PRODUCTION SECTION

UDC 539.4

Effect of Platen Restraint on Stress–Strain Behavior of Concrete under Uniaxial Compression: A Comparative Study

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The stress-strain model of concrete depends on the degree of frictional resistance across the loading surfaces of a test specimen depending on the antifriction medium used during testing. This article presents a comparative study of platen restraint on the behavior of concrete under uniaxial compression based on an experimental investigation. The effect of four commercially available antifriction media (neoprene, polyvinyl chloride, teflon, and grease) with different layer thicknesses on platen restraint have been studied for a normal strength concrete and a relatively high-strength concrete. Subsequently, the effect of platen restraint has been quantified using the analogy of toughness. The experimental results indicate that post-ultimate response of concrete is significantly affected by platen restraint. It is shown that the stress–strain curve obtained from a conventional uniaxial compression test not only describes specimen/material behavior but also represents interaction between specimen and loading platen. Among the four antifriction media used in this investigation, grease is the most effective in reducing frictional resistance. Failure patterns of the concrete specimens for different antifriction media are also subsequently analyzed.

Keywords: uniaxial compression test, platen resistant, antifriction medium, stress–strain behavior of concrete, failure pattern.

Introduction. Concrete has a wide range of applications as a modern construction material because of its capability of meeting high performance engineering requirements. The common ingredients for making concrete such as cement, aggregate and water are easily available in most parts of the world. A broad familiarity with the procedure for the batching, mixing, casting and curing of concrete has been naturally developed over the years. Concrete can be moulded into virtually any shape and size according to requirement. In structural applications, concrete is designed primarily to resist compressive loads since this material is very strong in compression as compared to tension. The compressive and flexural behavior of concrete is usually characterized by its strength in uniaxial compression and by its stress–strain behavior under such loading [1, 2]. For safe and economic design of concrete structures, it is of utmost importance to understand the stress–strain behavior of concrete precisely. During compression tests, the contact between metal end platens and the concrete specimen creates a frictional resistance at the ends of the specimen (platen restraint), which affects the stress–strain behavior of concrete. A brief review concerning the studies of platen restraint on the constitutive model of concrete is presented in the next paragraph.

Early researchers (Bresler and Pister [3], Iyengar et al. [4]) used a thrust bearing assembly by means of ball bearings to reduce friction in concrete cylinder testing. Hughes and Bahramian [5] used M.G.A. pad to reduce the friction for determining uniaxial compressive strength of concrete. An M.G.A. pad consists of a melinex polyester film, a layer of molyslip grease and a hardened aluminum sheet. The reason behind using aluminium sheet is that it has a similar lateral expansion to that of concrete under compression. Kupfer et al. [6] used brush bearing platens consisting of a series of small steel bars meant to flex with the deformation of concrete without buckling. Later comblike platens were used by many researchers (Buyukozturk et al. [7], Atan and Slate [8], Tasuji et al. [9]) to minimize the end friction. Several studies are also found in the literature to address the influence of other factors involved in concrete testing on the material model of concrete. Dhir and Sangha [10] studied the effect of several factors related to testing techniques on the stress–strain behavior of concrete such as specimen slenderness ratio, diameter of test platen used to transmit load from the testing machine to the test specimen, ratio of specimen diameter to maximum size of aggregate and the methods employed for strain measurement. Recent studies include the effect of reversed cyclic loads on bond strength deterioration of concrete members (Choi et al. [11]), hygrothermic effect on mechanical stresses and crack analysis of concrete (Dahmani [12]), effect of external bar retrofitting on the bearing capacity of RC beams (Vasudevan and Kothandaraman [13]), effect of AFRP bar reinforcement on flexural behavior of concrete beam (Buyukkaragoz et al. [14]) and effect of curing material (Yilmaz and Turken [15]) on the constitutive relationship of concrete. Comparative studies of different techniques to reduce platen restraint are discussed next. Gerstle et al. [16] carried out a comparative investigation using many different friction reduction methods such as cushion system, platens cured with febcure, combination of polyethylene sheets and grease, aluminum bearing platens and brush bearing platens. Kotsovos [17] experimentally investigated the effect of platen restraint on stress–strain relationship of concrete under uniaxial compression through a comparative assessment using neoprene rubber, MGA pad and brush platen. They suggested that as the end friction is reduced, the descending branch of stress–strain curve of concrete becomes steeper. Tschegg et al. [18] compared the use of brush platens and Teflon film to reduce frictional resistance and ventured that the ideal correction can be realized by a mechanism that is capable of following the lateral deformation of test specimen under compressive load and allows a homogeneous and constant force initiation in the specimen. Of late, Lee et al. [19] have used Teflon to reduce surface friction and they have concluded that Teflon is more effective than brush platens.

