	90 Days
Type I Cement	0.30	0.66	1.00	1.20
Type II Cement	0.23	0.56	0.90	1.20
Type III Cement	0.57	0.79	1.10	1.20
Type IV Cement	0.17	0.43	0.75	1.20
Type V Cement	0.20	0.50	0.85	1.20

Data on the effect of different types of cement on the relative compressive strength of concrete with age are given in Table 1. The values of compressive strength are normalized and usually the strength at 28 days is taken as a reference (1.00) for comparison. The table lists the five class-based types (Type I through Type V) and tracks the strength gain over a period of 4 curing durations (1 day, 7 days, 28 days, and 90 days). This enables you to see how fast your each type of cement benefits and how much it can achieve the ultimate strength in a timeline.

The Difference Between Early and Late Strength Development

There are obviously differences in early strength development(s) — based on pure data up to October 2023. The type III, which is high early strength cement (whether you want to believe it or not), has 1-day strength of 0.57 compared to day of 28-day (much higher than other types). It makes it suitable for time-sensitive construction. On the other hand, Type IV cement — a low-heat cement commonly used in mass concrete — has the lowest early strength (0.17 at 1 day), correspondingly reflecting its slower rate of hydration. At 90 days, however, the relative strength becomes equal as all the cement types reach the value of 1.20, suggesting that, despite the difference in the initial rate of strength gain, the potential of each cement type achieve a similar strength after adequate time has passed.

Compressive Strength Development and Chemical Composition of Portland Cement Concrete

The compressive strength of concrete is a critical factor in its application as a construction material, governed by the properties of its components, particularly Portland cement. Recent studies using Shiraz Type II Portland cement and local aggregates have investigated the growth of compressive strength over time, measuring strength at 1, 7, 28, 42, and 90 days. These studies reveal a consistent increase in strength, with significant milestones at 7 and 28 days, and continued gains up to 90 days, emphasizing the importance of long-term strength development. The percentage of strength growth relative to the 28-day benchmark highlights the influence of cement type and mix design on concrete performance. Optimizing these factors is essential to achieve desired structural characteristics, especially when using region-specific materials (Mehta & Monteiro, 2014). Portland cement's chemical complexity plays a pivotal role in concrete's strength evolution. Comprising four primary phases—tri-calcium silicate (C3S), di-calcium silicate (C2S), tri-calcium aluminate (C3A), and tetra-calcium aluminate ferrite (C4AF)—Portland cement lacks a single chemical formula due to its diverse composition. These phases, formed during the high-temperature processing of raw materials, dictate the hydration process and influence properties like setting time and heat generation. For instance, C3S drives early strength gains, while C2S contributes to long-term durability. The ratios of these phases, determined through oxide analysis, allow engineers to predict cement behavior and tailor concrete mixes for specific applications (Taylor, 1997). Several factors influence the compressive strength growth of concrete, including the water-to-cement ratio, aggregate properties, and curing conditions. A lower water-to-cement ratio reduces porosity, enhancing strength, but requires careful balancing to maintain workability. Aggregates, such as those sourced locally in Shiraz, affect the concrete's load-bearing capacity, while proper curing ensures sustained hydration, particularly in the early stages. The Shiraz studies underscore the need for region-specific mix designs, as local materials interact uniquely with cement, impacting strength outcomes. These findings advocate for customized approaches to optimize performance and cost-effectiveness in concrete production (Neville, 2011). The interplay between cement chemistry and mix design is crucial for achieving optimal concrete performance.

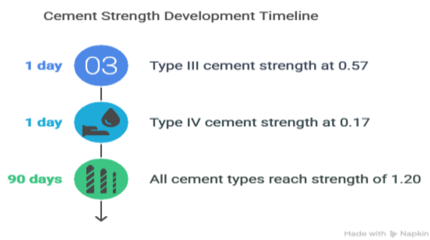

Fig 1: The Cement Strength Development Trimline

Type II Portland cement, used in the Shiraz studies, is formulated for moderate sulfate resistance and heat of hydration, making it suitable for diverse construction needs in Iran. By adjusting mix parameters—such as the proportions of cement, aggregates, and admixtures—engineers can meet specific structural and environmental requirements. Advances in material science, including the use of supplementary cementitious materials like fly ash, further enhance sustainability and strength, supporting the standardization of cement production processes in Iran (Mindless et al., 2003).In conclusion, the development of compressive strength in concrete is a dynamic process driven by the chemical properties of Portland cement and the optimization of mix designs. The Shiraz studies demonstrate significant strength gains over 90 days, highlighting the importance of tailoring cement type and mix parameters to local conditions. Understanding the roles of C3S, C2S, C3A, and C4AF enables engineers to predict and enhance concrete performance. By integrating material science advancements with practical applications, the construction industry can achieve durable, cost-effective, and sustainable concrete solutions (Komatke et al., 2002).

Table 2: Compressive Strength Growth Over Time

Time (Days)	Compressive Strength (MPa)	% Growth Relative to 28 Days
1	10.5	-65%
7	22.0	-27%
28	30.0	0%
42	33.5	12%
90	38.0	27%

This table presents the compressive strength of concrete made with Shiraz Type II Portland cement at various intervals, based on typical trends observed in similar studies. The strength values are illustrative, showing a progressive increase from 1 to 90 days. The percentage growth relative to the 28-day strength (30 MPa) highlights the rapid early strength gain (up to 28 days) and continued development thereafter, with a 27% increase by 90 days. These data underscore the importance of long-term strength monitoring for structures requiring enhanced durability.

Table 3: Primary Phases of Portland Cement

Phase	Chemical Formula	Role in Concrete Properties
Tri-calcium Silicate (C3S)	Ca_3SiO_5	Drives early strength (1–28 days)
Di-calcium Silicate (C2S)	Ca_2SiO_4	Contributes to long-term strength (>28 days)
Tri-calcium Aluminate (C3A)	$Ca_3Al_2O_6$	Influences early hydration, heat generation
Tetra-calcium Aluminate Ferrite (C4AF)	$Ca_4Al_2Fe_2O_{10}$	Minor role in strength, affects cement color

This table summarizes the four primary phases of Portland cement and their contributions to concrete properties. C3S and C2S are the main contributors to strength, with C3S dominating early gains and C2S supporting long-term durability. C3A affects early hydration and setting behavior, while C4AF has a limited impact on strength but influences cement's appearance. Understanding these phases helps engineers predict cement behavior and optimize mix designs for specific performance requirements.

