Effects of loading rates on concrete compressive strength

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Abstract. Concrete structures are subjected to loadings which can be static or dynamic and in most cases, both. Deeper understanding on how concrete behaves to different modes of loading needs to be assessed, particularly the rate; and to study its effects, a property of concrete such as its compressive strength requires to be examined in relation to the changes in the loading rates. Different loading conditions or rates can alter how cracks in concrete are formed in terms of crack velocity and crack intensity in regions where stress equals to the applied pressure. However, various studies have shown contradicting results with respect to how varying loading rates may affect the compressive strength of concrete. This research conducted 5 different concrete mixes to study the effect of loading rate on compressive strength of concrete. Concentric uniaxial loading, in terms of pressure as opposed to displacement, was loaded to the hardened concrete cube specimens at different loading rates increasing constantly at 0.2 MPa/s and 0.4 MPa/s which are within the standard limits. Moreover, loading rates beyond the extremes were also subjected in one of the mix design for study and analysis purposes. Results showed that there is a relatively minor relationship between the rate of loading and the strength in terms of compression for both specimen sizes in which the trend indicates that as the loading rate is increased, the compressive strength also increases but with minimal deviation in the magnitudes of the strengths.

1. Introduction

Loadings are transferred within structures in which the loading rates vary in terms of displacement, mm/s or pressure, MPa/s. The behaviour of concrete structures however, needs to be clearly understood and justified through series of experiments. Fracture and crack propagation would differ with different loading rates. Hence, studies will help understand its failure mechanism.

It is generally known that high loading rates have significant effect on the behaviour of concrete structural elements [1-2]. It was confirmed in the experiments carried out by Sharma and Ozbolt [3] that with increased loading rate, the loading capacity of concrete also increases. It is concluded that an increase in loading rate results in a minimal increase in both fracture toughness and nominal strength [4-5]. Similar results were obtained from the studies conducted by David et al. [6].

Concrete strength under any boundary condition and loading configuration closely relates to the crack formation and propagation [7]. It was found that under low and high loading rates there is a considerable difference in the tendency of crack velocity. Under low loading rates, from 10-4 mm/s to 10-1 mm/s, the main crack continued with increasing velocity. The late-stage velocity was around one order higher than that of the early stage. However, at high loading rates, from 10-2 mm/s to 10-3 mm/s, the main crack was found to propagate in an almost constant manner [8]. These researchers used loading rates in terms of displacement, mm/s which only takes into consideration the effects of altering the loading rates regardless of the contact area at the point of loading. On the contrary, this paper adopts the
loading rate in terms of pressure, MPa/s which takes into account the contact area. This is however still similar since the studies being carried out focus on the same objective in determining the effects with varying loading rates.

Bazant et al. [5] clarified that there would be a decrease in critical crack propagation for slower loadings in static fracture but this trend would differ in the dynamic fracture. The results from the experiments conducted by Hamoon and Hooshang [9] showed that the behaviour of concrete before and after peak loading is dependent on the loadings count as well as the loading rate; the graphs yielded from their experiments showed increased compressive strength with increased loading rate. Experiment by Ozbolt et al. [10] and Zhang et al. [11] also showed that the strength escalates with an increasing rate of loading. Lower loading rates result in reduced strength since cracks have more time to propagate and the mechanisms of creep predominate [12].

However, a study undergone by Zhou et al. [13] contradicts with the findings stated by researchers in the preceding paragraph. They stated that the distance of crack propagation between the starting point and the bifurcation reduces in value as the loading rate is increased within the standard limits; which means that cracks start to branch out after a short distance when subjected to higher loading rates hence would have the tendency to result in a lower maximum compressive strength. Moreover, they also concluded that with loading rate increments, the average velocity of cracks increases gradually. Therefore, concrete would fail at a lower compressive strength. Another study by Chen et al. [14] found that with increasing loading rate, the crack width and ductility decreases but the amount of shear crack within the concrete increases. This means that the brittleness of concrete increases when subjected to higher loading rates which lead to early failure and the increasing shear cracks also contributes to its early failure as well. Also from the experiment conducted by Ngo et al. [15], it was found that the crack velocity in concrete increased with the increase in the loading rate in terms of strain rate, i.e. displacement.