Most of the investigations carried out so far concerning the issue of platen resistant on stress–strain behavior of concrete are concentrated on biaxial or multiaxial stresses. Comparative studies on platen restraint using different antifriction media for uniaxial compression are very scarce in available literature, though such comparative assessments are quite useful for practical purposes. Since the effect of platen restraint has a considerable influence on post-ultimate material model of concrete, it is desirable to comprehensively investigate its effect to propose more precise constitutive models for concrete, which will enable more effective utilization of the strength after concrete reaches the ultimate strength with the adequate level of confidence. Moreover, brush platens, which are considered to be the most effective in reducing platen restraint, are relatively difficult to fabricate and hence there is the need to explore other antifriction media, which are readily available and easy to use in the routine testing of concrete in uniaxial compression. Objective of the present study is to experimentally investigate the effect of platen restraint on stress–strain behavior of concrete under uniaxial compression using four different commercially available antifriction media (neoprene, polyvinyl chloride (PVC), teflon, and grease) for normal as well as relatively high-strength concrete. The effect of layer thickness of different antifriction media has also been explored. The comparative assessment of the aforementioned four antifriction media with different layer thicknesses to minimize the effect of platen restraint, in case of normal as well as high strength concrete is first attempted in this study.

1. **Post-Ultimate Material Behavior of Concrete: Effect of Platen Restraint**. The effect of platen restraint on post-ultimate behavior of concrete is briefly discussed in this section for the convenience of common readers. Complete stress–strain behavior of

concrete under uniaxial compression is normally obtained by loading cylinder specimens at a constant rate of displacement, wherein the applied uniaxial load is transferred through steel platen as shown in Fig. 1a. The central zone of the cylinders under such uniaxial compression is subjected to a near-uniform uniaxial compressive stress (Fig. 1b), while a complex state of compressive stress (Fig. 1c) is imposed on the end zones due to the frictional resistance generated from the interaction between the specimen and steel platen.

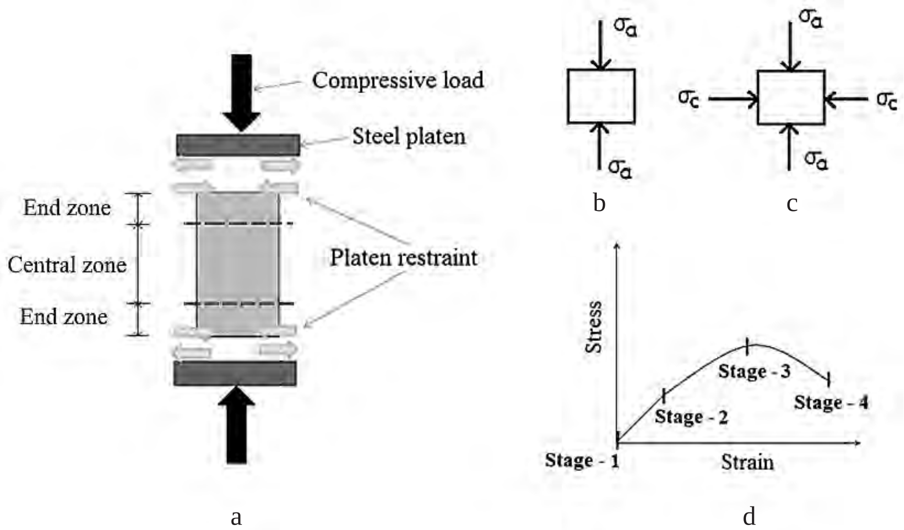


Fig. 1. Illustration of platen restraint in a typical uniaxial cylinder compression test (a); stress state of the elements of central (b) and end (c) zones; typical stress–strain behavior of concrete (d).