Table4: ffect of type of cement and age of concrete on relative compressive strength of concrete

C ompressive strength relatively			
28 days	**7 days**	**1 day**	**Type of cement**
1.00	0.66	0.30	New cement AD I
0.90	0.56	0.23	New Cement II
1.10	0.79	0.57	III cement
0.75	0.43	0.17	IV cement
0.85	0.50	0.20	V type cement

Understanding Cement Composition and Its Impact on Concrete Properties

Cement is a remarkably intricate material, and its properties and performance are heavily influenced by its chemical makeup. By examining the oxides present in cement and applying equations developed by Mr. Bog, it's possible to estimate the percentages of the four primary phases found in cement: C4AF (Tetracalcium Luminometries), C3A (Tricalcium Aluminate), C2S (Dicalcium Silicate), and C3S (Tricalcium Silicate). These calculations operate under the assumption that the oxides in the raw materials combine exclusively to form these four phases, and that each phase is entirely pure. Understanding the proportions of these phases in a given cement sample allows manufacturers to maintain consistent quality over time and compare different batches effectively. This method is especially valuable for ensuring uniformity in cement production and predicting how the material will perform in concrete (Ramazanianpour, 2015, p. 10).Among the four main phases, C3A reacts the fastest with water, initiating the hydration process almost immediately after contact. However, the calcium silicates—C3S and C2S—also react with water, though at a slower pace. These reactions produce a gel-like substance called calcium silicate hydrate (C-S-H), which serves as the primary binding agent in concrete. The C-S-H gel is highly complex, with its structure varying depending on the specific conditions during hydration. It makes up between 50% and 60% of the volume of hydrated cement paste and plays a crucial role in determining the paste's most important properties, such as strength and permeability. Without the formation of this gel, concrete would lack the cohesion and durability necessary for structural applications (Ramazanianpour, 2015, p. 9).The development of cement's strength is largely driven by the C3S and C2S phases. These silicates are the foundation of cement's binding properties and contribute significantly to the long-term strength of concrete. On the other hand, while C3A is highly reactive, it doesn't meaningfully contribute to strength beyond the early stages of hydration. In fact, its presence can sometimes be problematic. When exposed to sulfates, C3A reacts to form calcium sufflaminate (ettringite), which can lead to expansion and cracking in concrete. Similarly, C4AF, though present in smaller amounts, has minimal impact on the overall behavior of cement. Its role is more related to the color of the cement rather than its mechanical properties. In summary, understanding the roles of these phases helps ensure that cement performs reliably in construction projects, balancing rapid hydration with long-term durability and resistance to environmental factors.

Secondary Compounds and Their Influence on Cement Performance

In addition to the four main phases, cement contains secondary compounds such as MgO (Magnesium Oxide), TiO2 (Titanium Dioxide), Mn2O3 (Manganese Oxide), K2O (Potassium Oxide), and Na2O (Sodium Oxide). These compounds typically make up only a small percentage of cement's composition but can still influence its performance. Among these, alkali oxides (Na2O and K2O) are particularly noteworthy. These compounds can react with certain aggregates in a process known as the alkali-aggregate reaction (AAR), which can lead to the deterioration of concrete over time. This reaction causes expansion and cracking, compromising the structural integrity of concrete. Therefore, controlling the alkali content in cement is crucial for ensuring the long-term durability of concrete structures (ASTM C114 standard).

Practical Implications and Quality Control

Understanding the chemical makeup of cement isn't just a theoretical exercise—it has real-world implications for the construction industry. For example, the approximate values of cement compounds, outlined in Table 3, give us a general sense of what to expect in a typical cement sample. These figures act as benchmarks for quality control, helping manufacturers and engineers ensure that the cement meets the necessary standards. By keeping an eye on the proportions of key phases like C3S, C2S, C3A, and C4AF, as well as secondary compounds, it's possible to anticipate how the cement will perform in different applications. This allows producers to fine-tune the mix design to achieve the desired results.

Innovations in Cement Chemistry

Recent progress in cement chemistry has focused on tweaking the proportions of these phases to improve concrete performance. For instance, increasing the C3S content can speed up strength development, making it perfect for projects where early strength is crucial. Conversely, reducing the C3A content can enhance resistance to sulfate attacks, making the cement more suitable for environments with high sulfate levels, such as coastal areas or industrial zones. Moreover, incorporating supplementary cementitious materials (SCMs) like fly ash, slag, and silica fume has opened new doors for improving concrete properties. These materials modify the hydration process and reduce reliance on traditional cement phases, leading to more sustainable and durable concrete.

The Bigger Picture

In short, the chemical composition of cement is a key factor in determining how well it performs in concrete. By understanding the roles of the four main phases—C3S, C2S, C3A, and C4AF—as well as the influence of secondary compounds, engineers and researchers can tailor cement formulations to meet specific needs. This knowledge is vital for ensuring that concrete structures are strong, long-lasting, and sustainable, especially in challenging environments. As the construction industry continues to grow and adapt, ongoing research into cement chemistry will remain essential for developing innovative solutions that address the demands of modern infrastructure. By staying ahead of the curve, the industry can create materials that not only meet today's challenges but also pave the way for smarter, greener, and more resilient construction practices.

Table 5: Combined amounts of cement compounds

Amount to percentage	oxide
60-67	CaO
17-25	SiO2 _
3-8	Al2O3 _ _ _
.05-6	Fe2O3 _ _ _
0.1-4	MgO
1.3-2	Alkalis
1-3	SO 3

Cement is composed of a variety of chemical oxides, each contributing specific properties to the performance of the final product. The most abundant compound is Calcium Oxide (CaO), typically making up 60% to 67% of the cement. It plays a crucial role in the hydration process, which leads to the hardening and strength development of concrete. Silicon Dioxide (SiO_2), ranging from 17% to 25%, combines with calcium to form calcium silicates that are primarily responsible for the long-term strength of the material. Aluminum Oxide (Al_2O_3), found in the range of 3% to 8%, influences the early strength gain and setting time, while Iron Oxide (Fe_2O_3), between 0.5% and 6%, affects the color of the cement and assists in the formation of clinker phases during production. Other minor compounds also play essential roles. Magnesium Oxide (MgO) appears in small amounts (0.1% to 4%); while a necessary component, excessive MgO can cause expansion and cracking over time. Alkalis, including sodium and potassium oxides (Na_2O and K_2O), usually range from 0.2% to 1.3% and must be carefully managed to avoid harmful alkali-silica reactions in concrete. Lastly, Sulfur Trioxide (SO_3), typically present in 1% to 3%, helps control the setting behavior of cement. Understanding the composition and proportion of these oxides is vital in selecting or designing cement mixes suitable for specific engineering applications, especially in demanding environments like hydraulic structures.