Different rates contribute significant effects on compressive and tensile strengths of concrete; and indirectly affect the elastic modulus as well as the Poisson’s ratio. The key difference between different loading rates is the magnitude of energy transferred to the specimen in which an increased energy transferred per unit time to the concrete leads to the cracks choosing a more direct path to cause the concrete to break; rather than the cracks propagating around the aggregates and passing the looser paths, given the power generated by the imposed force, the cracks break the aggregates and choose the shorter path [9]. It was also verified experimentally that with increasing loading rates, the fracture surface tends to decrease [16]. Hence, this would result in an increase in maximum compressive strength.

From a logical perspective, it can be assumed that when cracks form and travel within the concrete which is subjected to lower loading rates, the cracks would have the time to change direction and propagate towards the weaker parts resulting in cracks in many directions causing earlier failure than that subjected to higher loading rates. Newton’s 3rd law applies to almost anything and in this case, the amount of reaction force from the concrete specimens will always be equal to the magnitude of the force that is applied onto the concrete specimen top area. However, the magnitude of the reaction will only be up to the limit of the strength of the concrete before it fails, i.e. the ultimate load capacity.

Following the preceding paragraphs, it can be seen that several researchers have conducted experiments to study the effects of loading rates on the behaviour of concrete in which some found that concrete compressive strength increases with higher loading rates whereas some found otherwise. Deeper understanding on how different loading rates affect concrete behaviour is crucial to building and construction industries. This research predominantly aims to confirm or create major comparisons which can lead to further discussions and interpretations for a better and wider understanding on how concrete behaves in different loading rates and conditions. This research is also a further investigation and directly relevant to the study made by Abdullah [17] concerning the effects of specimen sizes on the compressive strength of concrete to determine their significances towards the hardened properties of concrete. This study correlates to series of studies with respect to the determining various properties of concrete as a construction material that can be established in laboratory conditions. The purpose of the main study includes improvements in conveying core concepts to engineering students to ensure quality of programmes and/or for ensuring potential accreditation by respective professional bodies which are under the relevant institutions [18], as well as development of the university to be a leading research
and teaching centre in the field of concrete technology hence, shaping a sharper understanding in the behaviour of structures in different loading rates.

2.Experimental Programme

2.1.Materials, Specimen details and preparation

Results and data from 5 relevant mixes were extracted and context in the proceeding discussion are in relation to those mix designs. For all the mixes, the same type of cement was used which was Ordinary Portland cement (OPC). Fine aggregates used were from Sungai Paku and designated into F category. Specimens used were predominantly cubes of 100 mm dimensions, with 3 specimens being used to determine the mean properties at a particular age. Densities of cured cube specimens range between 2215 kg/m³ and 2375 kg/m³. Cubes of 100 mm dimensions were used as per Duraman [19] who had previously shown that 3 cube specimens of 100 mm dimensions were preferred being more optimally beneficial in similar laboratory conditions and yielded results which were statistically consistent. In addition, for mix M10, both cubes of 100 mm and 150 mm dimensions were used; the reason was due to studying the differences in effects due to both varying load rate and specimen sizes. Abdullah [17] had previously shown differences in concrete compressive strength due to different specimen sizes. It is therefore clarified that quantitative comparisons discussed in the next section are strictly between specimens of similar sizes i.e. 100 mm cube specimens, unless mentioned otherwise.