As the effect of platen restraint reduces away from the two ends of the specimen, the value of σ_c approaches to zero in the central zone (Fig. 1). During the test, cracks parallel to the direction of loading appear in the central zone of the specimen at a load level close to the ultimate load-carrying capacity (Stage 3). At this stage, stresses in end zones remain below ultimate strength and thus it remains uncracked, whereas the stresses in the central zone attain the ultimate strength value. Due to the presence of cracks in the central zone, the lateral expansion of the central zone becomes much higher, as compared to that of end zones resulting in the development of internal forces at the interfaces of these two incompatible zones. If the stresses in the end zone of a specimen are considered, two lateral stresses act there: the outward stresses exerted by the central zone due to incompatible lateral expansion of the two zones and the inward stresses exerted by the steel platen due to frictional resistance. With increasing lateral deformation of the central zone, the internal outward stresses acting in the end zones progressively neutralize the effects of the end friction and, eventually, at least one of the principle stresses in the end zone reaches the ultimate strength value resulting in the formation of cracks in this zone and the consequent failure of the total specimen.

The above discussion on the failure mechanism of a concrete specimen subjected to uniaxial compression implies that the extent of frictional resistance at the boundaries of the specimen plays an important role in the post-ultimate stress–strain behavior of concrete. With the increase in compressive stress, the concrete specimen reaches gradually to Stage 3 from Stage 1 when the stresses in central zone reach to its ultimate strengths. Up to Stage 3, the end zones remain uncracked. If the frictional resistance at the boundaries are reduced, the height of central zone will increase, resulting a more rapid collapse of the specimen after it reaches to the ultimate strength level. Thus it is of outmost importance to minimize the effect of platen restraint for understanding the behavior of concrete under pure compression. The present study focuses on the comparative performance of four different antifriction media in reducing the platen restraint.

2. **Experimental Details**. In the present investigation stress–strain relationships (for a normal strength concrete of grade M25 and a relatively high-strength concrete of grade M50) have been obtained by testing the standard cylindrical specimens with the antifriction medium sandwiched between the specimens and the platen in a stiff close-loop servo-controlled INSTRON make universal testing machine of 2500 kN capacity under a displacement rate of 0.0375 mm/min. Tests for each specimen have been terminated when the stress level reached to 0.4 times of the ultimate strength in the descending branch of stress–strain curve. Stresses have been calculated from applied loads and strains have been calculated using platen-to-platen displacement as well as displacement measured by LVDT (linear variable differential transformer) over a gauge length of 150 mm at the mid-height. The outputs of the LVDT have been fed to an automatic data acquisition system. At the end of each test, the mode of failure and crack patterns have been noted.

An extensive test program was undertaken for the present study with total 90 cylindrical concrete specimens having 150 mm diameter and 300 mm height (see Table 1).

Table 1

Test Program for Investigating the Effect of Platen Restraint on Stress–Strain Behavior of Concrete

Grade of concrete	Antifriction media	Layer thickness/weight of antifriction media	No. of test specimens
M25	No antifriction medium	–	5
	Neoprene rubber	1 mm thickness 3 mm thickness	5 5
	PVC	0.5 mm thickness 1 mm thickness	5 5
	Teflon	1 mm thickness 2 mm thickness	5 5
	Grease	5 g 10g	5 5
M50	No antifriction medium	–	5
	Neoprene rubber	1 mm thickness 3 mm thickness	5 5
	PVC	0.5 mm thickness 1 mm thickness	5 5
	Teflon	1 mm thickness 2 mm thickness	5 5
	Grease	5 g 10g	5 5

The test specimens were cast in cylindrical moulds of 150 mm diameter and 300 mm height and demoulded 24 h after casting. The cylinders were moist cured by complete immersion in a water tank till the date of testing. The curing tank water was changed every week and the compression tests were carried out after a nominal interval of 28 days from the date of casting. Five nominally identical companion specimens were tested for each parameter under investigation. Since in all cases the coefficient of variation in the measured compressive strengths of a group of five specimens was less than 5%, the average values of the measured strengths and stress–strain relationships has been reported here. The test cylinders were capped with a thin layer of stiff, neat Portland cement paste about 4 h after moulding by which time it was assumed that concrete had ceased settling in the moulds. Care was taken to ensure that the cement used for capping was nursed to a stiff paste for about 2 h before it was to be used in order to minimize the possibility of shrinkage of the cap. The planeness of the cap was checked by means of a straight edge and feeler gauge by taking three measurements on different diameters. ACI guidelines [20] have been followed for mix design. The mix proportions used in the present study are shown in Table 2 and other test results of the materials used for two grades of concrete are presented in Tables 3–7. A high range water reducing admixture (HRWRA) Glenium 51, based on high molecular weight polymers and sulphonated melamine formaldehyde has been used for achieving adequate workability. The nominal dosage of the HRWRA has been found to vary in the range 0.5 and 2.25% of the weight of cement, according to the workability requirements of the fresh concrete. All the antifriction media except grease have been cut into the size of 150×150 mm and placed in between the loading platens and concrete specimen at both ends. In case of grease, it has been uniformly applied on the steel platen and then a piece of thick paper has been placed between specimen and loading platens to prevent the direct contact of grease with specimen.