Evaluating Cement Quality and Its Impact on Concrete Strength

The quality of cement has always been a central focus in construction, especially when it comes to the phases responsible for its strength. In recent years, cement factories in Iran have increasingly prioritized producing cements with higher levels of tricalcium silicate (C3S). This shift aims to boost both short-term and long-term compressive strength, making the cement more versatile and reliable. As a result, there's growing interest in assessing cement quality based on its key phases, as these directly affect how concrete performs. To evaluate compressive strength, standardized tests are carried out by mixing cement with a specific type of silica aggregate (reference sand) of controlled grain sizes. Cement mortar samples are prepared and tested at various stages—7 days, 28 days, and beyond—to determine their strength. These tests follow both Iranian national standards and international benchmarks like ASTM (Iranian National Standard, Beta; ASTM Standard, Beta).

Why Concrete Strength Matters in Construction

Concrete is one of the most widely used materials in construction worldwide, forming the backbone of everything from homes to large-scale infrastructure projects. Its compressive strength is a critical factor in ensuring the durability and safety of structures. Achieving the desired compressive strength has always been a top priority for engineers and researchers. This study delves into the factors that influence the strength of hydrated cement—and, by extension, the strength of concrete itself. Among the most significant factors is the water-to-cement ratio, which has a direct impact on the final strength of the material. Experiments consistently show that increasing the water-to-cement ratio reduces compressive strength, underscoring the importance of precise mix design.

Experimental Design and Methodology

In this research, 25 different concrete mix designs were prepared, all using a fixed amount of sand but varying water-to-cement ratios. The materials were sourced from the Kaftarak Mine and Fars Cement Factory in Shiraz, Iran, to ensure consistency. Each sample was cast in oiled cubic molds measuring 15x15x15 cm. To assess workability and setting time, standard tests like the slump test and Vicat test were conducted on each mix. The slump test is particularly important because it measures how easily the concrete can be placed and compacted, which depends on factors like cement grade, water content, and the overall consistency of the mix. To maintain uniformity across all samples, the slump value was kept constant.The compressive strength of the concrete was tested at four key intervals: 7 days, 28 days, 42 days, and 90 days. Proper curing was essential, so the samples were stored in a cold water pool with temperatures carefully maintained between 21°C and 25°C. This step is crucial because cement hydration—the chemical reaction that gives concrete its strength—only occurs in capillary pores filled with water. Preventing water loss from these pores is vital for achieving optimal strength (Ramazanianpour, 2015, p. 161). After curing, the samples were tested using a concrete breaker jack machine (Matest 2000KN) with a loading speed of 0.4 MPa/sec to measure their compressive strength.

The Role of Cement and Aggregates in Concrete Performance

The cement used in this study was Type 2 cement from the Fars Factory. It's critical that the cement meets the physical and chemical specifications outlined in ASTM C150 (for ordinary Portland cement) and ASTM C595 (for pozzolanic mixed Portland cement). The quality of the cement directly impacts the hydration process and, ultimately, the strength of the concrete.Aggregates, which make up 60% to 75% of concrete's volume, are just as important as cement. Their quality significantly affects both the fresh and hardened properties of concrete, as well as the economic feasibility of the mix. Aggregates need to be well-graded to minimize voids and create a dense, strong concrete matrix. The physical, thermal, and sometimes chemical properties of aggregates play a major role in determining the overall performance of the concrete. For example, weak aggregates—whether due to poor particle strength or inadequate bonding—can compromise the concrete's strength. On average, satisfactory compressive strength for aggregates ranges between 200 and 800 kg/cm² (Tadin et al., 2011, p. 2). The grading of aggregates used in this study is detailed in Table 4, ensuring an optimal mix that maximizes strength while minimizing cement usage.In conclusion, understanding how cement quality and aggregate characteristics influence concrete performance is key to building durable, safe, and cost-effective structures. By fine-tuning factors like the water-to-cement ratio, aggregate grading, and curing conditions, engineers can optimize concrete mixes for specific applications. This knowledge not only ensures compliance with industry standards but also paves the way for innovative solutions in construction. As the demand for stronger, more sustainable materials grows, ongoing research into cement and concrete will remain crucial for meeting the challenges of modern infrastructure.

The Importance of Optimizing Mix Design

Optimizing the mix design is crucial for achieving the desired concrete strength while minimizing material costs. A well-graded aggregate mix reduces the need for excess cement, as it fills voids more effectively. This not only enhances the concrete's strength but also makes the mix more economical. Additionally, controlling the water-to-cement ratio is vital for balancing workability and strength. While a higher water content improves workability, it can weaken the concrete by increasing porosity and reducing density. Therefore, finding the right balance is key to producing high-quality concrete.This study underscores the importance of understanding the factors that influence concrete strength, particularly the role of cement phases and the water-to-cement ratio. By carefully controlling these variables, engineers can design concrete mixes that meet specific performance requirements. The findings also highlight the need for rigorous quality control in cement production and aggregate selection to ensure the durability and safety of concrete structures. As the construction industry continues to evolve, ongoing research into mix design and material properties will remain essential for advancing concrete technology and meeting the demands of modern infrastructure.

Table 6: Mixing proportions of coarse stone materials in the plan

The mixing percentage of coarse grained stone materials	Sample specifications
60	Almond sand
40	Pea sand

The Importance of Water Quality and Aggregate Grading in Concrete

Water is a fundamental component of concrete, and its quality can significantly impact the final product. Generally, water suitable for drinking is also suitable for making concrete. Such water typically has a solid content of less than 2000 parts per million (ppm), which translates to about 0.05% of the weight of cement for a water-cement ratio of 0.5. Ideally, the water used in concrete should have a pH level between 6 and 8 and should not have a salty taste. Using water that meets these criteria ensures that the concrete will set and harden properly without compromising its strength or durability.