The ratios of the fine aggregates to the coarse aggregates are in the range of 0.25 to 0.27; this is to keep the amount of fine aggregates to be minimal relative to the coarse aggregates for optimal voids in the concrete matrix to be filled with cement. Also, the w/c is kept in the range of 0.49 to 0.59 as well precisely for optimum strength purposes. The specimens were stored in a curing tank at 20°C ± 2°C and de-moulded after 24 hours. Table 1 below tabulates the relevant mixes 6-10 extracted from the overall experiment.

| Mix | Characteristic strength, MPa | W/C   | FA/CA | %Total aggregates |
|-----|-------------------------------|-------|-------|-------------------|
| M6  | 25                            | 0.59  | 0.26  | 80                |
| M7  | 25                            | 0.59  | 0.26  | 70                |
| M8  | 30                            | 0.55  | 0.25  | 66                |
| M9  | 35                            | 0.49  | 0.25  | 64                |
| M10 | 30                            | 0.55  | 0.26  | 66                |

2.2.Test Procedure

Concentric uniaxial loading was subjected to the hardened concrete cube specimens under the same loading rates 0.20 and 0.4 MPa/s for all specimens which is within the limits laid in BS1881-116:1983[20]. Specimens from one the mixes (M10) were tested for compression at loading rates out of the extent in the standards which were 0.1 MPa/s and 0.5 MPa/s in order to study the effect of the loading rate on the compressive strengths of concrete subjected to loading rates which deviates from the standard limits.

3.Discussion on Experimental Results

A brief insight to relate the statements discussed in the introduction and the results obtained in this project, it needs to be understood that different materials vibrates at different rates. Concrete is vibrating at its natural frequency and when subjected to a low loading rate, two possible theories can be deduced; at lower loading rate it causes energy to be transferred at a different frequency than the normal frequency in concrete in which the larger the difference, the higher the chance of the concrete to fail; or the second is that at lower loading rate the energy transferred causes energy to be transferred at frequency close to the natural frequency of concrete, hence causing resonance and eventually large oscillations leading to failure.
3.1. Compressive Strength of Developed Concrete

Table 2 shows only the results obtained from mixes 6, 7 and 9 which focuses on the compressive strengths of the specimens all tested at 14-day strength at two different loading rates.

| Mix | W/C | %Total aggregates | Loading rate | %Difference |
|-----|-----|-----------------|--------------|-------------|
|     |     |                 | 0.2 MPa/s | 0.4 MPa/s |            |
| M6  | 0.59| 80              | 22.32 | 23.94 | 7.26 |
| M7  | 0.59| 70              | 27.68 | 27.48 | 0.72 |
| M9  | 0.49| 64              | 30.24 | 31.72 | 4.89 |

![Figure 1](image_url)  
**Figure 1.** 14-day compressive strength of 100mm cube specimens at two different loading rates

The noticeable trend in the strengths obtained as seen from figure 1 is the generally known trend that as w/c decreases as well as percentage total aggregates, compressive strength increases and is independent of the loading rate used. For M6, as opposed to the compaction method used for the other four mixes, manual compaction as per standards was used. Despite of this different compaction method, the results still yielded as per findings of other researchers discussed in Section 1.

From figure 1, results shows that the higher the loading rate the higher the compressive strength, except for M7 where it showed otherwise. For both M6 and M9, results show that the compressive strength obtained for the loading rate of 0.4 MPa/s is approximately 7.26% and 4.89% higher than that of the compressive strength at a loading rate of 0.2 MPa/s respectively. Experiments by Ozbolt et al. [10] and Zhang et al. [11] resulted in the same trend as well.

For M7, this mix design is similar to M6 having the same w/c and FA: CA ratios but with the total percentage of aggregates by volume changed from 80% to 70%. This serves to check whether the trend would change at lower total percentage of aggregates. It can be deduced that the difference in average strength at two different loading rates is 0.72% which is fairly lower than that discussed in the preceding paragraph. As mentioned earlier, this mix has lower percentage of aggregates. Hence, it can also be
deduced that the lower the percentage of aggregates, the lower the difference in compressive strength but the compressive strength shows a lower value at higher loading rate which contradicts the results obtained by most researchers. It can be seen that the difference in loading rates has a relatively less significant impact on the compressive strength results.