Table 2

Details of Concrete Mix

Grade of concrete	Ordinary Portland cement	Fine aggregate	Coarse aggregate	Water	Water cement ratio
M25	1	1.73	3.14	0.46	0.46
M50	1	1.98	2.99	0.33	0.32

Table 3

Physical Properties of the Ordinary Portland Cement

Property	Unit	Test result	Limiting values as per IS 8112: 1989 [21]
Fineness by Blaine's air permeability test	m^2/kg	268	≥ 225
Soundness	mm	2.8	≤ 10
Specific gravity	–	3.14	3.14
Autoclave expansion	%	0.06	≤ 0.80
Normal consistency	%	26.5	30
Initial setting time	min	90	≥ 30
Final setting time	min	180	≤ 600
72 ± 1 h compressive strength	MPa	25.5	≥ 23
168 ± 2 h compressive strength	MPa	35.0	≥ 33
672 ± 4 h compressive strength	MPa	44.3	≥ 43

3. **Results and Discussions**. In this section, the experimental results obtained from the series of tests performed in this study are presented. Subsequently the results have been analyzed to investigate the effect of platen restraint. Stress–strain relationships obtained from the tests have been normalized with respect to their corresponding ultimate strength.

Table 4

Chemical Analysis of the Ordinary Portland Cement

Oxide composition	Test result (%)	Limiting values (%) as per IS 8112: 1989 [21]
Silica (SiO_2)	21.0	19–24
Ferric oxide (Fe_2O_3)	4.15	1–4
Alumina (Al_2O_3)	7.03	3–6
Calcium oxide (CaO)	61.68	59–64
Magnesia (MgO)	1.81	≤ 6
Sulphuric anhydride (SO_3)	0.92	≤ 3
Total alkali in terms of sodium oxide (Na_2O)	0.45	≤ 0.6
Insoluble residue	1.1	≤ 2
Loss on ignition	1.0	≤ 5

Table 5

Physical Properties of Fine and Coarse Aggregates (ASTM C33)

Physical property	Fine aggregates	Coarse aggregates
Fineness modulus	3.02	3.00
Specific gravity	2.61	2.67
Dry rodded mass (kg/m^3)	2017	1620
Water absorption (%)	1.0	0.50
Moisture content (%)	0–0.4	Zero

Table 6

Sieve Analysis Results of the Fine Aggregates

IS sieve size (mm)	Weight retained (g)	Percentage retained	Cumulative percentage retained	Percentage passing	Percentage passing for Grading as per ASTM C33 [22]
4.750	6.0	1.2	1.2	98.8	95–100
2.360	82.5	16.5	17.7	82.3	80–100
1.180	136.0	27.2	44.9	55.1	50–85
0.600	92.5	18.5	63.4	36.6	25–60
0.300	91.0	18.2	81.6	18.4	15–30
0.150	61.0	12.2	93.8	6.2	0–10
0.075	29.0	5.8	99.6	0.4	–

Table 7

Sieve Analysis Results of the Coarse Aggregates

IS sieve size (mm)	Weight retained (g)	Percentage retained	Cumulative percentage retained	Percentage passing	Percentage passing for Grading as per ASTM C33 [22]
20.00	0	0	0	100.00	100
19.00	1.00	10.50	10.50	89.50	90–100
12.50	6.89	69.32	79.82	20.18	20–55
9.50	1.07	10.76	90.58	9.45	0–15
4.75	0.91	9.15	99.73	0.27	0–5
2.36	0.02	0.20	99.93	0.07	–

The stress–strain curves depicting the effect of various antifriction media for two different grades of concrete are presented in Fig. 2, from which it is evident that the effect of platen restraint has no effect on the ascending branch of stress–strain curve, while the descending branches show considerable variations in their behavior for different antifriction media. Thus the ascending branch of stress–strain curve for concrete is independent of technique used for test and an intrinsic material property, whereas descending branch shows dependency on the technique used for the tests. It can also be observed that slope of descending branch of the stress–strain curve is the least when no antifriction medium is used, and the slope progressively increases as degree of frictional restraint decreases. Grease shows the highest slope in all the cases implying that it is most efficient in reducing frictional restraint among the four tested antifriction media. In the case of Neoprene rubber, peak strain is found to be higher for a relatively thick sheet (3 mm) because of large compressibility of a thick Neoprene sheet.