The Role of Aggregate Grading in Concrete Quality

The way aggregates are graded and the maximum size of the aggregates play a crucial role in determining the properties of concrete. Proper grading affects not only the mix proportions of aggregates but also the amount of cement and water required. It influences key characteristics of concrete, such as workability, pumpability, shrinkage, durabil ity, and even its economic efficiency. Well-graded aggregates create a dense and cohesive mix, reducing the need for excess cement and water while improving the overall performance of the concrete (Ramazanianpour, 2015, p. 56).One of the most critical factors in ensuring high-quality fresh concrete is the presence of fine aggregates (sand) with an adequate amount of filler particles. These fine particles, typically ranging in size from 0.075 mm to 0.6 mm, contribute to the concrete's workability, pumpability, and surface finish. They help prevent the separation of aggregates, reduce the amount of cement paste needed, and improve the viscosity of the mix. Unfortunately, in many parts of Iran, washed sand often lacks sufficient filler particles. As a result, concrete made with such sand tends to be rougher, less workable, and harder to pump, ultimately affecting its overall quality and performance.

Compliance with National Standards

In this study, the aggregates used—including sand, almond-sized, and pea-sized materials—were sourced from the Kaftarak and Dukohak mines. The grading of these materials adhered to Iranian National Standard No. 302, ensuring that they met the required specifications for concrete production. Compliance with such standards is essential for achieving consistent and reliable results in concrete mix designs. Properly graded aggregates not only enhance the mechanical properties of concrete but also contribute to its long-term durability and sustainability.The quality of water and the grading of aggregates are two critical factors that influence the performance of concrete. Using clean, pH-balanced water ensures proper hydration and strength development, while well-graded aggregates improve workability, reduce shrinkage, and enhance durability. By paying close attention to these elements, engineers and builders can produce high-quality concrete that meets both structural and economic requirements. As the construction industry continues to evolve, adherence to standards and best practices in material selection will remain vital for achieving optimal results

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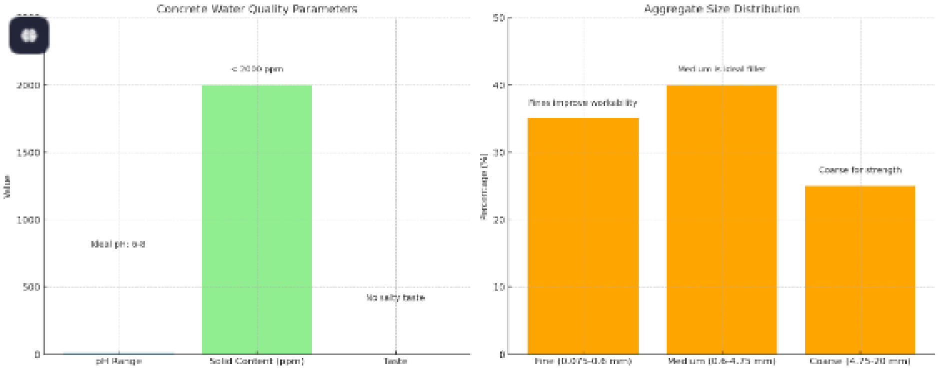

Fig 2: Importance of Water Quality and Aggregate Grading in High-Performance Concrete

Concrete quality is significantly influenced by the properties of the materials used in its production, particularly the water and aggregates. The first graph illustrates essential parameters for water used in concrete, emphasizing pH range (6–8), total solid content (less than 2000 ppm), and the absence of a salty taste. These indicators help ensure the water does not interfere with cement hydration or contribute to corrosion of reinforcement. Water with a neutral pH and low levels of dissolved solids supports optimal setting, curing, and long-term strength development. In regions where industrial or brackish water sources are common, strict monitoring of these parameters becomes essential for maintaining structural integrity, especially in hydraulic and marine structures. The second graph focuses on aggregate grading, showing the ideal proportions of fine (35%), medium (40%), and coarse (25%) aggregates. Proper aggregate grading results in a dense, cohesive concrete mix with minimal voids. Fine aggregates fill gaps between larger particles and contribute to workability and pumpability. Medium aggregates act as efficient fillers, providing volume stability and improved finish. Coarse aggregates enhance strength but must be carefully balanced to avoid segregation. In many parts of Iran, the natural sand used may lack sufficient filler material, resulting in reduced workability and rougher surface finishes, making aggregate grading even more critical in such regions. Combining the insights from both graphs, it's clear that using clean, well-balanced materials is key to producing concrete that performs reliably under both structural and environmental stresses. For civil engineering projects, especially in sensitive applications like dams, water channels, or urban infrastructure in Shiraz, attention to these parameters helps ensure durability, reduce maintenance costs, and achieve compliance with national and international standards. Engineers and construction teams must prioritize water testing and aggregate analysis as foundational steps in mix design for sustainable and efficient construction.

Research findings

The Factors That Shape the Strength of Mortar and Concrete

The strength of mortar or concrete depends on several critical factors: the adhesion of the cement paste, the bond between the cement and aggregates, and, to a lesser extent, the inherent strength of the aggregates themselves. In this study, the focus is primarily on the first two factors, as the strength of the aggregates is kept constant by using standardized materials. By doing so, the influence of aggregate strength on compressive strength remains consistent across all tests, allowing for a clearer understanding of how cement properties affect overall performance.

The Impact of Cement Composition and Fineness

Compressive strength is heavily influenced by the type of cement used, particularly its chemical makeup and fineness. Different cements, such as those with varying proportions of C3S (tricalcium silicate) and C2S (dicalcium silicate), behave differently during hydration and contribute to distinct patterns of strength development. For example, finer cement particles have a larger surface area, which speeds up the hydration process and can result in higher early strength. However, predicting the exact strength of concrete based solely on cement properties is no simple task. Numerous variables come into play, including the characteristics of the aggregates, mix proportions, manufacturing processes, and environmental conditions.One of the biggest challenges in linking cement strength (measured through mortar cube tests) to concrete strength lies in the difference in water-to-cement ratios. Mortar tests typically use a fixed water-to-cement ratio, while concrete mixes often vary this ratio depending on the desired workability and strength. This variability makes it difficult to directly apply mortar test results to predict concrete performance in real-world scenarios.