3.2. Early Strength of Concrete
Table 3 shows the compressive strength at 7-day for mix M8 for further comparison with the other mixes M6, M7 and M9. This also serves as a check for the consistency of the trend at different concrete age.

From the table 3 and the results as tabulated in table 2 it can be seen that as the strength of the concrete develops, i.e. forms a stronger concrete matrix, the percentage difference in compressive strengths between concrete specimens subjected at different loading rates also increases. Figure 2 depicts the possible quadratic relationship between the average compressive strength obtained from specimens subjected to two different loading rates and the percentage deviation between the two applied loading rates (0.2MPa/s and 0.4MPa/s).

| Mix  | Loading rate | %Difference |
|------|--------------|-------------|
|      | 0.2 MPa/s    | 0.4 MPa/s   |               |
| M8   | 28.99        | 29.56       | 1.96          |

Figure 2. Percentage (%) deviation in strength between loading rates 0.2MPa/s and 0.4MPa/s for mixes M6, M7, M8 and M9.

With the assumption that the 7-day and 14-day strengths of concrete do not differ much, it can be deduced from the figure 2 that there would be two limits of compressive strengths of concrete in which the difference in loading rate would have no effect. The graph shows that these predicted values would be around compressive strengths of 27.0MPa and 28.6MPa. If loading rates would not affect the compressive strength of concrete which could also mean that the concrete is resistant to any impact or loading condition, then it could be assumed and predicted that those specific compressive strengths correlates with an optimum mix of a particular characteristic strength of concrete.

3.3. Varying Loading Rate and Specimen Sizes
Figure 3 illustrates the differences in compressive strengths between 100mm and 150mm cube specimens at three different loading rates, i.e. 0.1, 0.3 and 0.5MPa/s with the first and the latter being extreme value that deviates from the standard loading rates used in other experiments.
Figure 3 illustrates the tabulated values in the proceeding Table 4 that shows the compressive strength results for Mix M10 at 14 day age loaded at three different loading rates of 0.10, 0.30 and 0.50 MPa/s. The purpose of this set of results was to determine any inter-relation of results with respect to different specimen sizes at different loading rates.

Table 4. Cubes tested at 14-day strength at different loading rates (Mix M10)

| Loading rate (MPa/s) | 0.1  | 0.3  | 0.5  |
|----------------------|------|------|------|
| 100mm                | 27.31| 27.43| 27.08|
| 150mm                | 40.62| 40.94| 41.64|
| % increase           | 48.70| 49.30| 53.80|

It can be concluded from table 4 above that regardless of the specimen size, compressive strengths increases as loading rate increases. Similar to the results discussed in the article done by Abdullah [17], loading rates has minor significance as opposed to specimen sizes as the difference in compressive strength deviates only slightly for the same specimen size subjected to different loading rates. However, this trend apparently applies up to the limit of 0.4MPa/s for 100mm cubes. It is recommended that further tests are done for concrete at other ages. These results are consistent with the findings by various researchers as discussed in the second paragraph in Section 1 and this is beneficial to attract more researchers to plan and conduct more experiments with the same objectives but expanding more types of conditions in relation to how different loading rates are applied onto concrete specimens, i.e. using biaxial concentric loadings.

4. Conclusions
The results from the preceding section are consistent showing visible and significant trends both with loading rates and specimen sizes. From these results it can be concluded that as loading rate increases, resulting compressive strength of concrete which has high percentage composition of aggregates also increases. It can also be understood that at low loading rates, cracks tend to propagate through weaker areas at a faster rate as opposed to concrete subjected to high loading rates. Compressive strength
increases as loading rate increases up to the maximum limit of 0.4MPa/s regardless of the specimen size. Moreover, when concrete is subjected to loading rates outside the standard limits, percentage increase in compressive strength for different specimen size is relatively low for 0.1 MPa/s loading rate; and percentage increase is relatively high for 0.5 MPa/s loading rate, i.e. directly proportional.

5. References

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