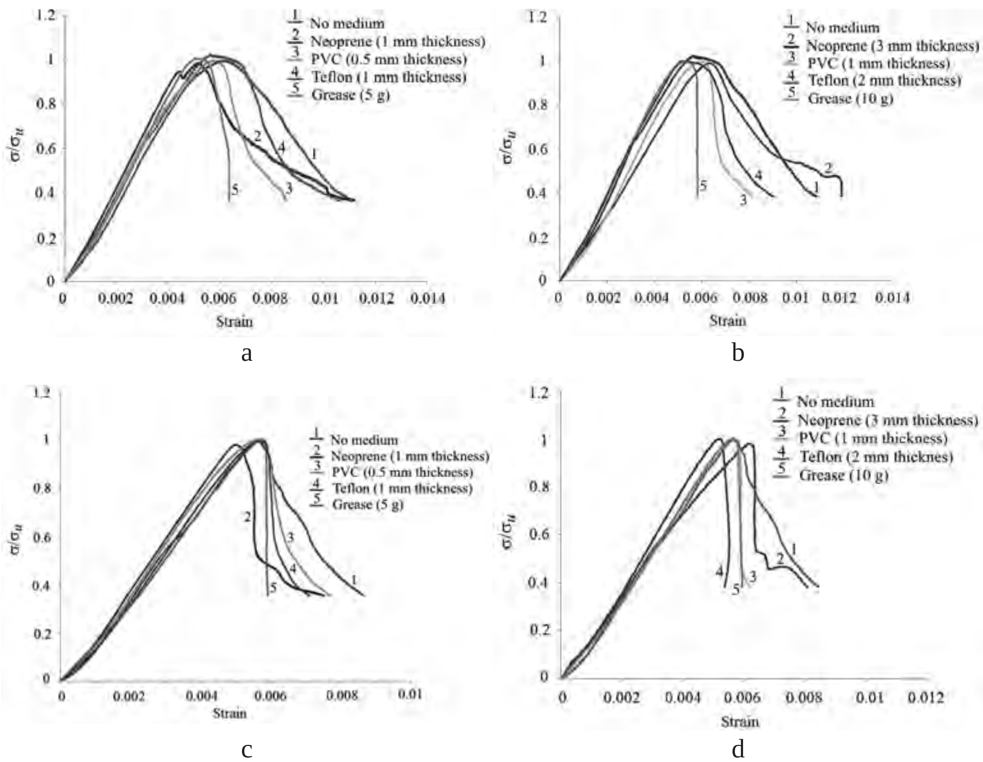
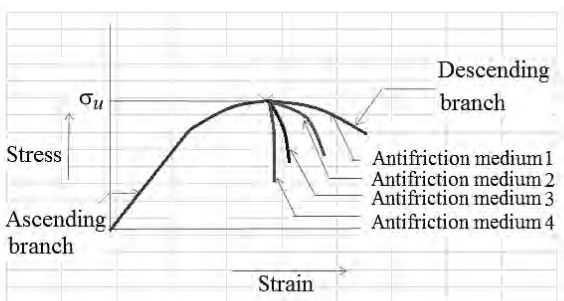


Fig. 2. Normalized stress–strain curve for concrete using different antifriction media (σ and σ_u denote the stress and ultimate strength, respectively): (a) M25 grade concrete (lower antifriction medium thicknesses); (b) M25 grade concrete (higher antifriction medium thicknesses); (c) M50 grade concrete (lower antifriction medium thicknesses); (d) M50 grade concrete (higher antifriction medium thicknesses).

Noteworthy is the fact that Fig. 2 exhibits a continuous increase of strain during the entire loading path. This is in contrast to the observation of Kotsovos [17] during the course of his investigation of platen restraint, in which he mentions a continuous decrease in strain below 80 to 90% of the peak-stress in the descending branch of the stress–strain curves. This phenomenon has been called ‘elastic recovery’ and has been attributed to the occurrence of continuous axial cracks which is supposed to cause unloading within the outer layers of the cylinders, the applied load being predominantly resisted by the core.