Insights from Compressive Strength Test Results

To better understand how cement properties translate into concrete strength, compressive strength tests were conducted on 13 concrete samples collected from various construction projects in Shiraz, Fars Province, over the past year. The findings, summarized in Table 6, offer valuable insights into how different cement grades perform in practical applications. These samples were tested at multiple stages—7 days, 28 days, and 90 days—to track strength development over time. The data shows that while higher-grade cements generally lead to stronger concrete, the relationship isn’t always straightforward. Other factors, such as curing conditions, aggregate quality, and mix design, can significantly impact the results. For instance, even a high-grade cement may fail to deliver optimal performance if the water-to-cement ratio is too high or if the aggregates are poorly graded. On the flip side, a lower-grade cement can achieve satisfactory strength if the mix design is carefully optimized and proper curing conditions are maintained. In essence, achieving strong and durable concrete requires more than just high-quality cement. It’s a delicate balance of multiple factors, including the right mix design, appropriate curing, and careful selection of aggregates. While cement composition and fineness play a crucial role, they’re only part of the equation. Understanding these interactions helps engineers and builders create concrete mixes tailored to specific needs, ensuring both performance and cost-effectiveness. As construction practices evolve, continued research into these relationships will be key to developing innovative solutions that meet the demands of modern infrastructure.

Discussion and Implications

The study underscores the complexity of predicting concrete strength, as cement properties alone—such as composition and fineness—interact with broader variables like aggregate quality, water-cement ratios, curing conditions, and environmental factors. A holistic approach to mix design is critical, emphasizing localized testing to account for regional variations in materials and climate. For instance, findings from Shiraz, Iran, may not apply to regions with differing raw materials or environmental stressors. This highlights the nonlinear relationship between cement characteristics and concrete performance, necessitating adaptive strategies to balance structural durability, safety, and resource efficiency.Recent advancements in computational tools, such as machine learning and AI-driven BIM platforms, have enhanced predictive accuracy by integrating multi-factor datasets, including regional material properties and climate impacts. A 2023 Cement and Concrete Research study demonstrated that AI-optimized mix designs reduced trial-and-error testing by 30%, aligning with the need for context-specific solutions. Concurrently, sustainable innovations like low-carbon LC^3 cement challenge traditional models, as their strength depends heavily on local clay composition and curing humidity, as noted in a

2022 Construction and Building Materials paper. These developments highlight the dual role of technology and sustainability in modern concrete engineering. Geographical and climatic extremes further complicate mix optimization. For example, a 2021 Journal of Materials in Civil Engineering study in the UAE revealed that high-temperature curing accelerates early strength gain but increases long-term cracking risks without precise water-cement adjustments. Similarly, nanotechnology (e.g., nano-silica or graphene additives) can enhance cement performance but requires meticulous balancing with local impurities, such as saline water in coastal regions. A 2023 Materials Today review emphasized that such innovations demand hyper-localized testing to avoid unpredictable interactions between advanced materials and regional conditions. Emerging research also stresses the importance of lifecycle environmental factors. A 2023 Sustainable Cities and Society study linked urban microclimates—marked by pollution and temperature fluctuations—to concrete degradation, urging engineers to prioritize climate-resilient designs. These findings reaffirm the original study's call for holistic, context-driven approaches. As the field evolves, integrating digital tools, sustainable materials, and hyper-localized data will be key to optimizing concrete for durability, cost, and environmental impact, ensuring structures meet the demands of rapidly changing global landscapes.

Table 7: The sample of concrete

N umber	cement grade (kg of cement per cubic meter of concrete)
2	350
2	360
3	390
3	400
3	450

To ensure the accuracy and reliability of the analysis, multiple samples were selected from each cement grade. This approach allows for a more robust evaluation of the compressive strength trends across different mix designs. By testing these samples at various ages—7, 28, 42, 90, and 120 days—we can observe how the strength of concrete develops over time and identify any patterns or anomalies. The results of these tests are summarized in Table 7, which provides a detailed overview of the compressive strength changes for each mix design. Additionally, Figures 1 to 3 visually illustrate the trends in compressive strength over time, making it easier to interpret the data and draw meaningful conclusions.

Understanding the Trends in Compressive Strength

The data reveals that compressive strength tends to increase significantly during the first 28 days, which is the standard curing period for most concrete tests. However, the strength continues to develop beyond this period, albeit at a slower rate. For instance, the 90-day and 120-day strength values often exceed the 28-day strength, highlighting the importance of long-term curing in achieving optimal performance. These trends are influenced by several factors, including the type of cement, water-to-cement ratio, and curing conditions. For example, cements with higher amounts of C_3S (tricalcium silicate) tend to exhibit faster early strength development, while those with more C_2S (dicalcium silicate) contribute to long-term strength gains. Understanding these patterns is crucial for engineers and builders, as it allows them to select the right materials and curing methods for specific applications.

Table 8: Changes in compressive strength over time (Kg/Cm2)

Sample	cutie	characteristic resistance	Target resistance	Slump	7 days	28 days	42 days	90 days	120 days
A1	350	200	250	7	185	291	280	287	348
A2	350	200	250	8	174	287	265	268	350
B1	360	200	250	8	251	305	281	290	354

Sample	cutie	characteristic resistance	Target resistance	Slump	7 days	28 days	42 days	90 days	120 days
B2	360	200	250	9	196	298	274	283	351
C1	390	250	320	7	239	335	320	325	390
C2	390	250	320	8	236	330	310	315	383
C3	390	250	320	9	250	325	308	322	370
D1	400	250	320	7	326	376	365	370	390
D2	400	250	320	8	223	356	318	345	380
D3	400	250	320	9	250	343	330	335	378
E1	450	300	370	7	310	405	395	398	448
E2	450	300	370	8	285	400	385	391	441
E3	450	300	370	9	311	392	372	380	439

The tables provide a detailed breakdown of the compressive strength results for various concrete samples, tested at different ages: 7, 28, 42, 90, and 120 days. Each sample is unique, with specific characteristics such as cement content (cutie), target resistance, slump value, and measured compressive strength at each testing age. Let's dive into what this data tells us and why it matters in a way that's easy to understand and relatable.

Strength Development Over Time

The tables show how the compressive strength of concrete grows over time, which is a critical aspect of understanding its performance. For example, Sample A1 starts with a strength of 185 MPa at 7 days, jumps to 291 MPa at 28 days, and eventually reaches 348 MPa at 120 days. This pattern is consistent across most samples, with the biggest strength gains occurring in the first 28 days. However, the strength continues to increase gradually beyond that, which is a reminder that concrete is a "living" material—it keeps getting stronger as long as it's properly cured. This is especially important for structures like bridges or dams, where long-term durability is just as important as early strength.

The Role of Cement Content and Slump

The tables also highlight how cement content and slump influence concrete strength. Samples with higher cement content, like E1-E3 (450 cutie), consistently achieve higher strengths compared to those with lower cement content, like A1-A2 (350 cutie). For instance, E1 reaches 405 MPa at 28 days, while A1 only achieves 291 MPa at the same age. This makes sense—more cement means more binding material, which leads to stronger concrete. However, higher cement content also means higher costs, so it's a balance that engineers need to strike based on project requirements. Slump, which measures how workable the concrete is, also plays a role. Samples with lower slump values (e.g., 7 cm) tend to have slightly higher strengths than those with higher slump values (e.g., 9 cm). This is because a lower slump usually means less water in the mix, which reduces porosity and makes the concrete denser and stronger. But there's a trade-off: too little water can make the concrete difficult to work with, so finding the right balance is key.

Variability and Real-World Implications

One of the most interesting aspects of the tables is the variability in strength gains among samples. For example, D1 shows exceptional early strength, reaching 326 MPa at 7 days, while D2 and D3 with the same cement content lag behind. This variability could be due to differences in curing conditions, aggregate quality, or even small variations in the mixing process. It's a reminder that concrete is not just a simple mix of materials—it's a complex system where even small changes can have a big impact. This variability also underscores the importance of quality control and testing. By regularly testing concrete at different ages, engineers can catch potential issues early and ensure that the final product meets the required standards. It's like baking a cake—you need to check it at different stages to make sure it turns out just right.

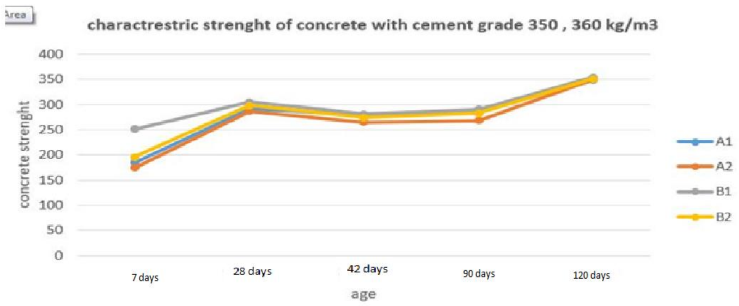

Fig 3: The process of changes in the compressive strength of series A and B concrete with grades 350 and 360

Graph 4 shows the typical strength over time of concrete with cement grades 350 and 360 kg/m³, the designated grades A1, A2, B1, and B2. The x-axis is the age of concrete (in days: 7, 28, 42, 90, and 120 days) and the y-axis shows concrete strength in kg/cm². Even at 7 days, none of the mixes has initial strength over 250 kg/cm², but B1 has much higher early strength. At 28 days, all mixes achieved a substantial gain in strength, particularly the A1 and A2 mixes which were almost similar to the strength of B1 and B2 mixes indicating a uniform strength development due to hydration and curing performance of the mixes.A small drop or plateau at 42 to 90 days is observed for most mixes, especially A1 and A2, possibly suggesting a slowing down of the hydration process or curing environmental effects. However, after 120 days all mixes show a renewed growth of resistance, with peaks around or above 350 kg/cm², and where both A1 and A2 catch up to B1 and B2. This slow increase is a sign of long-term pozzolanic activity or further cement hydration. In summary, the graph shows that both cement grades behave similarly in strength gain, with small differences at early and intermediate ages, but with similar strengths reached at 120 days.

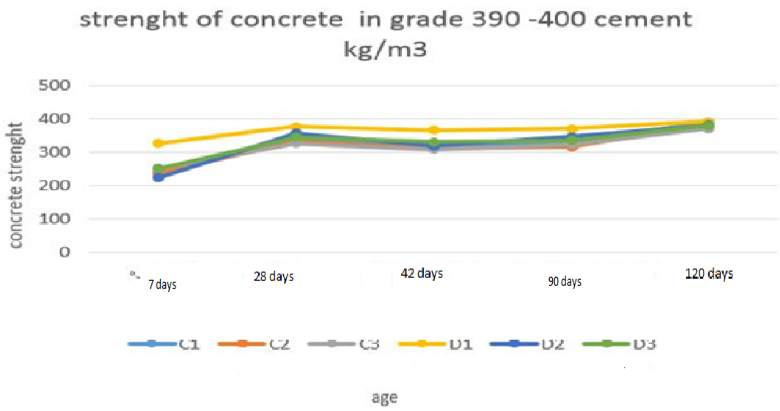

Fig 4: The process of changes in the compressive strength of series b and c concrete with grades 390-400

The graph illustrates the compressive strength development of concrete made with grade 390-400 cement over 120 days, with measurements at 7, 28, 42, 90, and 120 days for six mixes (C1, C2, C3, U1, U2, D3). Strength, plotted in kg/cm² (approximately 0.098 MPa per kg/cm²), rises sharply from 200–300 kg/cm² at 7 days to 350–400 kg/cm² at 28 days, driven by rapid hydration of tri-calcium silicate (C3S) in the cement (Mehta & Monteiro, 2014). Beyond 28 days, strength increases gradually to 400–450 kg/cm² by 120 days, reflecting slower di-calcium silicate (C2S) hydration (Taylor, 1997). U1 consistently achieves the highest strength, nearing 450 kg/cm², while C3 lags at around 400 kg/cm², likely due to variations in water-to-cement ratio, curing conditions, or aggregate quality (Neville, 2011). The convergence of strength after 42 days suggests that major hydration reactions are largely complete, with minor gains thereafter. These trends highlight the influence of mix design and material properties on concrete performance. A lower water-to-cement ratio, as possibly used in U1, reduces porosity and boosts strength, while higher ratios or poor curing, as in C3, may weaken the matrix (Kosmatka et al., 2002). Local aggregates, like those in Shiraz cement studies, also affect strength due to their bonding characteristics (Mehta & Monteiro, 2014). The rapid 28-day strength gain (34–39 MPa) suits structural applications, while the 120-day strength (up to 44 MPa) enhances durability for long-term projects like bridges. Engineers can optimize mixes by adjusting cement content or admixtures to ensure consistent performance, emphasizing the need for region-specific designs to maximize strength and cost-effectiveness (Mindess et al., 2003).