Interestingly, the load–displacement relationships furnished by Kotsovos [17] show a continuous increase of axial displacement during the entire loading history. It is reckoned in this investigation that the 'elastic recovery' identified by Kotsovos [17] is due to the relatively flexible loading frame and the strain reversal in the 'elastic recovery' will not take place if a stiff loading frame had been used. With the stiff loading frame of the present investigation, the effect of testing technique on displacement measurements has been minimized and the measured stress–strain relationships give a realistic description of specimen behavior. According to Kotsovos [17], the descending branch of the stress–strain curve describes the interaction between specimen and the loading platens and is not representative of the specimen behavior. This observation is supported by the trends noted in this investigation. Figure 2 shows that when grease is used as the antifriction media the descending branch becomes almost vertical implying a complete loss of load-carrying capacity as soon as the peak stress was attained. This 90° slope of the descending branch is indicative of the fact that platen restraint had been practically eliminated by the use of grease and for this case the descending branch of the stress–strain curve for the normal and the medium-strength concrete was similar.

The effect of platen resistant in concrete cylinder testing can be explained using the analogy of energy absorbed by specimen subjected to different degree of end resistance, which can be quantified by calculating the area under the stress–strain curve of concrete for a particular antifriction medium. For purpose of comparison a term 'Toughness' in this article has been defined as the area under normalized stress–strain curve, where the descending branch is considered up to $0.4\sigma_u$ (Fig. 3). Thus, toughness indicates the energy absorbed by a specimen until its failure and it is dependent on the slope of the descending branch of the stress–strain curve. As degree of frictional restraint increases, failure of specimen is delayed and, consequently, the toughness increases. Slope of the descending branch of stress–strain curve increases with the decrease of frictional restraint, implying the reduction in load-carrying capacity of the specimen after reaching its ultimate strength.



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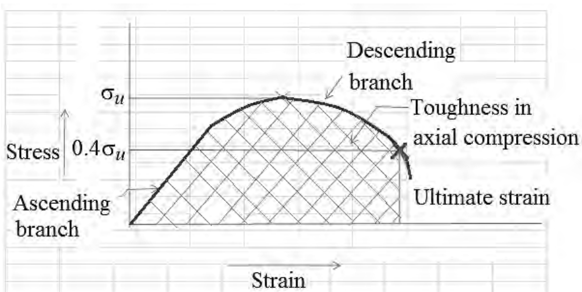

b

Fig. 3. Schematic representation of the stress–strain behavior of concrete with different degree of end friction (a); area under stress–strain curve (b). (Toughness in axial compression.)

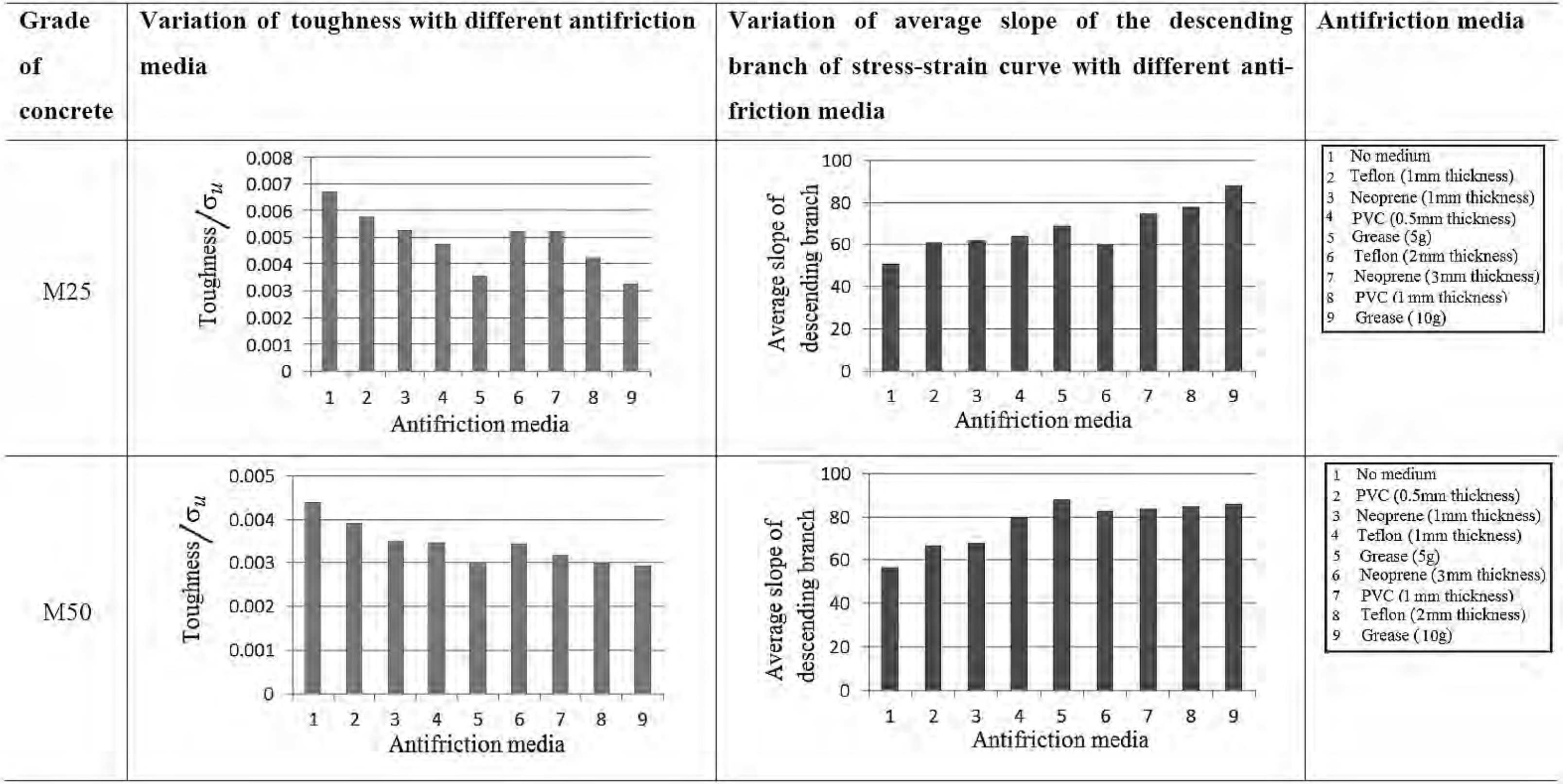

Fig. 4. Variation of toughness and average slope of the descending branch of stress–strain curve for concrete with different antifriction media.

Figure 4 shows the variation of toughness and average slope of the descending branch of stress–strain curve with different antifriction media. From Fig. 4 it is evident that as the toughness increases, the average slope of descending branch decreases implying a higher end friction for the particular antifriction medium. Grease shows the least value of toughness and highest value of average slope for both M25 and M50 grades of concrete. For higher thickness of antifriction medium, the toughness is lower, while the average slope of descending branch is higher. Observing the variation of toughness and average slope of descending branch for different cases of antifriction media with respect to those of no medium case, it can be concluded that the effect of platen restraint is more prominent for the lower grades of concrete.