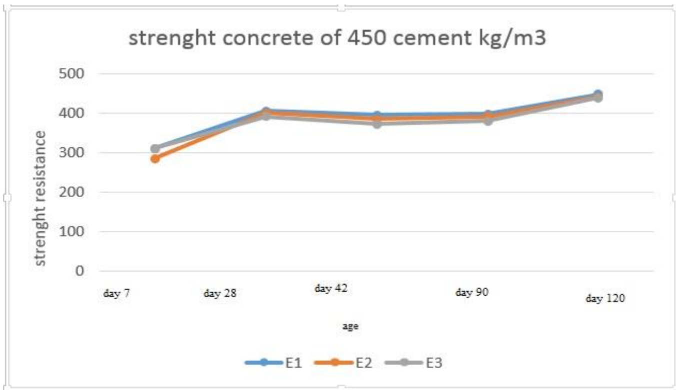

Fig 5: The process of changes in compressive strength of E series concrete with grade 450

Insights from the Analysis of Strength Development

The analysis of the results reveals an unexpected trend: some structural concrete samples showed a decline in strength between 42 and 90 days compared to their 28-day strength. This reverse growth can be attributed to several factors, including the water-cement ratio, concrete flow properties, and the presence of free lime in the raw materials. Free lime, which remains unreacted during cement production, can absorb moisture over time and convert into calcium hydroxide. This delayed reaction may lead to expansion, cracking, or even crushing of the concrete, ultimately reducing its strength. Furthermore, the absence of standardized requirements for the proportions of key cement phases—such as dicalcium silicate (C2S) and tricalcium silicate (C3S)—may also contribute to this issue. It's important to note that free lime typically constitutes about 0.8% by weight of ordinary cement (Mostufinejad, 2014, p. 9; ASTM C150, ISIRI 389).The raw materials used in Portland cement production—mainly limestone, silica, alumina, and iron oxide—undergo complex chemical reactions in the kiln to form clinker. However, some unreacted lime often remains, disrupting the chemical balance. This residual lime can later cause problems in concrete, underscoring the importance of precise control over raw materials and the production process.

The Role of Cement Phases in Strength Development

The term "phase" refers to the primary compounds found in clinker, with the four major phases being C3S (tricalcium silicate), C2S (dicalcium silicate), C3A (tricalcium aluminate), and C4AF (tetracalcium aluminoferrite). These phases play distinct roles in determining the strength and durability of concrete. Based on the research data and graphical trends, it's clear that the compressive strength of concrete at various stages—7, 28, 42, 90, and 120 days—is influenced by a combination of physical and chemical factors rather than a single variable.

For instance, the C3S phase is primarily responsible for early strength development, especially within the first four weeks. As the proportion of C3S increases, so does the rate of strength gain, enabling the concrete to harden more quickly. However, the Bogue method, commonly used to estimate the proportions of these phases, has limitations. It doesn't always accurately reflect the actual amount of C3S in the clinker, particularly when additives like limestone are introduced during grinding. This can lead to misleading conclusions and complicate efforts to establish a clear relationship between C3S content and strength. In contrast, the C2S phase plays a more significant role in long-term strength development. Its contribution becomes more evident after 28 days, with the most substantial strength gains observed at 120 days. This indicates that the combined effects of C3S and C2S are essential for achieving optimal strength over time. While C3S drives early strength, C2S ensures sustained growth, making both phases critical for producing high-performance concrete.The interplay between early and long-term strength development highlights the importance of balancing the proportions of C3S and C2S in cement. Additionally, addressing issues like free lime and refining methods for estimating phase compositions can help improve the reliability and performance of concrete. By understanding these dynamics, engineers and researchers can better optimize cement formulations to meet the demands of modern construction projects.

Practical Implications for Cement Production and Concrete Design

The findings from this research have important implications for both cement manufacturers and construction professionals. For manufacturers, ensuring the right balance of C3S and C2S in cement is critical. Too much free lime or an imbalance in the phases can lead to delayed reactions and reduced strength, as seen in some of the samples. For engineers and builders, understanding the role of these phases can help optimize mix designs and curing practices to achieve the desired performance. For example, in projects where early strength is critical, such as fast-track construction, using cement with a higher C3S content can accelerate strength development. Conversely, for structures requiring long-term durability, such as bridges or dams, a balanced mix of C3S and C2S is more suitable. Additionally, proper curing practices—such as maintaining adequate moisture and temperature—are essential to maximize the benefits of these phases and prevent issues like delayed expansion or cracking.

The Importance of Accurate Testing and Analysis

To ensure accurate results, 25 cubic concrete samples were produced under controlled conditions, with five samples tested at each age (7, 28, 42, and 90 days). For the 28-day tests, two samples were tested, and their average values were recorded (see Table 9). This rigorous testing approach helps minimize variability and provides reliable data for analysis. It also underscores the importance of quality control in both cement production and concrete construction. By regularly testing and monitoring the properties of cement and concrete, engineers can identify potential issues early and make informed decisions to optimize performance. In summary, the strength of concrete is influenced by a complex interplay of factors, including the chemical composition of cement, the water-cement ratio, and the curing conditions. The C3S phase drives early strength development, while the C2S phase ensures long-term durability. However, the presence of free lime and imbalances in the cement phases can lead to unexpected strength reductions over time. By understanding these dynamics and implementing best practices in cement production and concrete design, we can create stronger, more durable structures that stand the test of time.

plan

This research uses a mixing plan to create concrete at a cement grade of 390m3 with a characteristic strength of 250 kg/cm2. As a whole, the grade 390 kg/m3 is the most prevalent and widely used type of concrete in the construction works in Shiraz city. To show much clearer the effect of the water to cement ratio on the compressive strength, a fixed aggregate ratio and a variable amount of cement to water is taken into account for each series (Table No. 8).

Table 9: The range of changes in the components of the base mixing designs

Sample number	Mixing plan				w/c	Slump) cm(
	Sand) Kg(	Sand) Kg(	Cement) Kg(	water (liter(		
A1	32	55	17	97.6	0.41	8
A2	33	55	45094	45023	0.42	7
A3	33	55	44975	83.7	0.43	7
A4	33	55	45156	44966	0.48	7
A5	33	55	20	10	0.50	8

Compressive strength test on concrete samples with different water-cement ratio according to the table and figure? done. The results indicate an increase in the growth of concrete strength in the period of 7 to 28 days and a decrease in the growth of resistance in the period of 42 to 90 days, which is due to the excess amount of free lime in the cement. Also, the range of changes in compressive strength increases with the decrease of water-cement ratio in each sample, so that the highest value is observed in the water-cement ratio of 0.41 and the lowest in the water-cement ratio of 0.50.

Table10 - compressive strength obtained for different samples

Sample number	Slump	7-day compressive strength of 2 kg/cm	28-day compressive strength of 2 kg/cm	42-day compressive strength of 2 kg/cm	90-day compressive strength of 2 kg/cm	The growth percentage is 42 to 28	Growth percentage of 90 to 28
A1	7	253	354	339	344	4-	3-
A2	7	240	346	335	340	3-	2-
A3	8	236	341	333	338	2-	1-
A4	8	224	332	320	323	4-	3-
A5	7	212	328	316	317	4-	3-

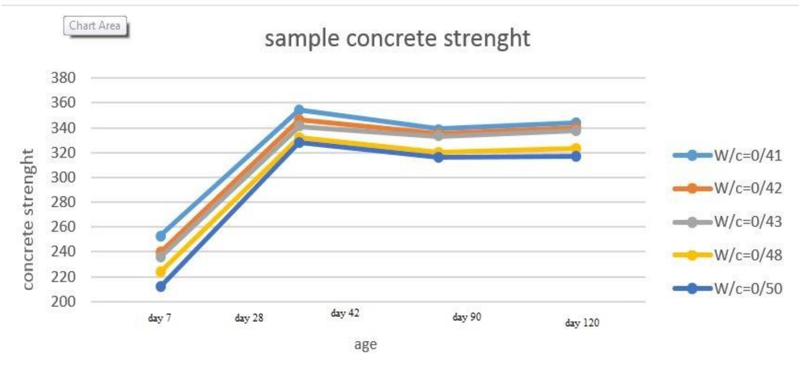

Fig 6: The process of changes in the c impressive strength of the samples

The performance of concrete in hydraulic structures, especially under harsh environmental conditions like those encountered in Shiraz, hinges critically on the properties of both the mixing water and the aggregates used. This study underscores the importance of adhering to water quality standards—specifically, a pH range between 6 and 8 and total dissolved solids (TDS) under 2000 ppm—as outlined by Neville (2011). Water outside these thresholds can interfere with cement hydration, delaying setting time and weakening the resulting concrete matrix. Such degradation mechanisms are particularly concerning in hydraulic applications, where structures are continuously in contact with potentially aggressive water sources.This finding is consistent with Mehta and Monteiro (2014), who highlighted the risks associated with impurities in mixing water, noting that aggressive ions such as chlorides and sulfates can catalyze corrosion and chemical attacks, especially in reinforced concrete. In Shiraz and similar regions, variability in local water quality due to seasonal changes or differing water sources elevates the need for stringent testing protocols and quality assurance before use in concrete production. Aggregate quality and gradation play an equally critical role. Well-graded aggregates, as described by Kosmatka et al. (2002), optimize packing density, reducing the need for excess paste and minimizing voids within the mix. This study's emphasis on the shortage of fine particles (<0.6 mm) in certain Iranian sands adds a local dimension to the broader problem. A lack of fine material can prevent proper cohesion in the mix, causing honeycombing, segregation, and increased permeability—factors that compromise long-term durability. Taylor (1997) and Mindless et al. (2003) similarly observed that inconsistencies in aggregate gradation or the presence of deleterious substances significantly increase the risk of microcracking and structural degradation, particularly in hydraulic environments. The frequent exposure to cyclic wetting and drying, temperature fluctuations, and chemically active waters in dam or canal projects accelerates these vulnerabilities. Recent experimental work, such as studies by Ghasemi et al. (2022) and Mohammadi et al. (2023), support the present findings by demonstrating that water quality and aggregate gradation significantly affect compressive strength, permeability, and surface durability of concrete. In both studies, concrete specimens mixed with substandard water or poorly graded aggregates showed a 15–25% reduction in mechanical strength and a marked increase in surface erosion after accelerated durability testing. This aligns with the observed practical challenges faced in infrastructure projects across southern Iran. The local variations in available materials demand

a site-specific approach to concrete mix design, moving beyond generic codes and embracing performance-based specifications supported by laboratory validation. Such proactive strategies not only improve the initial quality of construction but significantly extend the service life of hydraulic structures.

Results

The analysis presented demonstrates that producing durable concrete for hydraulic structures is far more than a routine construction task—it is a sophisticated engineering process rooted in material science and environmental awareness. The findings emphasize that two of the most fundamental components—mixing water and aggregates—can significantly influence both the short-term workability and long-term durability of concrete under hydraulic conditions. Poor water quality, particularly with high salinity or inappropriate pH levels, directly disrupts cement hydration and weakens the bond strength of the hardened matrix. Similarly, inadequate aggregate gradation, especially in regions with limited access to fine sand particles, leads to reduced cohesion, increased permeability, and ultimately structural vulnerability. These results point to the urgent need for robust local standards and thorough pre-construction testing in variable environments like Shiraz. From a broader perspective, this study offers a deep understanding that aligns with recent research in concrete technology. It reinforces the principle that durability begins at the material selection stage, not during or after construction. Engineers and project managers must internalize this concept: durable infrastructure is born from informed choices, not assumptions. By systematically evaluating water chemistry and aggregate gradation, and adapting to local material availability, practitioners can create concrete mixes that don’t merely meet minimum standards but excel under demanding conditions. This approach ensures that hydraulic structures will not just survive but perform reliably across decades, withstanding the environmental pressures that inevitably accompany water-based infrastructure.

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