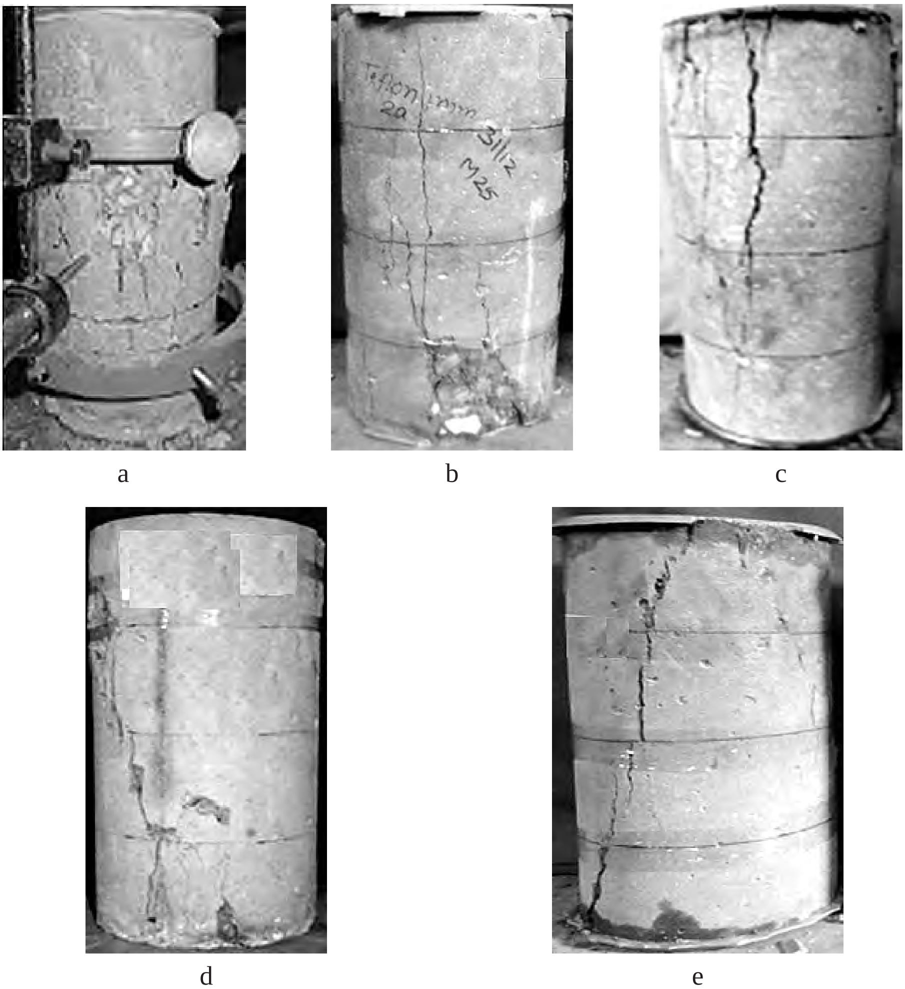

Fig. 5. Typical failure patterns of concrete specimens (M25 grade) for different antifrictional media: (a) no antifriction medium; (b) teflon (1 mm thickness); (c) neoprene (1 mm thickness); (d) PVC (0.5 mm thickness); (e) grease (5 g).

Typical failure patterns for M25 grade of concrete specimens tested under uniaxial compression using different antifrictional media are shown in Fig. 5. For the case of no antifriction medium, failure occurs with bulging of cylinder in central region, while the bulging becomes lesser when platen resistant is reduced by using different antifriction media. In case of grease, which shows the least frictional resistance (Fig. 2), such bulging has been found to be almost absent. Cracks throughout the height of specimens have been observed to appear when the end resistances are reduced. This observation can be attributed to the fact that the height of two end zones (as discussed in Section 1) of the specimen decreases with reduction of the end friction. Thus cracks appear almost throughout the entire height of specimen when antifriction media grease is used. In case of the test involving no antifriction media, the central zone of the specimen attains its ultimate strength when the stresses in the end zones remain below the ultimate strength, resulting bulging to appear in the central zone of the specimen as shown in Fig. 5a.

Conclusions. This article presents a comparative study on effect of platen restraint in the stress–strain behavior of concrete under uniaxial loading using four different commercially available antifriction media (neoprene, PVC, teflon, and grease). A stiff loading frame has been utilized in the present investigation to minimize the effect of testing technique on displacement measurements resulting more realistic description of specimen behavior. The results obtained indicate that the ascending branch of stress–strain curve of concrete is insensitive to platen restraint, while the descending branch is significantly affected. The descending branch becomes considerably steeper as the frictional restraint imposed by the end platens decreases, resulting more rapid loss of load-carrying capacity of the specimen. This sudden reduction in load-carrying capacity of concrete will have a considerable influence on the subsequent analysis and design process and should be accounted with adequate importance for safe design of concrete structures. Contribution of the present study is to access the comparative performance of different commercially available antifriction media to reduce the effect of platen restraint and thereby making it possible to test concrete under pure uniaxial compression. The effect of platen restraint has been quantified using a novel analogy of toughness in this article. Experimental results show that grease is the most efficient option for reducing the effect of platen restraint among the four tested antifriction media. Effect of platen restraint is found to be more prominent in case of lower grades of concrete. Failure patterns corresponding to different antifriction media have also been studied. The following general tendency is revealed: with a higher efficacy of the antifriction media in mitigating the platen restraint, the longitudinal cracks in the specimens increasingly penetrate the end zones of the cylinders. Considering the importance of studying the constitutive model of concrete under uniaxial compression with the least influence of platen restraint, more comparative investigations are needed to be carried out using other techniques. The results presented in this article can serve as a valuable reference for such future research in this field and the inferences drawn from this investigation can be useful for practicing engineers to choose proper antifriction media in concrete testing with the least influence of platen restraint.

Acknowledgments. The authors would like to acknowledge the financial support received from MHRD, India during the period of this research work.

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Received 14. 05. 2015